Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100)

Summary Report

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Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Summary Report

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NOTICE

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Although we sought input from these stakeholders throughout the study, the design, assumptions, inputs, methods, and results of PR100 were ultimately determined by the national laboratories conducting the study with guidance from DOE. Because members of the Steering Committee and Advisory Group hold diverse perspectives and priorities, being listed as a group member or study reviewer does not imply agreement with or endorsement of the material presented in this report.

Members of these groups are listed as follows, along with their affiliations. Not all members participated for the full duration of the study. The list includes all members of these groups throughout the study, and their affiliations at the end of their participation. Asterisks denote those who reviewed the final report, for which we are deeply grateful:

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Summary Report

The Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100) is a comprehensive analysis based on extensive stakeholder input of possible pathways for Puerto Rico to achieve its goal of 100% renewable energy by 2050. In this summary report of the *PR100 Final Report*,[1] we describe the background and motivation behind the study, provide an overview, summarize results, highlight key findings, and outline implementation actions for stakeholders to take in the immediate term and the near, mid, and long term to achieve Puerto Rico's energy system goals.

Background and Motivation

Puerto Rico's current electricity system is complex, isolated, reliant on imported fuels, and vulnerable to extreme weather events and other natural hazards. Decades of operational, maintenance, and financial challenges have resulted in a system that lags far behind accepted reliability levels. Puerto Rico experienced one of the longest power outages in U.S. history after Hurricane Maria in 2017, which caused billions of dollars in damage and led to nearly 3,000 excess deaths by one estimation (Santos-Burgoa et al. 2018) or more than 4,500 by another (Kishore et al. 2018), followed by long-duration outages after earthquakes in 2020 and Hurricane Fiona in 2022. Frequent outages continue to impact Puerto Ricans on a day-to-day basis, caused in part by the poor state of repair of the electric transmission and distribution grid and insufficiency of the current generation fleet, which is frequently unable to supply enough electricity to meet load under even normal, non-peak conditions (PREB 2022).

In 2019, the Puerto Rico legislature passed the Puerto Rico Energy Public Policy Act (Act 17) (Puerto Rico Legislative Assembly 2019), setting a goal for the Commonwealth to meet 100% of its electricity needs with renewable energy by 2050 and interim targets of 40% by 2025, 60% by 2040, the phaseout of coal-fired generation by 2028, and a 30% increase in energy efficiency by 2040. Yet, energy system recovery, efforts to increase resilience, and progress toward renewable energy targets have been uneven. With 3%–5% renewable energy on the grid by mid-2023, and total utility-scale renewable energy capacity of 226 MW as of October 2023 (~137 MW of which is utility-scale solar PV) (LUMA 2023b), achieving the 40% target by 2025 would represent an increase of at least 3 GW of additional renewable energy capacity if met with utility-scale solar. Although the procurement of utility-scale renewable energy has been slow, the pace of distributed solar PV adoption is accelerating, increasing from 228 MW of total installed generation capacity in June 2021 to 680 MW in October 2023 (LUMA 2023b), a 3× increase in just over two years.

Since Hurricane Maria in 2017, the U.S. government has provided unprecedented support to Puerto Rico. The Federal Emergency Management Agency (FEMA), the U.S. Department of Housing and Urban Development (HUD), and other agencies have committed historical levels of funding to restore and build a more reliable and resilient energy system for Puerto Rico.[2] The U.S. Department of Energy (DOE) and six of its national laboratories have provided Puerto Rico

[1] Access the final report from the PR100 website and data viewer, https://www.pr100.gov/.

[2] Obligated funds include FEMA hazard mitigation assistance ($7.8 billion), FEMA public assistance ($9.5 billion), U.S. HUD Community Development Block Grant (CDBG)–Disaster Recovery: Electric Grid ($1.9 billion), HUD CDBG Community Energy and Water Resilience Installations Program ($800 million), and the Puerto Rico Energy Resilience Fund ($1 billion). Funding figures come from the respective federal agencies.

energy system stakeholders with tools, training, and modeling support to enable planning and operation of the electric system with more resilience against future disruptions.[3] A memorandum of understanding between DOE, the U.S. Department of Homeland Security, HUD, and the Commonwealth of Puerto Rico signed in February 2022 (DOE 2022) enhanced collaboration among federal agencies and the Commonwealth.

