Report SL-016042 | Final Rev. 0 | December 22, 2020

Renewable Energy Integration Study

Prepared for the

Puerto Rico Electric Power Authority

Prepared by

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Version Log

Version	Issue Date	Sections Modified
Final Rev. 0	December 22, 2020	Initial Issue, Final Version

Issue Summary and Approval Page

This is to certify that this document has been prepared, reviewed, and approved in accordance with Sargent & Lundy's Standard Operating Procedure SOP-0405, which is based on ANSI/ISO/ASSQC Q9001 Quality Management Systems.

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Acronyms and Abbreviations

Acronym/Abbreviation	Definition/Clarification
AEO	Annual Energy Outlook
BESS	Battery Energy Storage System
DG	Distributed Generation
EIA	U.S. Energy Information Administration
FACTS	Flexible AC Transmission System
FFR	Fast Frequency Response
Hz	Hertz
IRP	Integrated Resource Plan
MTR	Minimum Technical Requirement
MVAR	Mega Volt Amps (Reactive)
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
POI	Point of Interconnect
PREB	Puerto Rico Energy Bureau
PREPA	Puerto Rico Electric Power Authority
PSS/E	Power System Simulator for Engineering
PV	Photovoltaic
RFP	Request for Proposal
RoCoF	Rate of Change of Frequency
RPS	Renewable Portfolio Standard
S&L	Sargent & Lundy
SCMVA	Short Circuit MVA
SCR	Short Circuit Ratio
SOC	State of Charge
USD	United States Dollars
US DOE	United States Department of Energy
WSCR	Weighted Short Circuit Ratio

Study Recommendations and Summary

This renewable integration study assesses the capability of the Puerto Rico Electric Power Authority's (PREPA) power grid to accommodate increased levels of inverter-based generation capacity. Additionally, this study provides several recommendations of projects and upgrades that will help PREPA provide electrical system reliability as additional renewable generation is installed for Puerto Rico to adhere to the Renewable Portfolio Standards (RPS). Given the results of the study contained herein, we identify the following recommendations for PREPA to provide a reliable electrical system while achieving the 2025 RPS goal of 40%.

- **Intermediate-Term Maximum Instantaneous Inverter-Based Limit of 60%** – Based on the results of Sargent & Lundy's (S&L) dynamic analysis of Puerto Rico's electrical grid, we recommend that instantaneous inverter-based generation (i.e., solar photovoltaic [PV], wind, and battery energy storage) levels in Puerto Rico do not exceed 60% for the near to intermediate future. Our findings indicate that there would not be sufficient electrical system inertia to maintain system frequency following a disturbance, if instantaneous inverter-based generation levels are allowed to go above 60%. This limit will help to mitigate the risk of system instability and load shedding as Puerto Rico installs more inverter-based generation. It should be noted that the 'instantaneous' limitation specifically refers to the amount of generation from inverter-based sources at a specific instance.

  It is possible to operate a power system at very low or zero inertia, but examples of such systems are limited. For example, zero-inertia AC microgrids exist, but these systems are small in size. Operating a larger power system with little to zero inertia requires further research and new approaches to maintaining grid frequency, many of which are being investigated by the energy industry now. For this reason, a 60% limit on instantaneous inverter-based generation levels is essential for the short and intermediate time frames, but not necessarily for the long term.

- **New Synchronous Generation** – Over 2,000 MW of legacy oil-fired generation and 450 MW of coal-fired generation is scheduled to be retired in Puerto Rico between now and 2027. As such, our analysis determines that new, highly efficient, thermal generation units, with rapid startup and ramp rate capabilities are needed to both facilitate the successful retirement of these legacy generation units and to provide electrical system stability / reliability as renewable energy generators are installed to meet RPS targets. Our analysis finds that without approximately 600-700 MW of new, state-of-the-art, flexible, thermal generation equipment, there will not be sufficient grid inertia to provide a reliable electrical system as Puerto Rico transitions heavily towards renewable energy generation. More specifically, we recommend a new combined cycle power plant in the San Juan area (the main load center in Puerto Rico) and flexible new peaking generation at critical locations around the island.

New thermal generation equipment will also help PREPA manage the interruption of generation from certain renewable energy resources due to cloud cover, tropical storms or hurricane events, in addition to helping PREPA manage any potential limitations on battery discharge durations. During major storms, this new thermal capacity could provide emergency generation, which is vital for the safety and security of the island's residents. Peaking generators and the combined-cycle power plant funded by FEMA 404 and 428 will help PREPA provide a reliable electrical system through Puerto Rico's ongoing transition to renewable energy.

- **Minimum Technical Requirements** – S&L endorses compliance with minimum technical requirements (MTRs) for new inverter-based resources. PREPA needs these requirements to manage system inertia and grid strength as inverter-based resources are added to the Puerto Rico electrical system. PREPA will be constantly evaluating how to safely incorporate large amounts of inverter-based renewable energy onto the grid. As a result, it is PREPA's expectation that the MTRs for inverter-based renewable energy generators will continually evolve in the future.

- **Synchronous Condensers** – Adding synchronous condensers improves overall system performance, both from the perspective of grid inertia and grid strength. Synchronous condensers, in addition to new synchronous generation described above, will be needed to support Puerto Rico's rapid transition to renewable energy. Synchronous condensers provide improved short circuit strength and inertia and will become necessary as more renewable energy projects are integrated into the electrical system. The exact location, number, and size of synchronous condensers needed will be determined once PREPA better understands more details concerning the locations and sizes of new inverter-based resources. Note that adding synchronous condensers can introduce angular instability, in addition to introducing potential challenges associated with protection systems and system maintenance. These challenges will have to be properly addressed as synchronous condensers are installed. Also, the addition of synchronous condensers does not preclude the need for synchronous generation due to the fact that synchronous condensers cannot provide generation that may be needed (i.e., during major storms, hurricanes, etc.).

- **Diverse Renewable Energy Generation** – We recommend a diverse mix of renewable energy generation for Puerto Rico, particularly from technologies that have different hourly generation profiles. By incorporating renewable energy technology diversity into the overall renewable energy development strategy, we expect that less energy storage systems will be needed (to shift generation from mid-day to the evenings) and the risk of renewable curtailment will be reduced.

Renewable energy generators that are dispatchable and synchronous are particularly important from the perspective of managing electrical inertia and meeting RPS targets. For this reason, we view the revitalization of the existing hydroelectric power plants as important (provided the economic business case makes sense). We are also currently evaluating a variety of biofuels as an alternative for portside thermal generators (making those synchronous generators RPS-contributing).

- **New Transmission Lines and Associated Electrical System Improvements** – System upgrades and adding / restoring transmission lines connecting the weak areas can provide additional paths for short circuit flow and thus increase system strength measured at any bus. Improvement and modernization of the Puerto Rico transmission system is an important part of improving system stability / reliability for the future.

- **Puerto Rican Electric Grid Analysis Models** – The importance for high quality and accurate electrical system modeling cannot be overstated, especially as PREPA implements massive improvements to the transmission and distribution system and as Puerto Rico embarks on a rapid transition away from existing thermal generation to renewable energy. As improvements to the Puerto Rican electrical grid are made, it will be important for existing electric grid models (i.e., Power System Simulator for Engineering [PSS/E] models) to be updated to capture all changes to the electrical system. Additionally, as inverter-based penetration levels increase, electro-magnetic transient system studies (which would better capture the impact of inverter-based generation on the grid under weak grid conditions) will likely need to replace traditional analysis tools. S&L will work with PREPA to develop a recommended path for analysis work, which will be in step with the growing integration of inverter-based projects.

1.0 Introduction

1.1. Background

In the aftermath of the 2017 hurricane season, the Puerto Rico Electric Power Authority (PREPA) suffered great losses across much of its electric power grid. In September, sequential hurricanes—Irma followed by Maria—devastated the electrical transmission and distribution system. Since these events, PREPA has faced the challenge of not only restoring the system, but also rethinking how the electrical system should be modified to be stronger, more reliable, and resilient.

In February 2018, PREPA's Governing Board released its vision statement as a guide for the future of the electric utility. One of its basic principles is that PREPA will strive to develop a more sustainable system and move away from its reliance on inefficient fossil fuel-based generation and transition to a diverse mix of renewable energy generation resources. Based on the principles of the new vision and the requirements imposed by applicable laws and regulations, PREPA prepared the Puerto Rico Integrated Resource Plan (IRP) 2018-2019 and issued it in draft form in June 2019. The IRP set a roadmap for the future development of the utility's electrical infrastructure with specific plans to improve the resiliency and reliability of its entire electrical generation and delivery systems, reduce the cost of energy to customers, and limit PREPA's future dependence on fossil fuels. The Puerto Rico Energy Bureau (PREB) reviewed the IRP plan and issued its Final Resolution and Order on the IRP on August 24, 2020, providing detailed findings, conclusions, and orders to PREPA.

PREB's Final Resolution and Order dictates the action plan that PREPA must follow as it lays the foundation for the future of Puerto Rico's electrical system. The key elements of the order directly pertaining to this renewable energy integration study are i) increased deployment of solar photovoltaic (PV) and battery resources as compared to PREPA's IRP proposal, ii) issuance of a series of Requests for Proposal (RFPs) for all forms of renewable energy resources that will allow PREPA to meet the Renewable Portfolio Standard (RPS) goals set forth in Act 82-2010 and Act 17-2019[1], and iii) retirement of PREPA's oil-fired plants (Aguirre Steam unit 1 & 2, Palo Seco Steam units 1-4, and San Juan Steam units 7-10) over the next five years.

1.2. Renewable Energy Integration Study

This renewable energy integration study assesses the capability of PREPA's power grid to accommodate increased levels of inverter-based resources (i.e., solar PV, wind, and battery energy storage system

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[1] These Acts established the RPS in Puerto Rico and require PREPA to procure given percentages of its power needs by renewable energy. The RPS milestones are set as follows: 20% by 2022, 40% by 2025, 60% by 2040, and 100% by 2050.

[BESS]) and provides several recommendations of projects and upgrades that will help PREPA provide electrical system reliability as additional renewable energy generators are installed for Puerto Rico to adhere to the Renewable Portfolio Standards (RPS).

Utilities face numerous challenges as they transition to an increased dependency upon inverter-based generation fleets. Besides ensuring the availability of sufficient generation and transmission capacity to meet the demand profiles of their system, utilities must also maintain enough flexibility in their system to accommodate the variability and uncertainty inherent with solar PV and wind generation. The system must also be able to provide reliable services while maintaining acceptable frequency and voltage levels during normal conditions and even after disturbances to system stability or the unexpected loss of components.

Section 2.0 of this report discusses challenges associated with increased penetration levels of inverter-based resources in Puerto Rico.

Section 3.0 discusses the electrical analyses that have been performed to understand impacts to the power system as inverter-based renewable energy generators are installed. The analyses focus on electrical system reliability, specifically how it is both impacted by higher levels of inverter-based renewable energy generators and how it can be improved.

Section 4.0 discusses generator dispatch and electrical system modeling that was performed to determine one possible portfolio of renewable energy resources that could be integrated for PREPA to meet its 40% RPS target for 2025 and to understand how all of Puerto Rico's generators (existing and new renewables modeled) would be dispatched to meet system loads. The analysis takes into account findings and recommendations that are identified from the electrical analyses discussed in Section 3.0 in order to provide a reliable electrical system.

Additionally, per PREB's request, Sargent & Lundy (S&L) has compiled a list of preferential locations for interconnection of inverter-based resources and the estimated power that can be injected into these locations (based on the scenarios studied). This list is provided in Appendix A.

2.0 Integrating Inverter-Based Generation into Puerto Rico

This section introduces the important considerations and challenges associated with properly integrated high levels of inverter-based generation – specifically those items that are applicable to Puerto Rico. Additionally, we provide discussions of recommended solutions that PREPA can implement to provide electrical system stability and reliability as this transition takes place.

The discussion in this section centers on the following two areas:

- **System Inertia** - Higher penetrations of inverter-based generation may lead to PREPA's power grid becoming more sensitive to large frequency variations caused by system contingencies, due to low electrical inertia of the system. Without proper mitigation, large frequency variations can lead to underfrequency load trips and outages
- **Grid Strength** - For higher penetrations of inverter-based generation, the electrical grid strength at various locations across Puerto Rico will decline if interventions are not taken. Weaker electrical grids are more susceptible to voltage collapse and system outages

Additionally, per the Puerto Rico Energy Bureau's (PREB) request, S&L has compiled a list of preferential technical locations for inverter-based resources and the maximum power that can be injected into these locations. This list is provided in Appendix A.

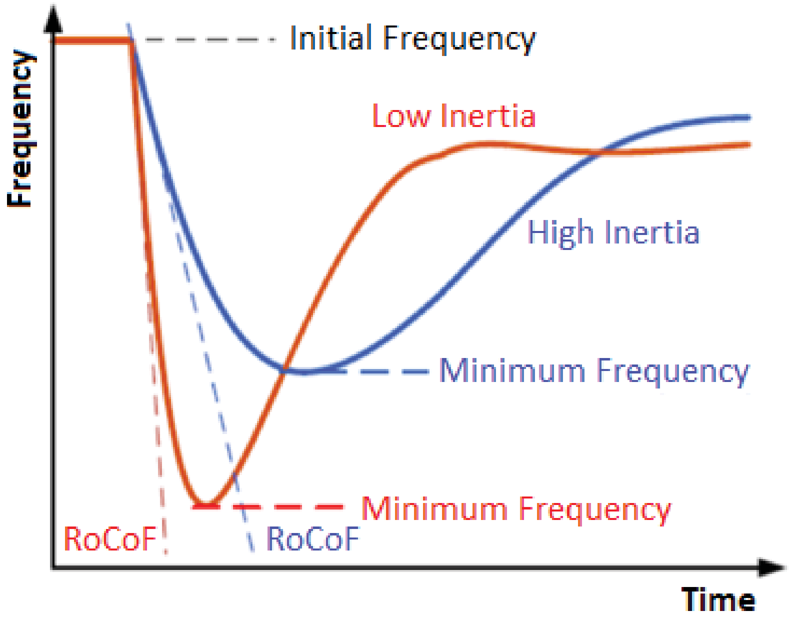
2.1. Power System Inertia in Electrical Grids

Power system inertia is defined by the North American Electric Reliability Corporation (NERC) as the "*ability of a power system to oppose changes in system frequency due to resistance provided by rotating masses*", where 'rotating masses' refers to the mass of large rotating (or synchronous) generators. Traditionally, thermal generators have provided system inertia to electrical systems; however, inertia can also be provided by other rotating machinery, such as industrial motors. In the event of a sudden electrical system disruption, such as a generator or transmission line outage, electrical systems with higher amounts of rotating inertia are more suitable for dampening frequency variations that could lead to system instability.

In contrast, inverter-based generators, which include renewable energy generators such as solar PV and wind (BESS is also an inverter-based resource, but is not classified as a generator), do not contribute inertia to the power grid. Thus, if inverter-based renewable energy penetration levels increase in an electrical system, coupled with a subsequent reduction in synchronous generation, there is a reduction in system inertia. In an electrical system without sufficient inertia, the impact of a large, sudden disruption on electrical system frequency may become more pronounced, increasing the risk of system instability. In the worst cases, this can result in required load shedding or power system collapse.

The following figure illustrates how system frequency can change following a system disruption (such as the sudden loss of a large generator) for different systems. For electrical systems with high levels of synchronous generation, the system frequency changes much more slowly (lower rate of change of frequency, or RoCoF) due to the fact that synchronous generators provide inertia, which helps to dampen the impact of the disruption on system frequency. Alternatively, electrical systems with higher penetration levels of inverter-based generation (and thus less inertia) experience much more rapid changes in system frequency (higher RoCoF) following a disruption. Large deviations in system frequency that occur rapidly are more likely to trigger system protection trips and load shedding, which can lead to cascading system issues.

Figure 2-1 — Example of System Frequency Following a Disruption



2.1.1. Improving Electrical Inertia in Puerto Rico

There are various ways to address the reduction in inertia expected as the amount of inverter-based resources rises in Puerto Rico. We highlight some of the potential solutions that we consider could be employed in Puerto Rico as follows. Additionally, our electrical system analyses (see Section 3.0) include some of these solutions.

2.1.1.1. Synchronous Generation

The traditional method in which system inertia can be maintained is by ensuring there are a sufficient number of synchronous generators online at all times to provide the inertia levels needed to withstand the impact of sudden system disruptions. An example of this can be observed in Ireland, which reached an annual renewable energy penetration level of 29% in 2018. At this point, Ireland's electrical system operator, Eirgrid, limited the allowed instantaneous penetration (MW) of inverter-based power sources to no more than 65% at any time. Analyses performed by Eirgrid have demonstrated that the probability of Ireland's electrical system becoming unstable in the event of large disruptions increases dramatically if renewable energy penetration exceeds the 65% limit; thus, Eirgrid mandated that at least 35% of system generation must be provided by synchronous sources at all times.

Dispatching synchronous generators in this manner may force system operators to deviate somewhat from an economic dispatch focus – this is especially true if only expensive synchronous generators are available to be dispatched for inertia support, or if synchronous generators need to be dispatched at less efficient partial load points (reducing fuel efficiency). Furthermore, operators may be required to curtail generation from inverter-based resources – the structure of the contracts in place between the utility and the inverter-based power plant may complicate the decision / ability to curtail. For this reason, we recommend that contracts for new inverter-based generators in Puerto Rico be structured in such a way that gives PREPA the flexibility to curtail inverter-based generation in a cost-effective manner in order to maintain system reliability / stability. System inertia can also be provided by synchronous renewable energy resources. Some examples of synchronous renewable resources include hydropower, geothermal, and spinning generators that burn biofuels or biomass.

We consider that limiting the amount of instantaneous inverter-based generation (similar to what has been implemented in Ireland) is a potential intermediate-term solution for Puerto Rico to help provide system stability / reliability. As inverter-based generation makes up larger and larger portions of total generation in large electrical systems, utilities are still determining the best methods to provide system reliability in the face of an inertia-less future. By setting temporary limits on the amount of instantaneous inverter-based generation, PREPA can help provide system stability / reliability in the near term as Puerto Rico transitions away from synchronous thermal generation into inverter-based renewable energy and energy storage.

2.1.1.2. Synchronous Condensers

Another solution that can support the grid in the face of potential stability issues tied to inverter-based resources is the addition of synchronous condensers. Synchronous condensers are rotating machines that support system strength, voltage, and inertia, but do not generate power. The variation in the excitation of the synchronous condenser may generate or absorb reactive power that can support the voltage regulation of the grid, improving the power factor in the surrounding area when needed. A synchronous condenser naturally stores kinetic energy in its rotational mass, which increases system inertia, and therefore increases the frequency stability of the system. From the perspective of inertial response support to the power grid, the location of the synchronous condensers is not critical (however, location does matter more from a grid strength perspective – see Section 2.2).

The addition of synchronous condensers may present stability challenges as synchronous condensers can introduce angular instability; thus, the impact of new synchronous condensers considered for Puerto Rico should be analyzed as part of the development process – as any additional synchronous generation to the power system would be analyzed. Synchronous condensers can be either converted larger synchronous generators or constructed new. Drawbacks of synchronous condensers not only include the fact that they are a more expensive solution to inertia challenges, but also the fact that synchronous condensers can introduce technical challenges associated with protection systems and system maintenance.

2.1.1.3. Fast Frequency Response Inverter-Based Resources

Inverter-based resources can provide a beneficial counterbalancing effect to offset low inertia levels if proper planning is used when integrating these resources. While these resources may reduce the amount of inertia in the system, they also have fast response capabilities and can inject energy into the grid during critical times to help mitigate the impact of a sudden disruption on system frequency. This is known as fast frequency response (FFR) and it describes the ability of some resources, including inverter-based generators, to increase the net supply of energy much faster than traditional mechanical responses from synchronous generators. Through this method, the high RoCoF that can be experienced in systems with low inertia levels can be balanced with a rapid response from FFR resources.

However, inverter-based power plants will not have the ability to provide this sudden energy injection unless they are designed and constructed with this ability in mind. For example, generation from the inverter-based resource needs to be limited to less than its full output – then the remaining available capacity can be used to quickly increase output as needed. For wind resources this requires reducing the output of the wind turbine, usually by changing the blade pitch angle. For solar PV resources, power electronics can be used to command the inverter to reduce output as needed. Output from these resources can then be rapidly increased to provide frequency support services. Alternatively, inverter-based resources can be paired with energy storage systems. To address this issue in Puerto Rico, PREPA has developed minimum technical requirements (MTRs) for future solar PV and wind energy generation, which requires that these generators are paired with energy storage systems capable of providing power injection during critical times (MTRs are discussed further in Section 2.5).

Note that when inverter-based resources were first beginning to be considered for frequency support, the term ‘synthetic inertia’ was initially used to describe the rapid response available from these resources, even though their response had nothing to do with the utilization of kinetic energy. Industry professionals now agree that the term synthetic inertia is inaccurate and ‘fast frequency response’, or FFR, is the preferred term to capture the rapid response of inverter-based resources. Research is ongoing to understand how to optimize the FFR services that can be obtained from inverter-based resources. Studies for systems where the majority of generation would come from inverter-based resources are in early stages – there is currently no large-scale example of an electrical system (i.e., the size of Puerto Rico), where system stability is maintained exclusively through FFR inverter-based resources.

2.2. Grid Strength

Grid strength is a term commonly used to describe how well areas within an electrical grid perform with respect to voltage magnitude and angle in response to small system perturbations. In a portion of a grid that is ‘stronger’, voltage magnitude and angle are relatively insensitive to changes (e.g., current injections from inverter-based resources). In contrast, an area with ‘weaker’ electrical strength occurs when that location within the grid has low short circuit currents with respect to the power flow. Sections of an electrical grid that are weaker are more sensitive to changes in real / reactive power, which can lead to local voltage instability. Weaker portions of electrical grids are more susceptible to voltage collapse and reliability outages.

The concept of grid strength is not new; however, as deployment of inverter-based resources has grown, the importance of quantifying and assessing grid strength has increased. Generally, areas in the electrical grid that are closer to larger, synchronous generators are stronger areas in the electrical grid than areas where there are great distances to synchronous generators. Traditionally, inverter-based generators require adequate grid strength to synchronize power electronics.

A key challenge associated with grid strength is that the best mitigation strategies and solutions can be site- and issue-specific. Different locations within the same electrical grid may require different solutions. Additionally, coordination with the inverter-based power plants is often required. As noted in a recent NERC guideline[2], “the solutions deployed are dependent on the system characteristics for each inverter-based resource interconnection, as well as the manufacturer capabilities of the inverter-based resource. Coordination and engagement with the manufacturer are critical to identify the best solution for each potential given weak grid issue.”

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[2] Integrating Inverter-Based Resources into Low Short Circuit Strength Systems, Reliability Guideline – North American Electric Reliability Corporation, 2017

Manufacturers of inverter-based generation normally indicate the minimum short circuit ratio needed for proper operation. The PREPA MTRs for renewable energy generation (solar PV and wind) interconnection also include a minimum short circuit ratio requirement.

2.2.1. Managing Grid Strength in Puerto Rico

There are a number of potential solutions that can help with Puerto Rico's grid strength – we list and describe some of these potential solutions in the subsections that follow. Additionally, our electrical system analyses (see Section 3.0) include some of these solutions.

2.2.1.1. Synchronous Condensers

As previously discussed, synchronous condensers are rotating machines that support system strength, voltage, and inertia, but do not generate active power.

Synchronous condensers can increase the short circuit level of the system, improving the system strength in the vicinity of the location of this equipment. This also improves the system voltage stability in weak interconnections. As noted, traditional inverter-based generators require adequate grid strength to synchronize power electronics. Synchronous condensers may be installed in certain weak areas to improve the system strength and provide dynamic reactive support.

It is important to note that the addition of synchronous condensers may present stability challenges as synchronous condensers can introduce angular instability; thus, the impact of new synchronous condensers considered for Puerto Rico should be analyzed as part of the development process – as any additional synchronous generation to the power system would be analyzed. Synchronous condensers can be introduced into the system through a) retired and converted large synchronous generators, b) newly manufactured dedicated condensing machines, or c) by integrating with new thermal generation equipment with integral clutched generator disconnects. Synchronous condenser deployment is generally a more expensive solution to manage grid strength and in addition to possible angular instability, synchronous condensers can introduce potential challenges associated with protection systems and system maintenance.

2.2.1.2. Generator-Specific Modifications

There are a number of modifications an inverter-based generator can make that can help to address a weak grid issue. Some of these include plant control changes (i.e., voltage control strategies), converter control changes (i.e., modifications to the power electronics controls), or reductions in plant capacity / power output. The effectiveness of each of these methods is case- and location-specific.

2.2.1.3. Transmission Reinforcement

Reinforcement of existing transmission lines can help to increase the short circuit ratio; thus, is a potential method to manage grid strength in some cases. Work to improve the transmission system in Puerto Rico is ongoing.

2.2.1.4. Battery Energy Storage Systems

These systems can provide fast frequency response and voltage control, but battery systems may also be subject to instabilities associated with weak grids (and do not provide inertia). This is especially true if the storage system does not have the proper control logic. One technology that would support the increase of renewable energy is grid forming inverter technology. Grid forming inverter technology would allow for operation of inverter-based generation without relying on synchronous condensers or synchronous generation, including scenarios with 100% of electrical load being supplied by inverter-based renewables. Battery energy storage systems with grid forming inverter technology have yet to be widely installed throughout the power industry.

2.3. Examples of Other Regions with High Penetrations of Renewable Energy

While renewable energy penetration levels have increased around the world, few locations have reached the threshold where high levels of inverter-based generation could lead to significant electrical stability issues. Texas, Ireland, South Australia, and Hawaii are some examples of regions that have significant instantaneous penetration levels of inverted-based renewable energy generation. These locations often see instantaneous inverter-based generation accounting for approximately 50% to 60% of total system generation. Each of these regions face unique challenges and solutions to maintain system reliability while operating at these inverter-based renewable energy generation levels.

As mentioned previously, Ireland reached an annual renewable energy penetration level of 29% in 2018. At this point, Ireland’s electrical system operator, Eirgrid, limited the allowed instantaneous penetration (MW) of inverter-based power sources to no more than 65% at any time. Eirgrid demonstrated that the probability of Ireland’s electrical system becoming unstable in the event of large disruptions increases dramatically if instantaneous inverter-based generation exceeds the 65% limit.