As part of this ongoing support to ensure recovery activities are aligned with Puerto Rico's renewable energy goals, in 2022 DOE and FEMA launched PR100, a study led by the National Renewable Energy Laboratory (NREL) with contributions from Argonne National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories. PR100 explored possible pathways for Puerto Rico to reach its goal of 100% renewable energy in the long term (by 2050), increase reliability and resilience in the immediate term (within the next few years), and work toward energy justice. The purpose of the study is to provide decision support and inform investment decisions for implementers of Puerto Rico's energy transition.

Concurrent with the study, LUMA, the transmission and distribution system operator for the government-owned Puerto Rico Electric Power Authority (PREPA), is developing an integrated resource plan (IRP) for Puerto Rico with a revised filing deadline of June 28, 2024 (PREB 2023b). In contrast with PR100, which DOE and the national laboratories conducted to answer stakeholder questions and inform investment decisions for Puerto Rico to achieve grid resilience and 100% renewable energy by 2050, the IRP is a detailed, 20-year plan the utility is required to update every three years with broad citizen participation that, "considers all reasonable resources to satisfy the demand for electric power services..., including those related to the offering of electric power…, and those related to energy demand" (Puerto Rico Legislative Assembly 2014). Although PR100 and the IRP are separate efforts, we coordinated with LUMA to ensure that PR100 results would inform the IRP, that the processes would be complementary, and to prevent contradictions or inconsistencies between the two efforts.

Study Overview and Approach

In PR100, we defined and modeled multiple pathways for decision makers to consider for Puerto Rico to achieve its energy goals, driven by community priorities and perspectives, similar to the approach taken in the Los Angeles 100% Renewable Energy Study (LA100) (Cochran and Denholm, eds. 2021). We scoped PR100 to achieve the study objectives in a way that would draw on and integrate the capabilities of the six contributing national laboratories. The study is organized into 11 tasks which are further grouped into five activities (Figure 1).

[3] Access publications and information about DOE's technical assistance to Puerto Rico from the DOE's Puerto Rico Grid Recovery and Modernization (https://www.energy.gov/gdo/puerto-rico-grid-recovery-and-modernization) and NREL's Multilab Energy Planning Support for Puerto Rico (https://www.nrel.gov/state-local-tribal/multi-lab-planning-support-puerto-rico.html) webpages.

Figure 1. The PR100 activities and tasks are led by six contributing national laboratories.

The lead laboratory for each task is listed in brackets.

PR100 Activities

The five activities of PR100 are shown in more detail in Figure 2. In Activity 1, we engaged extensively with stakeholders throughout the study to understand their perspectives and priorities for Puerto Rico's energy transition and to ground PR100 in the principles and practices of energy justice. As part of our energy justice analysis, Activity 1 also included assessments of infrastructure interdependency, resilience as measured by a social burden metric, and climate risk to consider the impacts of sea level rise and other effects of climate change on the future of Puerto Rico's energy system. All analysis results were evaluated through an energy justice lens to understand the benefits and burdens of the energy system as experienced by various stakeholder groups.