To minimize risks and allow for the secure operation of their electrical systems, operators in Ireland, Texas and South Australia normally limit (curtail) the output of inverter-based power sources, or require a minimum level of synchronous generation to be operating. Note that curtailment decisions rely on a complex set of variables, including the flexibility and availability of the remaining generation resources. Also, given that the contract between the inverter-based generator and utility impacts both whether curtailment is allowed and the associated cost, we recommend that contracts for new inverter-based generators in Puerto Rico be structured in such a way that gives PREPA the flexibility to curtail inverter-based generation in a cost-effective manner in order to maintain system reliability / stability. In addition to the option to curtail inverter-based generators, some system operators also attempt to minimize, via technical / operational constraints, the largest credible potential system disruptions.

Technical challenges, such as how to maintain grid strength, ensure adequate inertia, and control the rate of change of frequency, are expected to increase as inverter-based power source penetration levels rise. System-specific solutions need to be developed and implemented to maintain system reliability. This is a rapidly advancing area of research in the energy industry.

2.4. Previous Analyses of the Puerto Rico Power System

***Siemens Analysis* –** The reliability of the Puerto Rico power system under different proposed renewable energy and generation scenarios was analyzed as part of the report Siemens prepared for PREPA in July 2015, "*Integrated Resource Plan Volume II: Transmission Analysis*". The highest instantaneous penetration of inverter-based renewable energy generation studied in that report is 1,316 MW with 400 MW supplied by Distributed Generation. This level of inverter-based renewable power generation is equivalent to approximately 50% of instantaneous renewable penetration. The Aguirre generators were modeled to be still in service and as available for inertia and frequency support in the analysis. As part of the analysis, the largest modeled generator outage event (system disruption) for the 50% renewable energy penetration scenario was the loss of the 230 kV lines feeding the Bayamón substation. It is not clear how much generation loss occurred during this modeled event or what the frequency response would be if a large generator were tripped. In the report, Siemens states that this renewable energy penetration level could lead to large frequency excursions if the inverter-based renewable generation does not contribute to stabilizing the frequency (i.e., through FFR, battery energy storage tied to the MTR-compliant renewable energy power plants, etc.); however, the Siemens analysis does not investigate this statement further.

The impact of inverter-based renewable energy on power system reliability presented in the S&L analysis documented in this report differs from the initial Siemens analysis. In S&L's analysis, planned generator retirements (Aguirre, Palo Seco, and San Juan generators) are modeled in PSS/E and the PSS/E model is updated to include the renewable energy integration needed to meet the RPS targets. Also, the level of instantaneous inverter-based penetration considered in the S&L study is 60%, which is higher than the level studied in the Siemens report. In addition to these model updates, S&L considers a number of large generator trip events to analyze the frequency response. The S&L dynamic analysis is presented in detail in Section 3.1.

S&L Analysis of Renewable Energy Penetration Limit of As-Is System in 2020 – S&L conducted an earlier analysis of the PREPA system to determine the maximum instantaneous inverter-based renewable energy penetration level that can be incorporated into PREPA's power grid as it exists today, while maintaining acceptable frequency response. This analysis did not consider any additional grid-support equipment being added to the power system (i.e., new rotating generation, synchronous condensers, or transmission lines), none of the generators scheduled for retirement were removed, and existing control parameters were not adjusted in order to accommodate new renewable energy integration. The results from this analysis are considered to be a reasonable approximation of system operation, accounting for the fact that the PSS/E model is somewhat overly optimistic in that it provides quicker real power output in response to frequency decline than may be experienced in actual operation. S&L attempted to adjust for this and found the maximum inverter-based renewable energy capacity that can be integrated to the system as it exists today was 650 MW total of utility scale generation, which includes both existing and new inverter-based renewable energy generation. This value is a 'system as-is' value today and does not include expected system upgrades or energy storage systems that will be incorporated in the near future.

2.5. PREPA Minimum Technical Requirements

Previous power system studies performed for PREPA by the National Renewable Energy Laboratory (NREL) and U.S. Department of Energy (DOE), have demonstrated the need to establish specific MTRs for the interconnection of variable inverter-based renewable energy generation to the Puerto Rico electric grid.

MTRs are essential to significantly increase and optimize the penetration levels of renewables on the island. The main objective is to help PREPA manage impact that of inverter-based renewable energy generators have over the stability and reliability of the grid. One of the main technical requirements associated with this objective is ramp rate control, which allows limited control of the renewable energy power plant's active power output (MW) during sudden variations of solar irradiation (for solar PV power plants) or wind speed (for wind power plants). The MTRs can substantially reduce the negative effects of uncontrolled power output variations (ramp down / up) related to the typical variability of the solar irradiance and wind availability. Based on PREPA's operational experience with the current inverted-based renewable projects, MTRs are crucial both for the successful integration of these generators to the grid and reliable operation of the electrical system.

The operation of PREPA's electrical system with a high penetration of inverted-based generation also has to consider the displacement of system regulation and control capabilities normally provided by conventional synchronous generators. If this regulation capability is not included as part of the technical characteristics of the new inverter-based renewable energy power plants, the stability of the Puerto Rican electrical system could be compromised under certain circumstances. As such, the MTRs include a frequency response requirement (i.e., FFR and primary frequency response). Specifically, the renewable energy power plant should be able to contribute 10% of the maximum AC active power capacity during large frequency deviations (such as loss of large generator), emulating the traditional support provided by traditional synchronous generation. This characteristic will help the electrical system as inertia levels fall due to the retirement and replacement of synchronous thermal power plants with inverter-based renewable energy power plants.

PREPA shall be constantly evaluating how to safely incorporate large amounts of inverter-based renewable energy onto the grid. As a result, it is PREPA's expectation that the MTRs for inverter-based renewable energy generators will continually evolve in the future.

3.0 Electrical Grid Modeling

S&L performed an analysis to evaluate the stability of PREPA's anticipated power grid configuration in 2025, taking into account the *Final Resolution and Order on the Puerto Rico Electric Power Authority's Integrated Resource Plan*, issued by PREB. The focus of this analysis centers on the impacts of integrating large amounts of inverter-based generation into the Puerto Rican grid. More specifically, S&L focuses on the two different system impacts, discussed further in Sections 3.1 and 3.2:

- **System Inertia** – S&L analyzed the impact of higher penetrations of inverter-based resources to PREPA's power grid, focusing on how sensitive the grid becomes to large frequency variations caused by system contingencies. This study focuses primarily on system inertia
- **Grid Strength** – S&L performed an analysis on the impact to higher penetrations of inverter-based generation and local electrical grid strength across Puerto Rico

S&L performed this analysis using the Power System Simulator for Engineering (PSS/E) from Siemens PTI. The PSS/E model of the power grid was originally provided by PREPA and then modified by S&L to reflect the necessary generation portfolio modifications in 2025 to meet both the RPS targets and the items in the PREB resolution.

3.1. Power System Dynamic Analysis for 2025

S&L performed a transient stability analysis of the Puerto Rican electrical system in order to estimate the impact to system inertia as inverter-based renewable energy generators are developed. The primarily purpose of S&L's analysis is to understand Puerto Rico's power system reliability as more renewable energy generation is added to the grid. NERC defines a reliable power system as one that is able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity. Power system reliability analyses focus on times when the instantaneous inverter-based renewable energy penetration is at its highest. These times are when the ratio of inverter-based generation to total generation are at the highest.

This study provides recommendations for how PREPA can provide a reliable electrical system as RPS targets are pursued. The analysis focuses on the year 2025, taking into account the resolutions detailed in the *Final Resolution and Order on the Puerto Rico Electric Power Authority's Integrated Resource Plan*, issued by PREB. This assessment is performed by simulating large generator trip events and checking that frequency nadir (lowest point at which the frequency drops) and rate of change of frequency (RoCoF) are within the criteria set by the PREPA underfrequency load shedding settings.

The modeled scenario accounts for the required amount of renewable energy required for Puerto Rico to comply with the 2025 40% RPS target. The scenario considers a specific snapshot in time with the following characteristics:

- A typical sunny morning where solar PV generation is operating at or near its maximum capacity
- Energy storage systems (batteries) are assumed to be in charging mode. The battery storage systems are used to capture the excess inverter-based renewable energy generation during the daytime and shift it to the evening, night, or early morning
- Inverter-based generation accounts for **60%** of the total island power generation. This specific threshold was chosen in order to test the impact on electrical system stability if a system disruption occurred while inverter-based generation accounted for this percentage of total generation. To meet this requirement, any excess inverter-based generation was considered to be curtailed
- Fuel oil generators are retired, consistent with the *Final Resolution and Order on the Puerto Rico Electric Power Authority's Integrated Resource Plan* issued by PREB

Once modeled, S&L investigated the impact of various system disruptions on the electrical system. Additional inputs and assumptions are detailed as follows. Results are provided in Section 3.1.3.

3.1.1. Power System Dynamic Analysis Inputs and Assumptions

The inputs and assumptions considered for this analysis are provided in the following sections.

The analysis utilized PSS/E to study the impacts of 60% instantaneous renewable energy generation on power system reliability in 2025. The following existing oil-fired thermal generators are assumed to be retired by 2025:

- Aguirre Steam Units 1 and 2
- San Juan Units 7, 8, 9, and 10
- Palo Seco Units 1, 2, 3, and 4

The following table provides the thermal generation that was included in the PSS/E model. Note that *Pgen* is defined as the real power, or dispatched MW level of the generators modeled at the specific snapshot in time analyzed.

Table 3-1 — Modeled Thermal Generation

Generator Name	Dispatched Real Power, *Pgen* (MW)
AES 1	227
AES 2	227
Costa Sur 5	205
Costa Sur 6[1]	-
EcoEléctrica	275.5
San Juan 5 CC	191.1
San Juan 6 CC[1]	-
Total	**1,125.6**

Note: 1) Costa Sur 6 and San Juan 6 are not considered to be generating for the specific time analyzed in the model

The PSS/E model has been updated to include the desired amount of renewable energy (and energy storage) to meet the 2025 40% RPS target, while limiting instantaneous inverter-based generation to 60%. Table 3-2 is a summary of the renewable energy resources that were included in the PSS/E model. As previously described, this scenario represents a typical sunny morning where solar PV generation is near or at its maximum capacity and the energy storage systems are assumed to be charging. For this limiting 60% instantaneous inverter-based generation scenario, a specific combination of solar PV generation and battery charging with some PV curtailment is modeled; however, other combinations of renewable energy technologies are also possible.

Table 3-2 — Modeled Renewable Energy Generation

Resource Technology	Dispatched Real Power, *Pgen* (MW)	Generator Type	Notes
Distributed Generation (DG)	291	Inverter-based generator	Assumes DG locations are mostly behind the transformer meter. They are modelled in PSS/E by load reduction in eight PREPA operating regions. After the ~291 MW load reduction throughout the PREPA grid in PSS/E original model, the native load in the updated PSS/E model stays at ~2,335 MW
Hydroelectric	1.8	Synchronous generator	Assumes hydroelectric power plants are operating at their minimum stable points
Existing Renewables	65.6	Inverter-based generator	[redacted]
Shovel Ready PPOA Solar PV Projects	573	Inverter-based generator	
New Solar PV Resources	1,015	Inverter-based generator	

Table 3-3 provides a summary of the power output of the solar PV plants modeled in PSS/E by region. The solar PV and battery storage plants have been modeled at assumed locations dispersed throughout the island since the actual locations and sizes of future projects are still unknown.

Table 3-3 — Modeled Inverter-Based Renewable Energy by Region

Area	Dispatched Real Power, *Pgen* (MW)
[redacted]	120.3
[redacted]	159.6
[redacted]	225.8
[redacted]	161.1
[redacted]	268.8
[redacted]	253.0
[redacted]	305.0
[redacted]	160.0
Total Inverter-Based Renewable Energy	**1,653.6**

Table 3-4 is a summary of the BESS projects that are operating in charging mode as modeled in PSS/E.

Table 3-4 — Modeled BESS Projects in Charging Mode by Region

Area	Project Name	Dispatched Real Power, *Pgen* (MW)
[redacted]	[redacted]	-30
	[redacted]	-30
	[redacted]	-20
[redacted]	[redacted]	-50
	[redacted]	-25
[redacted]	[redacted]	-50
	[redacted]	-50
[redacted]	[redacted]	-20
[redacted]	[redacted]	-25
[redacted]	[redacted]	-25
	[redacted]	-30
	[redacted]	-50
MW Charging		**-405**

The dispatch scenario tabulated in Table 3-5 is a summary of the case with target inverter-based generation.