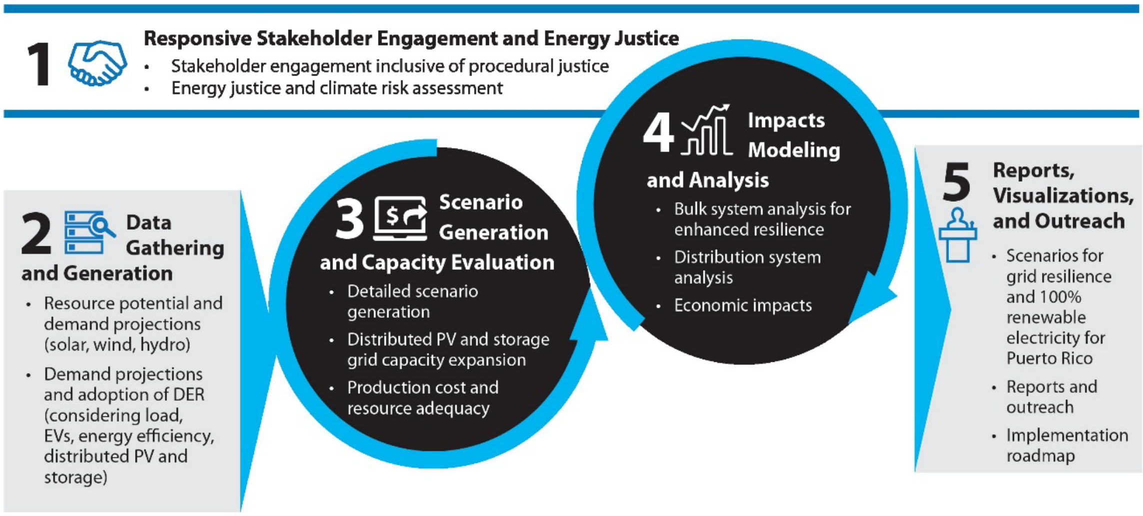

Figure 2. PR100 activities

In Activity 2, we gathered and generated data to use as inputs to the models. We sought stakeholder feedback on types and sources of input data, assessed the location-specific value of renewable energy resources in Puerto Rico, and evaluated areas of land and sea available for renewable energy development guided by local land use priorities. We projected electricity demand in Puerto Rico out to 2050, incorporating end-use loads, electric vehicle (EV) adoption, and energy-efficiency measures; and we modeled the adoption of distributed solar photovoltaics (PV) and storage.

In Activity 3, we defined four possible scenarios (later reduced to three) and two scenario variations, based on extensive stakeholder input, which are discussed in more detail in the Scenarios section. We modeled the scenarios to understand, based on established constraints, the cost-optimal capacity mix of energy technologies capable of delivering reliable power by year through 2050, as well as production cost and resource adequacy. In this activity we assumed that the transmission and distribution networks were repaired sufficiently to support reliable operation of the electric system, and that these repairs were completed with federal funding. Investments modeled in this activity were driven by the need to (1) achieve an adequate generation fleet to support customer demand and (2) accomplish goals established in Act 17.

In Activity 4, we analyzed the impact of the modeled scenarios on the transmission system, including its resilience to future disruptions. We studied the impacts to the distribution system and related considerations, such as microgrids. And we conducted economic impact analysis to explore potential effects on retail rates, including metrics related to changes in household income by income group under each scenario and job creation.

In Activity 5, we published progress updates at the 6-month and one-year mark of the study in addition to these final results in Spanish and English. Disseminations include this *PR100 Final Report*, a website and data viewer, public webinars to kick off the study and to accompany progress updates, and a public event to present our results and set the stage for implementation.[4] We conducted broad outreach to ensure that the results reached everyone with a role in the implementation of Puerto Rico's energy future.

Through the tasks and activities of PR100, the questions we sought to answer were as follows:

Guiding Questions

- What investments and actions are needed immediately to ensure a reliable energy system for Puerto Rico right away while enabling long-term objectives?
- How can Puerto Rico ensure that the new system is resilient to extreme weather events?
- What are possible pathways to achieving Puerto Rico's 100% renewable energy target by 2050?
- What kinds of big changes could reaching 100% renewable energy mean for local infrastructure —like building new transmission lines or upgrading distribution feeders to increase hosting capacity for distributed generation?
- If Puerto Ricans adopt energy technologies like electric vehicles, how might that change the total demand for electricity?
- What are the impacts of the energy transition on jobs and the local economy?
- What needs to be done to support an equitable energy transition for all Puerto Ricans?