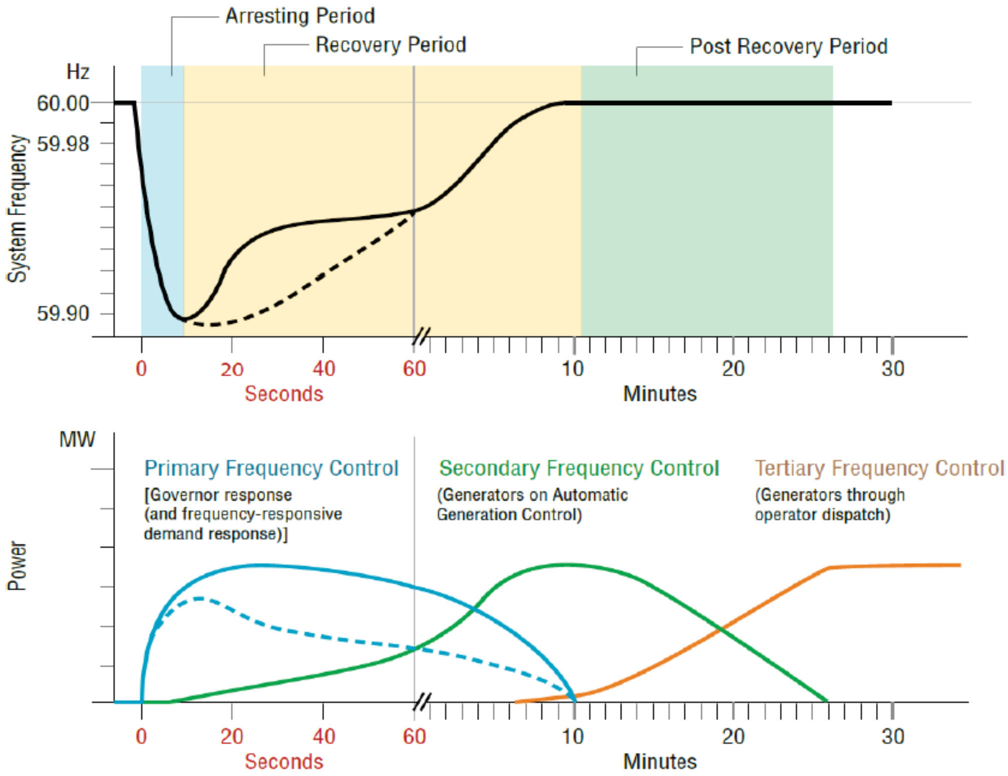
Table 3-5 — PSS/E Model Summary

Generation	*PGen* (MW)		Load	MW
Thermal	1,126		**Native Load (Original)**	2,626
Hydro	1.8		**Load (Metered)[2]**	2,335
Existing Renewable Energy Power Plants	65.6			
New Renewable Energy Power Plants	1,588			
Distributed Generation[1]	291			
BESS (Discharging)	-		**BESS (Charging)**	405
Total Generation[3]	**3,072**			

Notes: 1) Distributed generation is accounted for as net load in the PSS/E model
2) Load (Metered) is equal to native load minus distributed generation
3) Inverter-based renewable energy generation is equal to 60% of total generation [60% = (Existing Renewable Projects + New Renewable Projects) / (Thermal + Hydro + Existing Renewable Projects + New Renewable Projects)

The power system frequency is used to measure the balance between power generated and power consumed. The sudden loss of power generation creates an imbalance between generation and consumption and the frequency will decrease, as is shown in Figure 3-1.

Figure 3-1 — Frequency Response Definitions [Source: LBNL]



The rate at which the frequency decreases (referred to as the rate of change of frequency or RoCoF) and the lowest point at which the frequency drops to (frequency nadir) can be used to help determine the likelihood of the electrical system remaining stable. As described earlier, the inertia of the system will oppose changes in system frequency in response to a loss of generation. As the instantaneous renewable penetration increases and the system inertia declines, the RoCoF will change at a much quicker rate and frequency will decline quickly, resulting in less time for the primary frequency response to inject power. Figure 3-1 also provides the sequence of events that typically define frequency recovery. These fall into three categories: primary, secondary, and tertiary.

In this analysis, the largest loss of generation events are used to evaluate the frequency response of the system operating at a 60% instantaneous renewable energy penetration. The loss of generation events evaluated are listed below:

- The loss of the 230 kV transmission line connecting EcoEléctrica Power Plant to the rest of the PREPA grid (275 MW)
- The loss of Costa Sur Unit 5 (205 MW)
- The loss of 120 MW of solar PV at Aguadilla
- The loss of 120 MW of solar PV at Palo Seco

This analysis also investigates the impact of adding synchronous condensers as a way to help improve system inertia. We also analyzed the benefit of the inverter-based renewable energy generators being MTR compliant, specifically with the ability to provide FFR.

3.1.2. Power System Dynamic Analysis Limitations

The importance for high quality and accurate electrical system modeling cannot be overstated, especially as PREPA implements massive improvements to the transmission and distribution system and as Puerto Rico embarks on a rapid transition away from existing thermal generation to renewable energy. As improvements to the Puerto Rican electrical grid are made, it will be essential for existing electric grid models (i.e., PSS/E) to be updated to capture all changes to the electrical system. We note that there are a number of limitations to this analysis. First, the location, size, and design parameters of the solar PV, wind, and battery storage plants that will be in place by 2025 are unknown at this time. Therefore, S&L made assumptions based on input from PREPA in order to study this scenario. In addition, as with any modeling software, PSS/E is only able to provide an approximation of system operation within a certain level of accuracy, based on the inputs available. We recommend PREPA pursue additional, more detailed modeling as more specific details surrounding the renewable energy projects and energy storage systems to be developed on the island become known.

Additionally, we note that as inverter-based penetration levels have increased in various regions around the globe, the electrical industry has begun to recognize that there are limitations with the traditional analysis tools in studying the impact of inverter-based generation on the grid – instead there has been increased interest in electro-magnetic transient software tools (which would better capture the impact of inverter-based generation on the grid under weak grid conditions). Because of this, we envision that electro-magnetic transient system studies will likely be needed as Puerto Rico integrates higher levels of inverter-based generation. S&L will work with PREPA to develop a recommended path for analysis work, which will be in step with the growing integration of inverter-based projects.

3.1.3. Power System Dynamic Analysis Results and Discussion

The results of the analysis are summarized in Table 3-6 for four separate loss of generation events. The largest loss of generation event is the loss of the EcoEléctrica power plant, which was dispatched at a total of 275 MW under this scenario. The frequency nadir drops to 58.4 Hz, which falls just below the first PREPA instantaneous underfrequency load shedding setting of 58.6 Hz. The dynamic analysis results indicate that the PREPA power system can nearly maintain frequency response with a 60% renewable energy (inverter-based) penetration limit. The RoCoF for this event is also near 1 Hz/sec, which is the equal to the PREPA underfrequency load shedding setting.

Table 3-6 — Dynamic Analysis Results Without Synchronous Condenser Support

Generators Tripped	MW Lost	Nadir (Hz)	RoCoF (Hz/s)
CS 5	205	58.6	-0.60
EcoEléctrica	275	**58.4**	-0.93
Aguadilla New PV	120	59.3	-0.36
Palo Seco New PV	120	59.4	-0.23

Adding synchronous condensers throughout the system improves the frequency nadir for this event as well as decreasing the RoCoF. The synchronous condensers can help overcome some of the challenges associated with high renewable energy integration by supplying reactive power, increasing system strength, increasing system inertia, and providing better dynamic voltage recovery after system faults. The synchronous condensers that were included in the PSS/E to improve the frequency response are tabulated in Table 3-7.

Table 3-7 — Modeled Synchronous Condenser Location and Size

#	Synchronous Condenser Bus	Area Name	Capacity (MVAR)
1	[redacted]	[redacted]	200
2	[redacted]	[redacted]	200
3	[redacted]	[redacted]	200
4	[redacted]	[redacted]	200
5	[redacted]	[redacted]	200

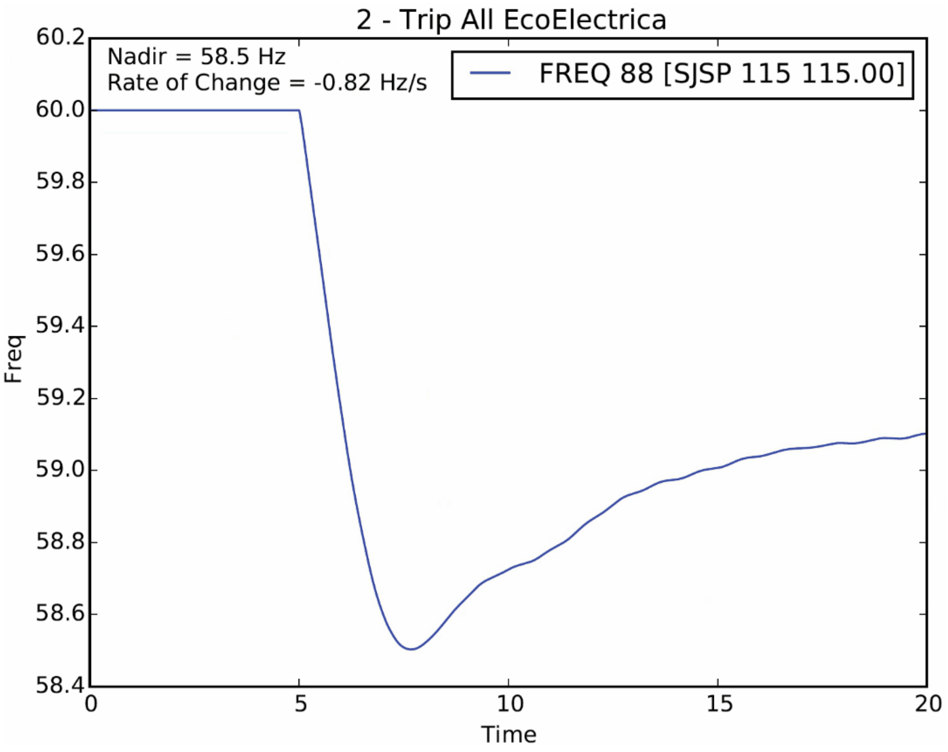
All the synchronous condensers in these locations are assumed to be connected at their respective 115-kV bus via a step-up transformer. While the optimal location and ratings of the synchronous condensers has yet to be fully analyzed, S&L chose these locations in an effort improve modeled system performance from a stability standpoint and based on the system strength analysis described in Section 3.2.

The results for the previous cases with the synchronous condensers included are summarized in Table 3-8. The power system frequency for this event is shown in Figure 3-2. As can be seen in the following table, the system performs marginally better with synchronous condenser support than without. That said, the frequency nadir for the EcoEléctrica case is still just under the 58.6 Hz, which is the first PREPA instantaneous underfrequency load shedding setting.

Table 3-8 — Dynamic Analysis Results with Synchronous Condenser Support

Generators Tripped	MW Lost	Nadir (Hz)	RoCoF (Hz/s)
CS 5	205	58.6	-0.54
EcoEléctrica	275	**58.5**	-0.82
Aguadilla New PV	120	59.4	-0.29
Palo Seco New PV	120	59.4	-0.22

Figure 3-2 — Frequency Response after EcoEléctrica Trip



Solar PV and battery storage have the ability to quickly inject power into the grid when the frequency of the power system begins to decline. This capability is referred to as "fast frequency response" and is used to help slow down the decline in frequency following a loss of generation event and lessen the frequency nadir. The dynamic model used in this analysis includes this capability to inject power (or reduce battery charging) when the power system frequency begins to decline.

S&L also analyzed a scenario where the new PV and standalone energy storage systems were MTR compliant and able to provide FFR. We observed that system frequency response (both RoCoF and frequency nadir) does improve; however, a loss of a large generator would still result in substantial challenges associated system frequency response.

Based on the results of this analysis, S&L strongly recommends MTR compliance for new inverter-based resources for the intermediate future. It is possible that the requirement of MTR compliance for new inverter-based resources could be relaxed in the long term, but this would require future analysis as the Puerto Rico electric system improves and evolves.

Additionally, S&L recommends that instantaneous inverter-based generation levels in Puerto Rico do not exceed 60% for the near to intermediate future. Our analysis indicates that the risk of system instability and load shedding following a disruption will increase substantially if instantaneous inverter-based generation levels are allowed to go beyond 60%. It is important to note that this limitation will likely be able to be eased in the future as system upgrades / modification are implemented and alternative methods of managing low system inertia become more widespread.

3.2. System Strength Analysis for 2025

S&L used the PSS/E model described in the previous section to evaluate system strength in locations throughout the Puerto Rican power system by performing a screening level analysis both under normal operating conditions and after system contingencies. For this analysis, a contingency is defined as when a transmission system element (line or transformer) experiences a forced (unplanned) outage. The "weak" system areas that were identified in the analysis may require additional support from synchronous condensers in order to maintain stable operation of the inverter-based renewable energy generation.

The system strength is associated with the equivalent impedance seen from the resource's terminals into the bulk power system. Usually, a "weak" system will show higher voltage sensitivity due to changes in active/reactive power injections/consumptions. Although the challenges associated with weak grid conditions are system-specific, the tools/metrics to identify weak areas or potential weak grid conditions can help system planners to improve reliability. There are several tools which can be used to quantify the system strength. Short Circuit Ratio (SCR) is defined as the ratio between short circuit apparent power

(SCMVA) measured from a 3LG fault at a certain location to the MW rating of the inverter-based resource connected to that location. However, SCR is an appropriate metric to evaluate the strength at the point of interconnect (POI) if there are no other inverter-based resources electronically close to the POI under consideration. When multiple inverter-based resources are interacting in a small area, the usage of SCR to determine the system strength is less accurate and another method should be used. If the electrical coupling between non-synchronous generations must be considered, the weighted short circuit ratio (WSCR) can be used to estimate the system strength. WSCR can be defined as:

$$WSCR = \frac{\sum_i^N SCMVA_i * P_{MW,i}}{\left(\sum_i^N P_{MW,i}\right)^2}$$

Where,

$SCMVA_i$ = Short circuit capacity at bus *i*, without any contribution from inverter-based generation

$P_{MW,i}$ = The MW output of non-synchronous generation to be connected at bus *i*

N = Total number of resources fully interacting with each other

The POI of the inverter-based power plant must have a SCR above **5.0** to comply with PREPA's minimum short circuit requirements as described in the PREPA MTRs.

For this analysis a WSCR of less than or equal to 5.0 is considered a weak grid area.