Stakeholder Engagement and Energy Justice

While the national laboratories had scoped PR100 to conduct modeling and analysis about how Puerto Rico could reach 100% renewable energy, once the study began we worked closely with members of an Advisory Group to define the scenarios to be modeled such that the results would answer their questions about trade-offs and projected outcomes between multiple pathways to achieve Puerto Rico's energy goals. We also sought their feedback on study methods, inputs, assumptions, and results. As of October 2023, the Advisory Group had 116 confirmed members representing 73 organizations, including universities and other research institutions; federal and Puerto Rico government entities; solar and storage industries; finance, legal, community-based, and environmental organizations; retail, manufacturing, and consultants; and other sectors. A Steering Committee of leaders from federal and Puerto Rico government agencies[5] provided additional guidance (see Acknowledgments, page iv, for a list of members and affiliations).

In the second year of the study (Year 2), we broadened our engagement to include a community engagement tour and industry sector roundtables, conducted in partnership with the Puerto Rico Grid Modernization and Recovery Team led by U.S. Secretary of Energy Jennifer Granholm.

[4] Access publications and information about DOE's technical assistance to Puerto Rico from the DOE's Puerto Rico Grid Recovery and Modernization (https://www.energy.gov/gdo/puerto-rico-grid-recovery-and-modernization) and NREL's Multilab Energy Planning Support for Puerto Rico (https://www.nrel.gov/state-local-tribal/multi-lab-planning-support-puerto-rico.html) webpages.

[5] FEMA, HUD, PREPA, LUMA, Genera PR, the Puerto Rico Energy Bureau (PREB), the Puerto Rico Department of Housing (PRDOH or Vivienda), the Puerto Rico Department of Economic Development and Commerce (DDEC) Energy Policy Program, and the Central Office for Recovery, Reconstruction and Resiliency (COR3).

Through these events, we deepened our understanding of how communities and organizations are affected by the current energy system and what they want and do not want to see in the energy system of the future. The four primary groups of stakeholders with which we engaged are shown in Figure 3.

Figure 3. Four primary groups of stakeholders with which we engaged

We partnered with the Hispanic Federation in Puerto Rico to advise on stakeholder engagement and contribute to planning and facilitation of stakeholder meetings and community events. We found that partnering with a local organization to facilitate events and advise on our engagement strategy was immensely valuable, and ultimately expanded and deepened our connection with stakeholders and strengthened the study overall. We also partnered with a group of professors and graduate students at the University of Puerto Rico Mayagüez for input on PR100 and to support collaboration with related research efforts at the university. The University of Puerto Rico Mayagüez produced a series of memos summarizing their input on PR100 modeling and energy justice metrics, which informed modeling decisions and scenario development (Castro-Sitiriche et al. 2023; Irizarry-Rivera et al. 2023; Lugo-Hernández et al. 2023).

Through our work with stakeholders, we deepened our understanding that individuals and organizations across Puerto Rico have divergent experiences, priorities, and visions for the future energy system. Some are strong proponents of a highly distributed system while others favor a larger role for utility-scale renewables. We heard from stakeholders that rooftop solar and storage and preservation of agricultural land are high priorities in communities across Puerto Rico; common challenges include not having property title, structural concerns that make buildings not suitable for rooftop solar, frequent flooding, and energy-dependent water systems that do not work during outages. Findings from research conducted by project partners at University of Puerto Rico Mayagüez highlight the need to focus on duration to restore power to 100% of customers after outages and prioritize resilient, renewable energy access for the last 5% of customers who are most vulnerable to long-duration power outages.

An overarching activity of PR100 was to ground the study in principles and practices of energy justice, which are defined in the literature as, "…the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system" (Baker, DeVar, and Prakash 2019). The five pillars of energy justice that we sought to integrate throughout the study are procedural, recognition, distributive, restorative, and transformative (see Figure 4 for definitions). We involved an inclusive group of stakeholders, adhered to just practices for energy planning, and conducted an energy justice literature review with a focus on Puerto Rico that included local knowledge. When we asked Advisory Group members about their visions for a just energy transition for Puerto Rico, themes that emerged were:

- Energy access, affordability, reliability, and resilience
- Community participation
- Economic and workforce development
- Siting and land use
- Environmental and health effects
- Public sector implementation.

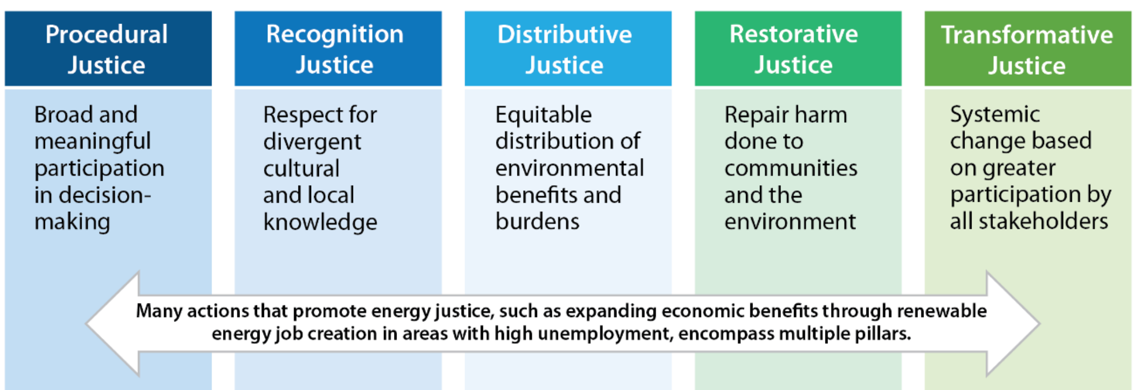

Figure 4. Five pillars of energy justice

Sources: Jenkins et al. (2016), Heffron and McCauley (2017), Baker et al. (2019), and Lee and Byrne (2019)

Scenarios

Based on extensive stakeholder engagement, it became clear that the extent of Puerto Rico's reliance on distributed generation is a key uncertainty regarding Puerto Rico's policy and investment strategy over the coming years. To explore the implications of varying levels of distributed generation, we worked closely with stakeholders to define three scenarios to answer questions about tradeoffs and possible outcomes for PR100.[6] We defined Scenario 1 as the economic adoption of distributed energy resources (DERs) based primarily on bill savings and value of backup power for building owners (Economic) and Scenario 3 as the maximum deployment of DERs on all suitable rooftops (Maximum). Because resilience was a high priority, we defined Scenario 2 between the bookends to extend DER adoption beyond Scenario 1 levels to very low-income households (0%–30% of area median income) and those in remote areas who

[6] Initially, we defined four scenarios, and based on preliminary modeling results, we reduced the number to three scenarios. See (Blair et al. 2023) (page 3) for a detailed discussion.

would not have bought systems solely based on economics (Equitable). The three scenarios modeled in PR100 are shown in Figure 5.