3.2.1. System Strength Analysis Methodology

The system strength analysis was done using the PSS/E model and modeling inputs / assumptions are consistent with those described in Section 3.1.1.

It is assumed that the total solar PV sites MW output is consistent with the analysis discussed in Section 3.1.1 and all the BESS units are absorbing active power from the grid. We have assumed that all the BESS have discharged to their minimum State of Charge (SoC) during the night-time hours and are beginning to recharge with full MW capacity.

For simulation purposes, the following methodology has been followed:

1. The short circuit MVA from a 3LG fault at each of the PV project POI is measured for normal and adjacent N-1 contingency conditions. Here 'adjacent' refers to any incoming or outgoing 'in-service' lines and 'in service' transformers at the POI.

2. If any equipment (transmission line, transformer) connecting the bus (POI where SCMVA is being measured) is permanently out of service, it is excluded from both normal and contingency condition calculations.
3. If any bus is represented as the same POI for multiple resources (PV, wind, BESS, etc.), P_{MW} is calculated using the summation of all MW ratings of the resources. Although the BESS resources are modelled as load (charging) in the steady state analysis, it has been assumed that they will contribute to the SCMVA during a fault.

Other assumptions pertaining to this study are:

1. **PV and BESS Project Locations:** Most of the new PV and BESS projects are interconnected to 115-kV substations. The suitable locations are chosen based on the available incoming/outgoing line loading at the substations.

2. **Line Loading:** After adding the solar PV and BESS projects in the PSS/E model, the MW output of these projects were adjusted so that the line loading remains below 90% of the rated capacity. However, this considers all the BESS projects are charging (drawing active power mostly produced by the solar PV). Since most of the solar PV and corresponding BESS projects share the same POI, the line loading did not change much for most of the cases.

3. **Synchronous Condenser Locations:** Since the synchronous condensers are also interconnected on the 115-kV buses on the identified weak areas, suitable bus locations are found to be limited. The synchronous condenser locations are limited since they were placed near to the solar PV and BESS project locations in order to get the maximum SCMVA contribution.

4. **Adjacent N-**1 **Contingency**: The short circuit strength study only considers adjacent N-1 contingencies. Changing the project locations may require analyzing a different set of N-1 contingencies and hence change the WSCR values.

In this study, interconnecting the synchronous condensers to a different voltage level (i.e. 230 kV) is not explored. However, further investigation is required for determining suitable 230-kV substations as synchronous condenser's interconnection point.

3.2.2. 2025 System Strength Analysis Results – Without Upgrades Considered

The WSCR results under normal conditions are shown in the following map. Different colors are used to indicate the different types of PV and wind projects:

- Red for currently operating PV and wind projects (as of today in 2020)
- Green for projects that currently are non-operating but would likely be operating in the near future. These are the projects known also as the ‘shovel-ready’ PV projects, or PV projects that have already obtained many of the approvals required for development
- Yellow for new PV + BESS projects, or projects that have not been defined, but could be as part of future RFP’s for renewable energy

Note that the threshold for a ‘weak’ area of the grid is a WSCR of less than 5.0. The WSCR analysis shows that the [redacted] part of the island, with a WSCR score of 4.5, already resembles a weak grid condition without considering any contingencies. Additionally, the [redacted] region is a potential weak grid area, with a WSCR of 5.36.

Figure 3-3 — WSCR Analysis for 2025 RPS, No Upgrades (Normal Conditions)

[redacted]

The worst case WSCR results for the N-1 contingencies analyzed are summarized in Figure 3-4. As can be seen in the map, several additional areas are below the acceptable limit of 5 from the PREPA MTRs for the N-1 contingencies analysis. The grid is particularly weak on the [redacted] portion of the island, in the [redacted], and in the [redacted].

Figure 3-4 — WSCR Analysis for 2025 RPS, No Upgrades (N-1 Contingencies)

[redacted]

Both [redacted] stem upgrades / modifications, PREPA will be challenged to maintain adequate grid strength in the future as more inverter based resources are added across Puerto Rico. The following section provides our analysis of the electrical system grid strength as upgrades / modifications are performed.

3.2.3. System Upgrades Considered to Improve System Strength

3.2.3.1. Synchronous Condensers

Synchronous condensers can help overcome some of the challenges associated with high renewable energy integration by supplying reactive power needs, increasing system strength, increasing system inertia, and providing better dynamic voltage recovery after system faults. In this study, the system strength of various locations across Puerto Rico have been re-evaluated after placing synchronous condensers in the weak grid areas. The synchronous condensers used in the analysis are tabulated in Table 3-9.

Table 3-9 — Synchronous Condenser Location and Size

#	Synchronous Condenser Substation	Area Name	Capacity (MVAR)
1	[redacted]	[redacted]	200
2	[redacted]	[redacted]	200
3	[redacted]	[redacted]	200
4	[redacted]	[redacted]	200
5	[redacted]	[redacted]	200

All the synchronous condensers in these locations are assumed to be connected at their respective 115-kV bus via a step-up transformer. Placement of the synchronous condensers has resulted in an estimated WSCR improvement to a certain extent, especially in those weak grid areas seen in the previous subsection (more details are provided in Section 3.2.4). However, the optimal location and size of the synchronous condensers are yet to be investigated.

3.2.3.2. New Transmission Lines and Other System Upgrades

Adding new transmission lines or restoring existing lines connecting the weak areas can provide additional paths for short circuit flow and thus increases SCMVA measured at any bus in those weak areas. In our study, the WSCR calculations have been compared after the line 36600 (San Sebastian to Dos Bocas) restoration to evaluate the system strength in Mayagüez area. This line was considered to be restored because it is a main transmission line to the Mayagüez area, which was identified as a weak grid location.

Other options to consider to improve system strength are:

1. **Downsizing the projects:** Since the WSCR value is inversely proportional to the summation squared of the MW ratings of the projects, downsizing the projects in the potential weak areas can improve the WSCR value to a certain extent. However, we note that smaller PV projects are likely to be more expensive than larger projects due to economies of scale
2. **Moving projects to strong areas:** Moving some of the solar PV and BESS projects from the weak areas to strong areas (if possible) can improve the WSCR in the weak areas to a certain extent. However, the WSCR would need to be re-calculated after moving a project
3. **Optimizing synchronous condenser location and size:** If multiple synchronous condensers are used instead of one and scattered around the project locations, there is the potential of better SCMVA contribution from them while considering N-1 contingencies. Moreover, the maximum SCMVA contribution from a synchronous condenser occurs when placed at the nearest possible

bus from the project POI. Since the optimal size and placement of the condensers both depend on the project size and locations, further investigation needs to be performed determining the optimal project locations.

3.2.4. System Strength Analysis Results – With Upgrades Considered

3.2.4.1. Results with Adding Synchronous Condensers

The system strength for 2025 RPS study has been re-evaluated after adding synchronous condensers in [redacted] weak grid areas. A summary of the updated WSCR results under normal conditions is in Figure 3-5.

A direct WSCR improvement on the [redacted] (from 4.5 to 6.8) and [redacted] (from 5.36 to 7.58) project areas are noticed after placing the synchronous condensers near these areas as shown in Figure 3-5. A slight improvement on the WSCR values in the adjacent areas are also noticeable. We note that no areas analyzed show a WSCR value of less than 5.0 for this case.

Figure 3-5 — WSCR Analysis with Synchronous Condensers (Normal Conditions)

[redacted]

The results for the WSCR N-1 contingency analysis are summarized in Figure 3-6. During the worst case N-1 contingencies, it is evident that only two potential areas (the [redacted] areas highlighted in red rectangles in Figure 3-6) are not capable of maintaining the minimum SCR requirement even with the support from synchronous condensers. Further detailed analysis should be done in these areas if solar PV or BESS projects are to be added in these areas.

Figure 3-6 — WSCR Analysis with Synchronous Condensers (N-1 Contingencies)

[redacted]

3.2.4.2. Results with Restoring Line 36600

The WSCR results summaries illustrated in Figure 3-7 and Figure 3-8 includes the impact of the line 36600 (San Sebastian to Dos Bocas) restoration alone without the addition of synchronous condensers. The restoration of the line has improved the WSCR value (from 4.5 to 4.69) in the [redacted] part of the island during normal conditions. There is also a slight WSCR value improvement in the [redacted] part of the island. However, the 36600-line restoration alone cannot bring the WSCR value to the minimum desired limit even under normal conditions.

Figure 3-7 — WSCR Analysis with Line 36600 Restoration (Normal Conditions)

[redacted]

As shown in Figure 3-8, the WSCR results with N-1 contingencies, the number of potential weak areas is roughly the same as before the line restoration.

In the western part of the island, contingencies considered were both line 37200 (Victoria to Anasco) and line 39100 (Victoria to Mora) outages – these resulted in a WSCR value [redacted] In the eastern part of the island, the Juncos to Rio Blanco line segment on line 36200, the Rio Blanco to Daguao line segment on line 36200, the Juncos to Humacao line segment on line 41400, the Humacao to Yabucoa line segment on line 41400, the Rio Blanco to Humacao line segment on line 36300, and the Humacao to Yabucoa line segment on line 36300 outages will reduce short circuit path to the project locations and hence result in a lower WSCR value.

Figure 3-8 — WSCR Analysis with Line 36600 Restoration (N-1 Contingencies)

[redacted]

3.2.4.3. Results with Both Synchronous Condensers and Restoring Line 36600

The WSCR analysis with the 36000 line restoration and the synchronous condensers are depicted in Figure 3-9 under normal conditions and in Figure 3-10 under N-1 contingencies. There is a significant WSCR improvement on the [redacted] part of the island (from 4.5 to 6.98) and the [redacted] part of the island (from 5.36 to 7.58) after the addition of the synchronous condensers and line restoration.

Figure 3-9 — WSCR Analysis, Syn. Cond. + Line 36600 Restoration (Normal Conditions)

[redacted]

For the WSCR N-1 contingency results, only two potential areas (the [redacted] part of the island as highlighted in red in Figure 3-10) do not meet the minimum SCR requirement. However, all areas result in improved WSCR values when the synchronous condensers are added and the 36600 line is restored.

Figure 3-10 — WSCR Analysis, Syn. Cond. + Line 36600 Restoration (N-1 Contingencies)

[redacted]

3.2.5. Further Discussion of System Strength Analysis

The system strength analysis has identified the weak areas and potential weak grid areas for the PREPA 2025 RPS scenario. The placement of the synchronous condensers is expected to result in improvements to system strength in the identified weak areas ([redacted] parts of Puerto Rico) during normal conditions. However, the results show that placing the five synchronous condensers is not enough to increase all area WSCR values to above the MTR threshold required under the N-1 contingency cases analyzed. Other options that can be explored in the identified weak areas under normal and contingency conditions in order to meet the MTR minimum SCR include adding more synchronous condensers, downsizing the solar PV and BESS projects, and moving the solar PV and BESS projects to other areas of the grid. Once project locations and sizes are known, it is recommended that a more detailed WSCR analysis be conducted in order to identify potential solutions.

3.3. Grid Support Requirements in Short, Mid, and Long-Term

To meet short- and mid-term renewable energy goals, it is important that the grid has additional support so that power system reliability is maintained. The proposed grid support options are presented in this section.

- **Maximum Instantaneous Inverter-Based Limit of 60% (Short / Mid-Term)** – Based on the results of S&L's dynamic analysis, we recommend that instantaneous inverter-based generation level in Puerto Rico do not exceed 60% for the near to intermediate future. Our analysis indicates that the risk of system instability and load shedding following a disruption will increase substantially if instantaneous inverter-based generation levels are allowed to go beyond 60%.

- **Synchronous Condensers (Short / Mid-Term)** – Adding synchronous condensers improves overall system performance, both from the perspective of grid inertia and grid strength. Synchronous condensers, in addition to new synchronous generation described above, will be needed to support Puerto Rico's rapid transition to renewable energy. Synchronous condensers provide improved short circuit strength and inertia and become necessary as more renewable energy projects are integrated into the electrical system. The exact location, number, and size of synchronous condensers needed will be determined once PREPA better understands more details concerning the locations and sizes of new inverter-based resources. Note that adding synchronous condensers can introduce angular instability, in addition to introducing potential challenges associated with protection systems and system maintenance.
- **New Transmission Lines and Other System Improvements (Short / Mid-Term)** – Adding new transmission lines or restoring existing lines connecting the weak areas can provide additional paths for short circuit flow and thus increase system strength measured at any bus.
- **New Synchronous Generators (Short / Mid-Term)** – As described earlier, power system inertia is important in maintaining power system reliability. Rotating synchronous generation (traditionally thermal power plants and hydroelectric power plants) has supplied this inertia to the PREPA power system. As large existing thermal power plants are set to retire in the short-term, the inertia of the system will begin to decrease, which will lead to an increase in the likelihood of load shedding events. Thermal power plants not only provide inertia, but can reliably provide power during periods of time when solar PV and/or wind resources are unavailable and energy storage has been fully discharged. These periods include long durations of heavy cloud cover and/or following a large weather event where PV panels or wind turbines are damaged.