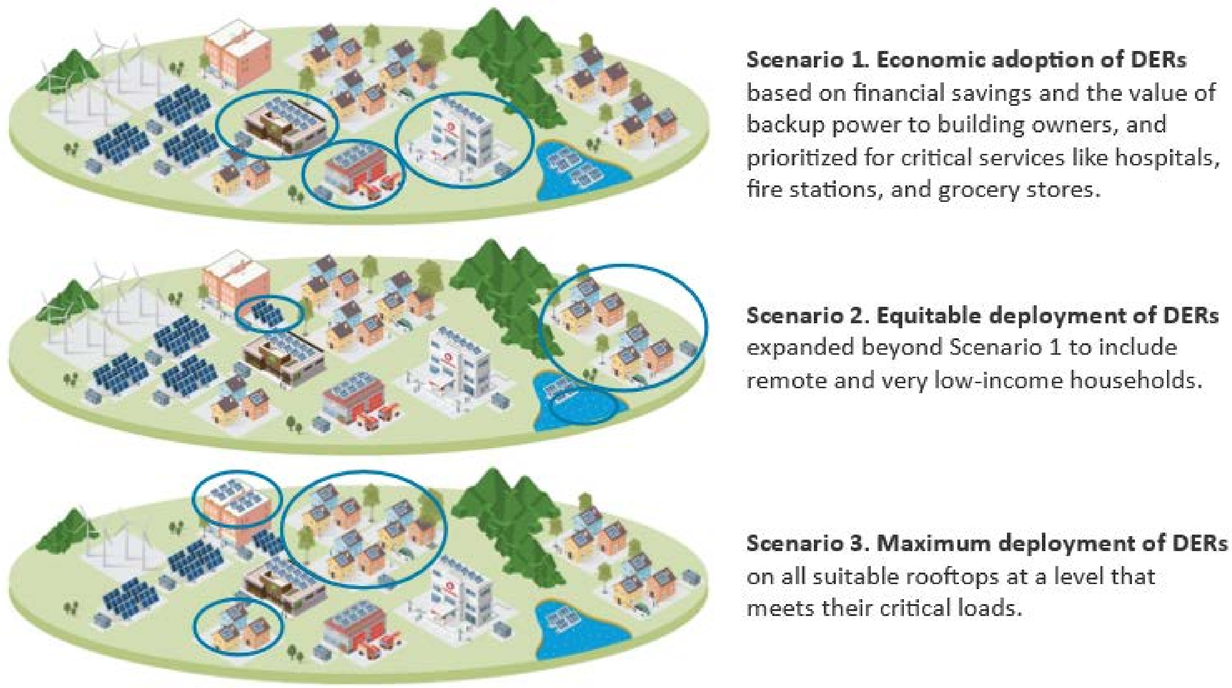

Figure 5. Three scenarios modeled in PR100, distinguished by varying levels of DER adoption

Differences between scenarios are circled in blue.

We defined remote communities based on outage duration after a major disruption such as Hurricane Maria, typical outage durations in the absence of a storm or other disruptive event, and input from local experts, including project partners at the University of Puerto Rico Mayagüez. For modeling Scenario 2 (Equitable), we defined remote communities as the 18 municipalities in Puerto Rico represented in Figure 6.

Figure 6. Scenario 2: Map of modeled remote municipalities in Puerto Rico

We also defined two variations, or sensitivities, to apply to the three scenarios. The land use variation includes two variants, Less Land and More Land, based on stakeholder feedback that the preservation of agricultural land is a high priority for many people. Figure 7 shows the developable area (shaded yellow) for utility-scale solar PV in each land use variant. Modeling this variation allows for an assessment of whether Puerto Rico's renewable energy goals can be met by developing utility-scale projects only on land not designated for agricultural purposes, or whether development on agricultural land may be required to meet demand with 100% renewable energy.

In both land use variants, development of utility-scale solar PV and wind is restricted from areas such as roadways, water bodies, protected habitats, flood risk areas, slopes greater than 10%, and agricultural reserves. In the Less Land variant, development of utility-scale projects is also restricted from areas identified for agricultural use in the 2015 Land Use Plan (Puerto Rico Planning Board 2015). In the More Land variant (Figure 7, bottom), 638 km^2 are available for solar development, with technical potential of 44.66 GW; in Less Land (top) the developable area is 203 km^2 with technical potential of 14.22 GW.