  The addition of new thermal power plants and peakers will address these concerns by supplying inertia to the system and supplying reliable power generation to meet demand when solar PV and wind resources are unavailable. The need for additional thermal generation is described in greater detail in Section 4.3 .
- **New Technologies to Support a High Penetration of Renewable Energy (Mid / Long-Term)** – It is possible to operate a power system at very low or zero inertia, but examples of such systems are limited. For example, zero-inertia AC microgrids exist, but these systems are small in size. In larger-sized regions with high annual percentages of inverter-based generation, there would be periods where the system might operate at 100% instantaneous inverter-based generation levels. This would be equivalent to operating at a nearly zero-inertia; however, to operate a larger power system at this level inertia requires research and new approaches to maintaining grid frequency, many of which are being investigated by the energy industry now. Grid-forming inverters have the ability to create grid voltage and frequency which are naturally part of synchronous machines. To date, no grid code to our knowledge has specific guidelines about grid-forming inverters. In Great Britain, a formal Grid Code Working Group is being established to draft a preliminary non-mandatory requirement for grid-forming inverters.

4.0 Generator Dispatch and Electrical System Modeling

4.1. Description of Analysis

S&L performed electrical system modeling utilizing the PLEXOS modeling software, incorporating the results of the electrical and grid analysis presented in Section 3.0. The primary objective of the electrical system modeling was to analyze the expected operation of PREPA's system in 2025 and subsequent years, taking into account the resolutions detailed in the *Final Resolution and Order on the Puerto Rico Electric Power Authority's Integrated Resource Plan*, issued by PREB. In addition, we also evaluated the impact of additional generation portfolio modifications in 2025 (i.e., a new combined-cycle power plant in the San Juan area, the replacement of peaking generators, and incorporating a diverse set of renewable energy generation technologies) to determine if these modifications would better position PREPA to be able to provide a reliable electrical system as both RPS targets are pursued and system costs are minimized.

4.2. Analysis Inputs and Assumptions

The electrical system model utilized for this analysis was developed in PLEXOS, an industry-accepted electrical system simulation software, and incorporates the most recent generation, transmission / distribution, and operational information from the PREPA system. The PLEXOS model utilized for this analysis was benchmarked using both historical operation data provided by PREPA and output from the existing PREPA planning model currently utilized by PREPA's Planning Department.

The model incorporates the planned generation additions and retirements by the year 2025 (which is the year corresponding to when Puerto Rico is required to meet the 40% RPS target). The model further incorporates the 60% limitation associated with the maximum level of instantaneous generation from inverter-based resources (i.e. solar PV, wind, energy storage) identified and discussed in Section 3.0 of this report. Therefore, the model dispatches generators to maintain at least a 40% instantaneous generation level from synchronous sources (i.e. thermal or hydroelectric generators) at each hour of the simulation. As will be discussed later, this constraint primarily affects system dispatch during the middle of the day, when there is significant amount of generation from the inverter-based renewable energy resources.

Finally, the model defines a number of inputs probabilistically (i.e., via Monte Carlo simulations) in order to properly capture the impact of input variance. These inputs include generator forced outages, hourly renewable energy generation (both wind and solar PV), and system load. Input values are based on a combination of information provided by PREPA and data from PREPA's 2019 Integrated Resource Plan (IRP).

4.2.1. Modeled Generation

4.2.1.1. Thermal Generation

The following table provides the thermal generation that was included in the PLEXOS model of PREPA's system in 2025. The model excludes Aguirre Steam units 1 & 2, Cambalache unit 1, Costa Sur units 3 & 4, Palo Seco units 1-4, and San Juan units 7-10, which is consistent with PREPA's planned retirements / unit operating status.

Table 4-1 — Modeled Available Thermal Generation (2025)

Generator Name	Capacity (MW)
Large Thermal Generators	
AES 1 & 2	454
Aguirre CC 1 & 2	592
Cambalache 2 & 3	165
Costa Sur 5 & 6	820
EcoEléctrica	530
Mayaguez 1 – 4	220
San Juan 5 & 6	440
Frame 5 Gas Turbine Generators[1]	
Aguirre (2 units)	42
Costa Sur (2 units)	42
Palo Seco (6 units)	126
Daguao (2 units)	42
Jobos (2 units)	42
Vega Baja (2 units)	42
Yabucoa (2 units)	42
Total	**3,599**

Note: 1) These units could potentially be replaced (in a modified configuration) as part of the FEMA award funding (S&L recommends this replacement occurs)

Modeled forced outage rates are based on historical generator operation and are consistent with PREPA's internal planning model and the most recent revision of the IRP. Planned outages for the thermal generators for 2025 are modeled per PREPA's input for maintenance cycles for each generator. Heat rate curves were developed for thermal generators based on historical generator operational data provided by PREPA.

4.2.1.2. Renewable Energy Generation

The following table shows the renewable energy resources that were considered for this analysis. This renewable energy portfolio would allow Puerto Rico to meet the 2025 40% RPS target; however, other combinations of renewable energy technologies are possible. Note that the hydroelectric generators provide synchronous generation, while the solar PV and wind resources provide inverter-based generation.

Table 4-2 — Modeled Available Renewable Energy Generation (2025)

Resource Technology	Capacity (MW)	Generator Type	Notes
Existing Renewable Energy Generation	308	Inverter-based generator	Assumes that any needed repairs have been performed and planned upgrade projects have increased power plant capacity, as agreed on in recent PPOA renegotiations
Distributed Generation (DG)	430	Inverter-based generator	DG level is based on IRP's projection of available DG for 2025
Hydroelectric Generation	100	Synchronous generator	Assumes hydroelectric power plants have been restored to their installed capacities
New Solar PV Generation	2,150	Inverter-based generator	S&L developed hourly resource generation profiles for each region. [redacted]
New Wind Generation	600	Inverter-based generator	Hourly resource generation profiles were obtained from PREPA's existing planning model. [redacted]
Total	**3,588**		

Accounting for the modeled system stability limitation that no more than 60% of all instantaneous generation can come from inverter-based generators (see Section 3.0), a large capacity of energy storage is needed to capture excess inverter-based renewable energy generation during the daytime and shift it to the evening, night, or early morning. Our modeling indicates that with the integration of the 2,750 MW of new inverter-based renewable energy resources shown in Table 4-2 (new solar PV and new wind resources), an estimated [redacted] of energy storage resources are needed for PREPA to be able to both meet the 2025 RPS target and ensure that no more than 60% of all instantaneous generation comes from inverter-based generators. For reference, the most recent version of the IRP did not include any limitations on instantaneous inverter-based generation; thus, the estimate of required energy storage needed in the IRP is much lower than what our analysis indicates.

4.2.2. Fuel Considerations

Fuel price forecasts are based on the 2020 Annual Energy Outlook (AEO) from the U.S. Energy Information Administration (EIA), adjusted for PREPA's existing fuel supply agreements. While uncertainty remains concerning the long-term impacts of COVID-19 on fuel commodity markets, S&L assumed that markets will trend towards the prices forecasted in the 2020 U.S. EIA AEO over the next years. Table 4-3 presents the fuel prices that are used in the model for 2025. A forecast for No. 6 fuel oil is not included since all No. 6 fuel oil-fired generators are modeled to be retired prior to 2025 (consistent with PREB's *Final Resolution and Order on the Puerto Rico Electric Power Authority's Integrated Resource Plan)*. The difference in the natural gas cost between the two locations is due to the different gas supply agreements, with Naturgy (for EcoEléctrica and Costa Sur) and New Fortress Energy (for San Juan).

Table 4-3 — Modeled Delivered Fuel Prices (2025) (USD per MMBtu)

Diesel (All Plants)	Natural Gas (EcoEléctrica / Costa Sur)	Natural Gas (San Juan)
[redacted]	[redacted]	[redacted]

4.3. Analysis Results and Discussion

4.3.1. Anticipated System Operation in 2025

The results of the analysis demonstrated several important findings. Most importantly, by limiting the maximum amount of instantaneous inverter-based generation to 60%, more synchronous generation was dispatched during the peak solar PV generation hours than what would have been dispatched if the 60% limitation was not included. In fact, when we simulated the system without the 60% limitation included (i.e., allowing instantaneous inverter-based generation levels to go above 60% without restriction), inverter-based generation would consistently account for upwards of 80% of total instantaneous generation during the middle of the day – occasionally spiking to above 90%. As discussed in Section 3.0, such high levels of instantaneous inverter-based generation can lead to major electrical system stability issues.

Figure 4-1 provides the average hourly levels of inverter-based generation with the 60% limitation in effect (the figure presents an average of each hour simulated for 2025, averaged over all Monte Carlo simulations). As can be seen, hourly inverter-based generation primarily spikes during the middle of the day due to the high generation levels of both the installed solar PV and wind power plants. The figure also highlights that the 60% limit on inverter-based generation is hit primarily between the hours of 9 a.m. and 2 p.m. Between these times, three important items occur:

- Synchronous generators are dispatched to ensure that at least 40% of instantaneous generation comes from synchronous sources
- Energy storage systems capture excess renewable energy generation that cannot be used to serve load
- Any renewable energy generation both in excess of what is needed to serve load and in excess of what can be captured by energy storage systems is curtailed

Figure 4-1 — Hourly Inverter-Based Generation Levels in 2025

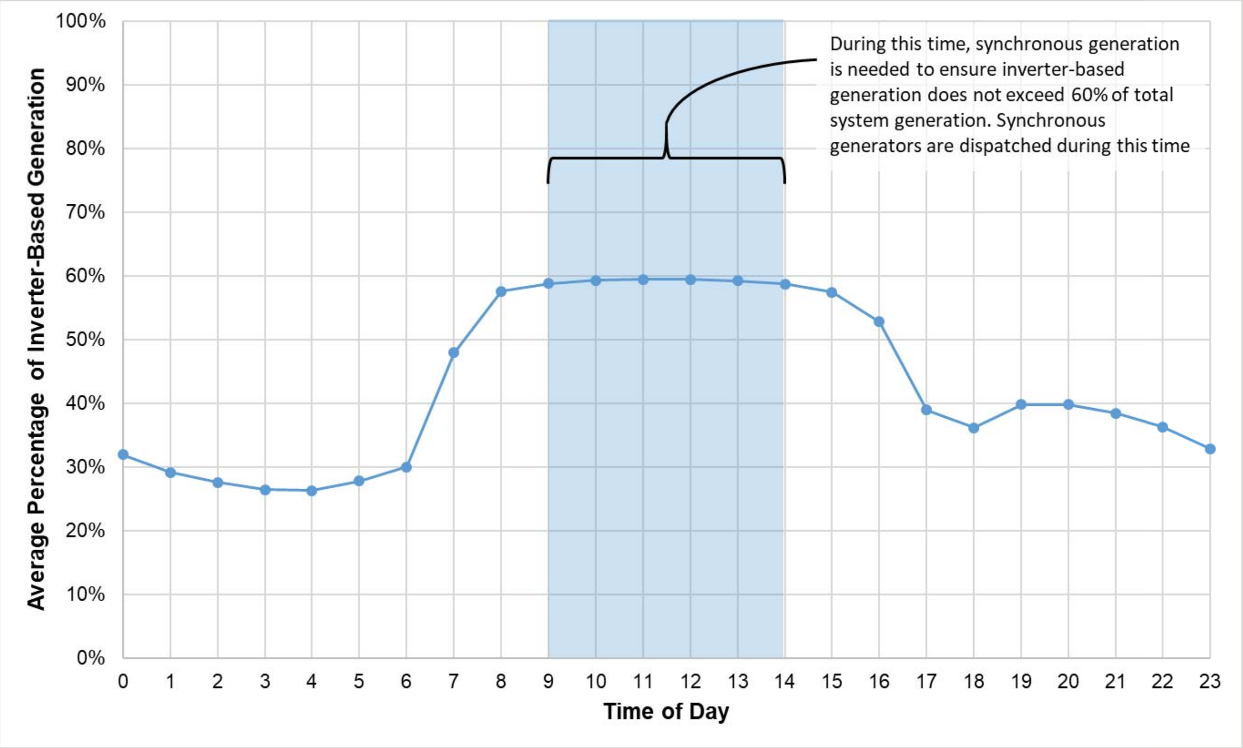


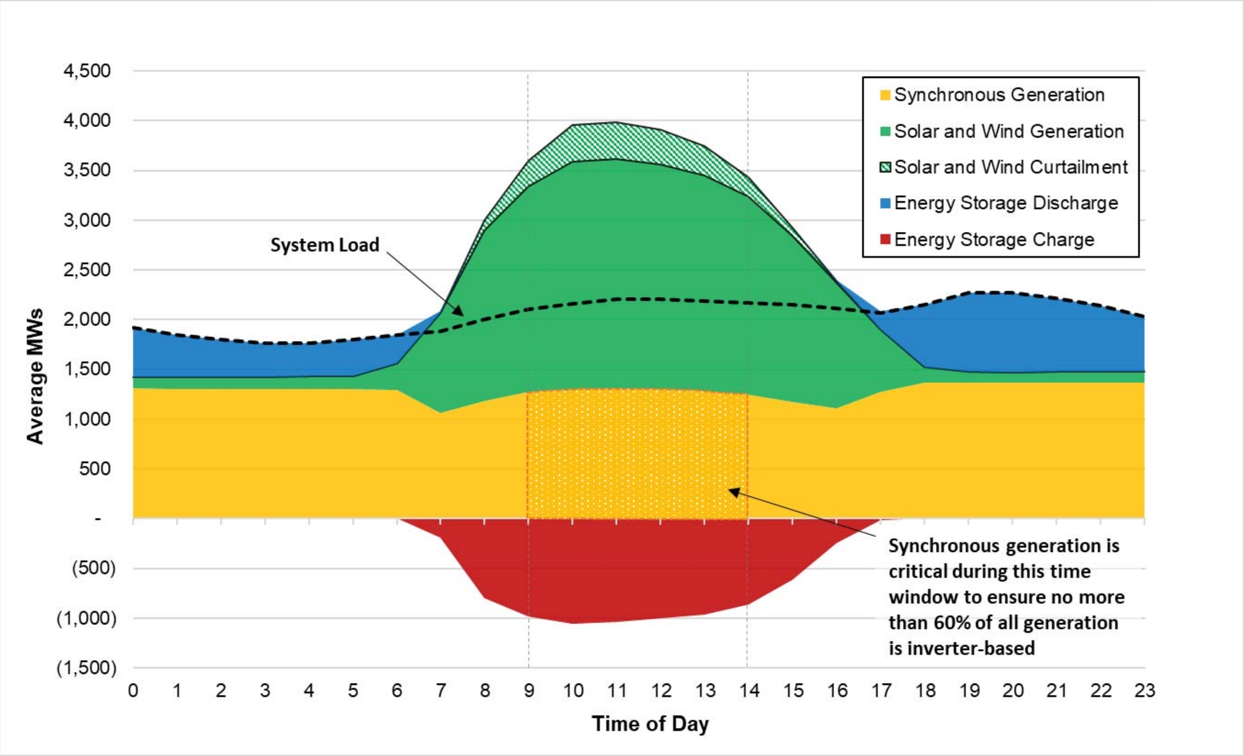
Figure 4-2 provides more visibility into the different types of generators operating throughout the day (similar to Figure 4-1, Figure 4-2 presents an average of each hour simulated for 2025, averaged over all Monte Carlo simulations). We note the following key items related to the information depicted in this figure.

- The figure clearly illustrates the reason why the 60% instantaneous inverter-based generation limit primarily is hit between the hours of 9 a.m. and 2 p.m. During these times, generation from the new solar PV and wind resources pushes total system generation well above what is needed to meet system load (illustrated by the dashed black line in Figure 4-2).
- During the middle of the day, the energy storage systems charge using the excess wind and solar PV energy (the charging load from these storage resources is illustrated by the red section in Figure

4-2, represented as negative MWs). The energy storage systems discharge energy in the evening, night, and early morning (blue sections).

- On average, approximately 1,350 MW of synchronous generation are needed consistently between the hours of 9 a.m. and 2 p.m. to ensure that there is not more than 60% of total generation coming from inverter-based generators on an instantaneous basis. The amount of synchronous generation needed occasionally peaks to over 1,600 MW during summer months. Modeling also indicates that approximately 90% of the synchronous generation dispatched between 9 a.m. and 2 p.m. is provided by three power plants: AES coal, EcoEléctrica, and San Juan. These power plants have historically also been the most reliable thermal generators in Puerto Rico.
- Some solar PV and wind generation is curtailed (light green section) during the middle of the day. We note that this figure presents an average of annual hourly system operation over many Monte Carlo simulations; thus, there are some days when there is no curtailment and others when the model indicates that curtailment is required. In general, curtailment primarily occurs during the summer months when solar PV generation is highest and not all excess generation can be captured by energy storage systems. [redacted]

Figure 4-2 — Average Hourly System Dispatch



4.3.2. Impact on System Reliability

Table 4-4 provides the thermal synchronous generators that are assumed to be available in 2025.

Red shading in the table represents generators that are either expected to be retired soon thereafter or are generators that have dispatch limitations due to high forced outage rates or environmental permitting constraints. We do not consider that these generators will be sources of reliable synchronous generation much further beyond 2025; thus, while the table shows that 3,599 MW total of thermal synchronous capacity is available in 2025, we estimate that only 1,355 MW will be available in future years beyond 2025. Once planned and forced outages are taken into consideration, it is likely that there will be times when the total available synchronous capacity will be less than 1,000 MW. As previously noted, on average 1,350 MW of synchronous generation (with occasional spikes up to 1,600 MW) are needed between the hours of 9 a.m. and 2 p.m. so that there is not a shortage of electrical inertia in the middle of the day. As a result, unless additional synchronous generators are developed, there will not be enough synchronous capacity available for PREPA to reliably operate the electrical grid as Puerto Rico's renewable energy penetration levels increase for RPS compliance. As previously noted, we view the 60% limit on instantaneous inverter-based generation to be necessary for the short / intermediate time frame, but not necessarily for the long term as alternative strategies to manage low system inertia are developed.

Table 4-4 — Available Thermal Synchronous Generators in 2025

Plant Name	Capacity (MW)	Notes
Large Thermal Generators		
AES 1 & 2	454	To be retired in 2027.
Aguirre CC 1 & 2	592	These units have historically had high forced outage rates (approximately 20%) and are among the most expensive generators in Puerto Rico. Additionally, both units are near 45 years old and will likely be retired in the intermediate term.
Cambalache 2 & 3	165	These units are also among the most expensive generators in Puerto Rico. We note that unit 1 could potentially be replaced as part of PREPA’s Necessary Maintenance Expense funding. We recommend this occurs per the reasons outlined in this report.
Costa Sur 5 & 6	820	While Costa Sur has been a dependable source of low-cost generation, the units are located in an active seismic zone that led to recent unit damage and associated forced outages. Additionally, the units are near 50 years old and will likely be retired in the intermediate term.
EcoEléctrica	530	
Mayaguez 1 – 4	220	These units are also among the most expensive generators in Puerto Rico.
San Juan 5 & 6	440	
Frame 5 GTs		
Aguirre (2 units)	42	These units have historically had high forced outage rates (in many cases over 40%) and also have slow ramp rates as compared to newer peaking units. These units are also among the most expensive generators in Puerto Rico. Note that these units could potentially be replaced (in a modified configuration) as part of the FEMA award funding. S&L recommends this replacement occurs per the reasons outlined in this report.
Costa Sur (2 units)	42	
Palo Seco (6 units)	126	
Daguao (2 units)	42	
Jobos (2 units)	42	
Vega Baja (2 units)	42	
Yabucoa (2 units)	42	

Total Capacity	**3,599**	
Total Capacity After Retirements, Limitations, and Unit Reliability (Removing Red Shaded Units)	**1,355**	This value is too low for PREPA to be able to maintain adequate electrical system inertia levels.

Notes: 1) All No. 6 fuel oil-fired units are assumed to be retired by 2025 (i.e., at San Juan, Palo Seco, and Aguirre)
2) Hydroelectric generators also contribute to synchronous generation – 100 MW are modeled as operating

4.4. Required System Improvements in the Intermediate-Term

The following section provides our intermediate-term recommendations, which can be categorized into two distinct areas of focus: additional thermal synchronous generation and renewable energy technology diversity.

4.4.1. Additional Synchronous Generation

Many of the synchronous generators considered to be operational in 2025 are expected to retire soon after or have limitations (e.g., high forced outage rates, emissions restrictions, etc.) that restrict their ability to operate. As a result, there will not be enough synchronous generators available to provide system reliability as Puerto Rico's renewable energy penetration levels increase and longer-term solutions are implemented. We recommend that additional synchronous generation be developed, focusing on three different sources:

- Replacement of existing thermal peaking generators with reliable, flexible, and efficient generators
- Development of a high efficiency, flexible, natural gas-powered combined-cycle power plant near San Juan
- Revitalization of the existing hydroelectric power plants to increase their capacity and availability

If PREPA were to perform each of these items above, it could add over 700 MW of reliable, synchronous, dispatchable capacity to Puerto Rico. This would better position PREPA to be able to provide system reliability as renewable energy generators are installed to comply with RPS targets. In addition, PREPA could better navigate through the retirement of the AES coal power plant, the retirements of other aging thermal generators (e.g., Costa Sur 5 & 6 and Aguirre CC 1 & 2), and minimize system production costs. We provide further discussion of each of these recommendations in the subsections that follow.

4.4.1.1. Peaking Generator Replacement

At present, PREPA lacks a reliable fleet of low-cost peaking generators. Peaking generators are important sources of flexible (quick starting and ramping), synchronous generation in electrical systems across the globe. In areas with high penetrations of solar PV and / or wind generation, the flexible dispatch characteristics of peaking generators can help to offset solar PV / wind generation volatility – improving overall system stability. As we have discussed in previous sections, Puerto Rico will be in need of synchronous generation in the coming years. PREPA has indicated that peaking generator replacement costs may be covered under FEMA funding. If FEMA funding can be used to cover the capital costs of the peaking generation replacement, the primary remaining costs that PREPA would be responsible for would only be fuel and operations and maintenance costs. FEMA funding would help make the replacement of peaking generators an economical option for PREPA, as we discuss further below.

We have provided the following comparison (Table 4-5) of a natural gas-fired peaking generator to an equally sized 4-hour BESS. Note that thermal peaking generators and BESS are not perfect substitutes for one another, given there are fundamental differences between the two types of technologies. Specifically, a thermal peaking generator is a synchronous generator, while BESS is a technology that transfers energy from one time to another – we consider both technologies to be essential to helping Puerto Rico meet RPS targets. While the technologies are fundamentally different, a comparison of the costs between a gas-fired peaking generator and a 4-hour BESS does offer some high-level insight into the economic differences between the technologies, specifically if FEMA funding can be used for peaking generator replacement.

Based on our discussions and work with PREPA on the upcoming renewable energy / energy storage RFP plans, we understand that developers of future BESS projects in Puerto Rico are likely to be compensated through some form of a capacity payment-based arrangement. For this comparison, we have assumed that a BESS project would be paid a [redacted] capacity payment (consistent with our experience managing recent RFPs for other utilities) and the energy to charge the BESS would be equal to [redacted] [redacted]. The cost of energy to charge the BESS is included in this comparison for two reasons. First, the battery cannot operate if it is never charged, similar to how a thermal generator cannot operate without fuel. Second, at high renewable energy penetration levels, the solar PV and wind generators will have to be substantially curtailed mid-day if BESS are not installed.

Table 4-5 — Estimated Comparison of FEMA Funded Peaking Generator to BESS

Natural Gas Simple Cycle Mobile Generator FT8 MOBILEPAC 25 DLN (per IRP)		
MW	23	MW
Capacity Factor[1]	10%	-
Generation	20,148,000	kWh
Heat Rate[2]	11,120	Btu/kWh
Fuel Consumption	224,046	MMBtu
Fuel Cost[3]	[redacted]	$/MMBtu
Fuel Cost	[redacted]	*$*
Variable O&M[2]	[redacted]	$/MWh
Variable O&M	[redacted]	*$/Year*
Fixed O&M[2]	[redacted]	$/kW-year
Fixed O&M	[redacted]	*$/Year*
Total	[redacted]	**$/Year**

Battery Energy Storage (4 Hour)		
MW	23	MW
Charge Hours[4]	876	Hours
Capacity Payment	[redacted]	$/kW-Year
Capacity Payment	[redacted]	*$/Year*
Solar PV / Wind Energy Cost[5]	[redacted]	$/MWh
Charge Energy Cost	[redacted]	*$/Year*
Total	[redacted]	**$/Year**

Notes: 1) Capacity factor value is based on S&L's electrical system simulations
2) Value consistent with IRP, O&M costs escalated to 2025
3) Value consistent with IRP, but accounts for recent Naturgy / NFE negotiations
4) The number of charge hours are specified to provide a consistent comparison basis to the peaking generator. We assume the BESS charges at 23 MW for 876 hours per year (10% of total annual hours)
5) Value is consistent with the IRP's solar PV LCOE estimates for 2025

The natural gas peaking generator is somewhat less expensive than the BESS if FEMA funding can be utilized for the installation of the peaking generator. In addition, peaking generators provide needed synchronous generation (a benefit not captured in the above financial comparison). [redacted] this comparison is only intended to illustrate that replacement of peaking generators can be economically beneficial to Puerto Rico if FEMA funding can be used.

Beyond providing synchronous generation, peaking generation would provide an additional safeguard for areas that are prone to becoming disconnected from the grid when transmission infrastructure is damaged by extreme weather events. Additionally, peaking generators will also provide backup and support to the renewable energy generators; peak power demands that cannot be met during the early years of renewable energy generation and / or limited energy storage can be managed with these new peaking generators. Also, as tropical storms cross or pass near the island, the ability to utilize renewable energy generation will likely be limited, and in these circumstances energy storage systems will be depleted within a short period of time. During these conditions, the new peaking systems will provide essential emergency generation services for the safety and security of the island's residents.

We also note that there are existing black start gas turbine units at each of the Costa Sur and Aguirre sites that are not fully functional. We recommend these be replaced with 60 MW black start generation systems provided by FEMA 428 funding. The purpose of these black start systems is to provide plant power to the Costa Sur and Aguirre facilities so that the main thermal plants may be restarted without an external power feed. The original black start equipment is no longer adequate to perform this duty. In the aftermath of the 2017 hurricanes, severed grid connections and island-wide blackouts prevented the south coast plants from restarting due to this deficiency.

4.4.1.2. New Combined-Cycle Power Plant in the San Juan Area

S&L considers that a new combined-cycle power plant in the San Juan area is important and will maximize PREPA's ability to provide a reliable electrical system as more inverter-based generation is installed on the island. Currently, the AES coal power plant is among the most reliable and inexpensive generators in Puerto Rico and is expected to be a significant producer of synchronous generation all the way until its scheduled retirement in 2027. Our modeling estimates it will provide a third of all of Puerto Rico's annual synchronous generation in 2025.

Whether PREPA replaces the AES coal power plant with a combination of renewable energy generation and BESS or with a new thermal generator, the requirement that there be sufficient electrical system inertia to provide system stability at all times does not change (at least until proven alternative methods to manage low system inertia become available). In the event that AES is retired and replaced with renewable energy generation plus BESS, PREPA would need to rely on other installed synchronous generators to make up for AES' retired generation. At present, there is not a long-term solution for where this needed synchronous generation will come from.