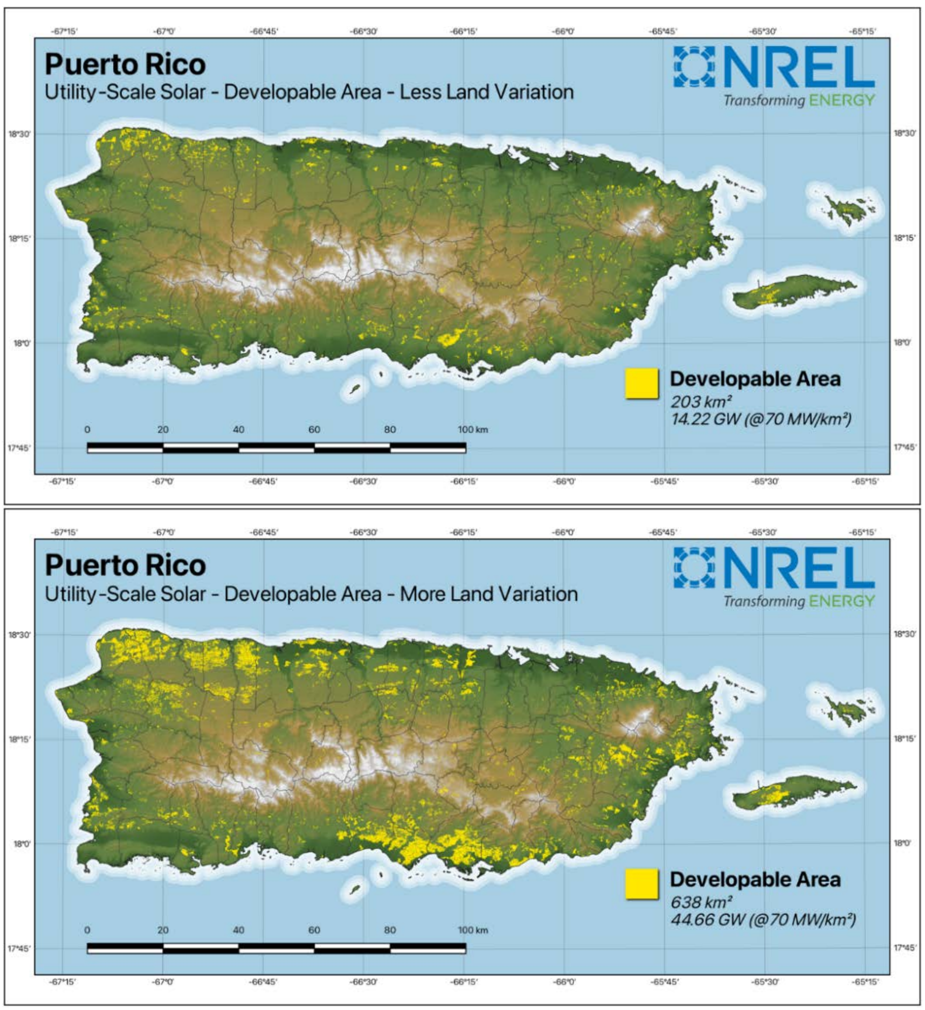

Figure 7. Two land use variations: Less Land (top) and More Land (bottom)

The developable area for utility-scale solar PV is shaded yellow.

Due to the uncertainty around electric load projections out to 2050, we also defined an electric load variation with two variants, Mid case and Stress (Figure 8, page 10). The purpose of defining a Stress load variant in addition to the Mid case was to help decision makers not to under plan in the event the load does in fact increase and to account for uncertainty in the inputs to the end-use load calculation. As discussed in the Summary of Results and Key Findings, capacity expansion and resource adequacy modeling show that total capacities are higher in the Stress scenario variations, and that additional capacity is required in both Mid case and Stress scenario variations to meet demand and reliability metrics without the need for deployment of emerging technologies.

Projecting electric load involved modeling changes in end-use load parameters, such as population size, manufacturing employment, gross domestic product, and climate; and taking into consideration the load impacts from electric vehicle (EV) adoption and energy efficiency. The Mid case end-use load projection showed slightly decreased end-use electricity sales over time, primarily due to forecasted long-term declines in population and real gross national product. To account for a possible future in which loads do not decline as projected, we developed a Stress load which assumes the combination of end-use loads and energy efficiency will result in flat annual electricity sales and electric loads from FY23 to FY51. Adding projected growth of electric vehicle adoption and resultant electricity loads results in increasing load as shown in the Stress load projection in Figure 8.