A new combined-cycle power plant would help PREPA navigate the retirement of AES and produce the synchronous generation needed to help provide system reliability. In addition, a new combined-cycle power plant would offer the following benefits:

- A new gas-fired combined cycle, including key LNG system integrations for fuel, inlet chilling and cooling duties, coupled with a low-load stand-by auxiliary power consumption, would be a best-in-class design and the most efficient thermal power plant on the island. We estimate that the plant would have a heat rate approximately 15% lower than the heat rate of the San Juan 5 & 6 generators and EcoEléctrica (the current most efficient thermal power plants in Puerto Rico). Higher efficiency would translate to lower fuel consumption levels (on a per MWh basis) and thus lower costs. This new plant would be classified as "Highly Efficient Fossil Fuel Generation" as defined by PREB in their March 20, 2019 resolution.

  The following table presents estimated marginal generation costs for the thermal generators modeled in 2025. The marginal generation cost is defined as the expected added cost for each additional MWh the generator produces. We would expect a new combined-cycle power plant to have a marginal cost below EcoEléctrica's marginal cost.

Table 4-6 — Estimated Large Thermal Generators Marginal Cost in 2025 ($/MWh)

Plant	Marginal Cost ($/MWh)
AES 1 & 2	55
EcoEléctrica	70
San Juan 5 & 6	80
Costa Sur 5 & 6	110
Mayagüez, Aguirre CC 1 & 2, Cambalache 2 & 3	200+

- A new combined-cycle power plant would be much more flexible than the AES coal power plant and is thus better suited to helping PREPA provide electrical system reliability as RPS targets are pursued. Large coal power plants are not able to start-up / shut-down and ramp up / down quickly (at least not as quickly as a combined-cycle power plant) and these characteristics are essential for generation portfolios with high numbers of renewable energy power plants due to the volatile generation profiles of renewable energy. Furthermore, a new combined-cycle power plant could be designed in such a way to maximize its flexibility even further through the use of smaller combustion turbines, steam cycle bypass, and other methods.

- Currently, the majority of the generators in Puerto Rico are located in the south, while the majority of the electrical demand is located in the north. The proposed new combined-cycle power plant would be located near the island's electrical load in the San Juan area, which would equate to less reliance on the north-to-south transmission network, thus, improved overall system reliability.

- A new combined-cycle power plant would better position PREPA for the coming retirements of Costa Sur units 5 & 6 and Aguirre CC units 1 & 2, which are both power plants that produce synchronous generation.

- The natural gas infrastructure is already in place in the San Juan area (i.e., the New Fortress natural gas terminal), meaning that development and permitting of a new combined-cycle power plant should be more streamlined.

4.4.2. Hydroelectric Power Plant Revitalization

The existing hydroelectric power plants have three key benefits: they are renewable energy generators, they provide synchronous generation to improve system inertia, and they are dispatchable generators. The fact that the hydroelectric power plants not only can provide electrical inertia to the Puerto Rican grid, but also can simultaneously contribute to PREPA meeting the RPS targets, makes the hydroelectric power plants valuable assets in Puerto Rico's transition to renewable energy. In addition, the hydroelectric power plants are dispatchable generators, meaning PREPA has control over when the power plants generate electricity (with the caveat that there is some seasonal variability in the amount of available hydroelectric resource). In contrast, wind and solar PV generators are traditionally not dispatchable, meaning that PREPA has little control over when these generators are able to produce electricity (outside of PREPA's option to curtail), unless they are aligned with energy storage systems.

We understand that PREPA is currently working to determine the potential cost to revitalize the hydroelectric power plants, which will be followed by a cost-benefit analysis. We recommend that the cost-benefit analysis considers the unique benefits that the hydroelectric power plants provide over comparable generation technologies; namely the fact that they contribute to RPS requirements, are dispatchable, and contribute to system inertia.

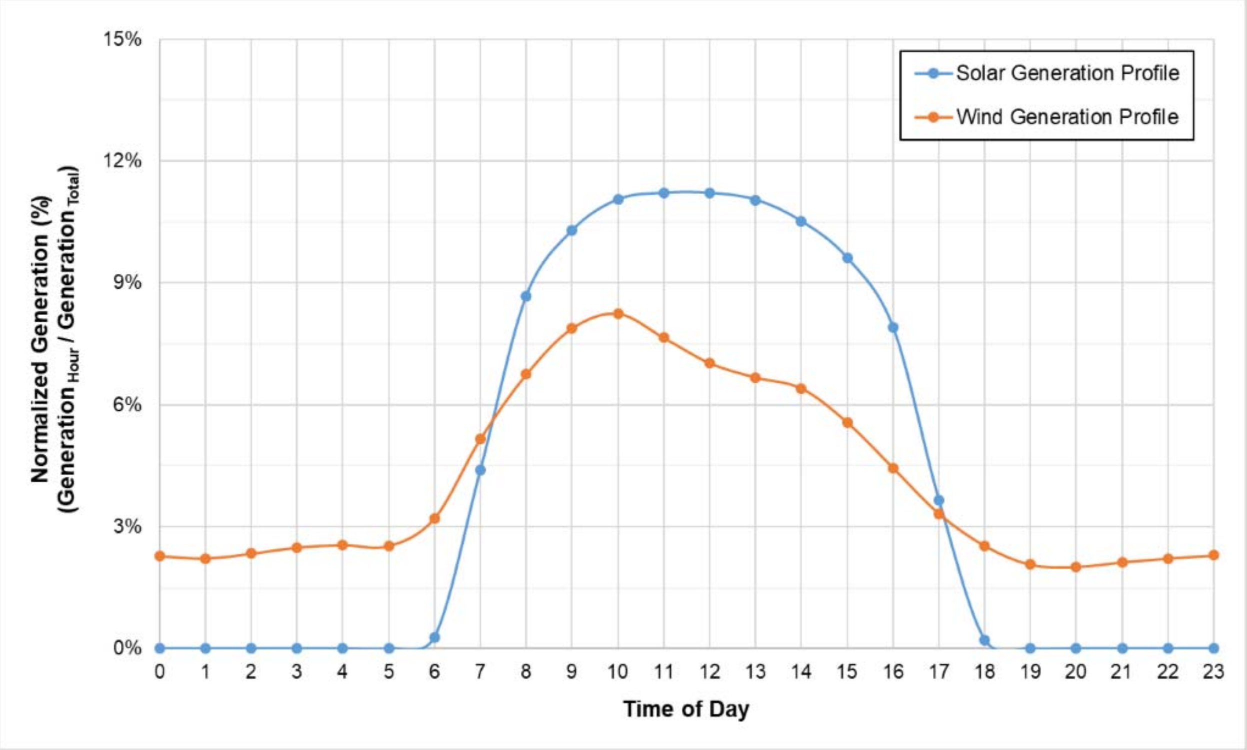
4.4.3. Diverse Renewable Energy Generation

As is noted in Table 4-2, our modeled portfolio includes 600 MW of new utility-scale wind power plants. It is our opinion that wind generation could be an important part of Puerto Rico's future renewable energy portfolio. The reason for this is because wind generation is more distributed throughout the day and night, as opposed to solar PV generation, which is concentrated between the hours of 8 a.m. and 4 p.m. We again note that both wind and solar PV generation are inverter-based generation sources.

The following figure provides a comparison of average hourly solar PV to the modeled Punta Lima wind power plant generation profile (normalized by the total daily generation of each technology). Each point plotted in the figure represents the average percent of total daily generation for that hour (i.e., approximately

7% of the total daily generation at the wind power plant is expected to occur between noon and 1 p.m.). The figure clearly shows the differences between solar PV and wind generation throughout the day.

Figure 4-3 — Average Hourly Solar PV vs Wind Generation Profiles



By having a less concentrated generation profile, wind energy provides two noteworthy benefits:

- Wind generators contribute a smaller proportion of their total daily generation to the middle of the day than solar PV generators (approximately one-third of annual generation from wind comes during times when there is no solar PV generation). This means that for increasing amounts of installed wind capacity to installed solar PV capacity, less synchronous generation would be needed to provide system inertia in the middle of the day.

- Likewise, higher proportions of installed wind capacity to installed solar PV capacity should equate to lower amounts of required energy storage. This can be explained by first considering a future where most of Puerto Rico's renewable energy comes from solar PV generators. For high amounts of solar PV energy, the concentrated generation profile of solar PV power plants will require that large amounts of energy storage systems are installed so that the solar PV energy generated during the middle of the day can be shifted to the evening, night, and early morning. In contrast, wind generation is less concentrated to the middle of the day; thus, a lower number of energy storage systems would be needed to shift wind generation away from the middle of the day to other times.

We note that both the wind and solar PV generation profiles have similar shapes – meaning that windy days in Puerto Rico often appear to coincide to when the sun is shining. However, our analysis does indicate that the differences are large enough that there would potentially still be a notable benefit if larger amounts of wind capacity were included in the overall Puerto Rico renewable energy portfolio.

In addition, we recommend that other renewable energy sources be considered for Puerto Rico's renewable energy transition. As previously discussed, we view the revitalization of the existing hydroelectric power plants as important from the perspective that the hydroelectric power plants are both dispatchable and synchronous renewable energy generators. We are also currently evaluating a variety of biofuels as an alternative for portside thermal generators (making those generators RPS-contributing).

Appendix A. Preferential Project Locations and Size

Per the Puerto Rico Energy Bureau's (PREB) request, S&L has compiled a list of preferential locations for the interconnection of inverter-based resources and the estimated power that can be injected into these locations (based on the scenarios studied). This list is compiled based on two types of analyses:

- The thermal limits of the system under different equipment contingencies as described in PREPA's transmission planning criteria
- The maximum power that can be injected into a substation before the system strength is reduced to unacceptable levels as defined in the minimum technical requirements (MTRs).

These results are summarized in the following table. The overall MW limits is the minimum of the MW limits identified in the two analyses. Note that the list is of preferential locations, which is far less than the total number of potential interconnection locations in Puerto Rico. This list only includes 115 kV substations and sites that could accommodate greater than or equal to 100 MW. SCR stands for short circuit ratio.

Table 1: Preferential Locations for Utility Scale Interconnections

Model (PSS/E) Bus Name	Estimated Transfer MW Limit	Estimated SCR MW Limit	Estimated Overall MW Limit
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

Model (PSS/E) Bus Name	Estimated Transfer MW Limit	Estimated SCR MW Limit	Estimated Overall MW Limit
[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

The following notes pertain to the previous table:

A) Two scenarios were analyzed to determine the preferred location and estimated limit on the MW injection, per the analyses performed. The table includes the estimated limiting MW value out of the two scenarios studied. The first scenario studied is with thermal generation as-is (no retired generation) and the second is a 2025 case with Aguirre, Palo Seco, and San Juan oil-fired generators are retired. The estimated limiting MW value is also highlighted in the table, indicating if the MW injection is limited because of transfer limit constraints or SCR constraints.

B) The transfer limit analysis is used to determine preferential locations by identifying the estimated limiting MW that can be added to a substation before any transmission system element (transmission line, transformer) is overloaded, or there is an increase in overloading under normal operating conditions and under contingencies based on PREPA's transmission planning criteria. These contingencies include loss of a single transmission line, loss of a single transformer, and loss of two transmission lines sharing a right of way.

C) The SCR analysis is used to determine the amount of MW that can be added to a substation before the SCR reaches 5.0. This value is defined in the minimum technical requirements as the minimum SCR that a solar PV, wind, or battery energy storage site can have before additional upgrades to the system need to be made. An SCR below 5.0 requires more detailed analysis for new renewable energy generation (inverter-based) and battery storage interconnections. Without correctly tuning inverter settings, the system could experience voltage oscillations or voltage collapse. This analysis is also done under a single transmission line contingency. A loss of a transmission line connected to the substation is not uncommon and reduces the SCR; therefore, it is reasonable to consider the loss of a transmission line when calculating the SCR.

D) The location and status (in service or out of service) of synchronous machines / generators has a significant impact on system strength. If generators near substations are turned off, the system strength is reduced and the substation under study would not be able to accommodate as much renewable energy generation or battery energy storage from a system strength perspective. If generators near the substation under study are operating, the system strength can increase and would be able to accommodate more renewable energy generation or battery energy storage. The generator status of nearby power plants should be considered when adding renewable energy generation and battery energy storage.

E) The analysis looks at a single substation at a time and does not consider the increase in renewable energy generation and battery energy storage at multiple substations at the same time.

The preferred interconnection locations are summarized in the maps of Puerto Rico below in the following figures. Each of the dots represents the preferred location that was identified based on the analysis. The radius and color of each of the dots represent the amount of MW inverter-based generation that can be added to each location before either a thermal limitation or short circuit ratio limitation is reached. A darker red indicates more MW can be injected at the location and a lighter yellow indicates less MW can be injected at the location. More detailed, magnified maps of locations labeled 'Area A, B, C, and D' are provided on the following pages.

Figure 1 — Puerto Rico Map of Preferred Interconnection Locations

[redacted]

Figure 2 — Area A: Preferred Interconnection Locations

[redacted]

Figure 3 — Area B: Preferred Interconnection Locations

[redacted]

Figure 4 — Area C: Preferred Interconnection Locations

[redacted]

Figure 5 — Area D: Preferred Interconnection Locations

[redacted]