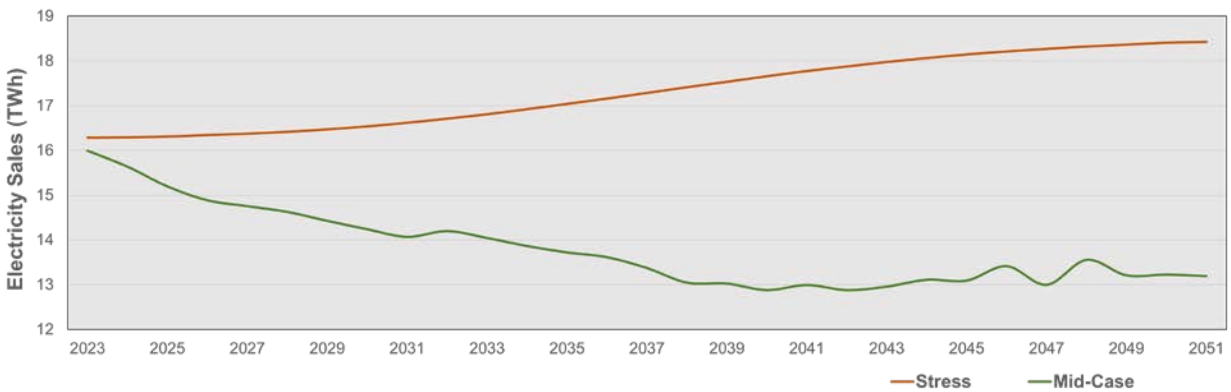

Figure 8. Two annual electric load variations: Mid case (green) and Stress (orange)

Combining the three scenarios with two variations, each with two variants, resulted in 12 total scenario variations modeled in PR100. Scenario identifiers referenced in the study results combine the scenario number with letters to represent the scenario variations, such that 1LS, for example, represents Scenario *1* (Economic), *L*ess Land, *S*tress load. See Appendix A for a table of the 12 scenario variations and their scenario identifiers.

Ultimately the range of scenario variation modeling results is fairly small in the next few years; one of the primary takeaways from the analysis overall, discussed further in Implementation Actions, is that regardless of scenario or source of renewable energy, increased capacity is needed on the system immediately to achieve a robust[7] electricity system for Puerto Rico.

[7] Throughout this report the term “robust” refers to the state of repair of the electric system.

Summary of Results and Key Findings

This section provides a summary of PR100 study results and key findings. We start at a high level with results of an assessment of renewable energy resource potential in Puerto Rico, followed by an evaluation of the demand for electricity and how it is projected to change over time considering end-use loads and adoption of energy efficiency measures and electric vehicles. Then we present results of a series of interdependent modeling and analysis exercises evaluating the defined scenarios and variations through 2050 given targets defined in Act 17 and additional assumptions and constraints listed in Appendix B. For each relevant scenario-variation we modeled the adoption of distributed solar and storage by income group, build-out of generation capacity, resource adequacy, and production cost to meet demand and system requirements, impacts on the transmission and distribution systems, and economic impacts. We also conducted assessments of infrastructure interdependency, social burden, and climate risk for Puerto Rico, which are not discussed in this summary report.

Detailed results of these analyses—including methodologies, assumptions, inputs, and interpretations for each topic—can be found in the *PR100 Final Report*.

Resource Assessment

We conducted assessments of a variety of renewable energy resources in Puerto Rico to evaluate whether the resource potential of solar, wind, hydro, and other sources is sufficient to meet Puerto Rico's goal of 100% renewable energy.[8] To answer this question, we generated high-resolution, multiyear resource data sets for land-based wind, offshore wind, as well as wind and solar forecast data, and evaluated the resource potential of hydropower and ocean thermal resources. We assessed the developable area and technical potential for utility-scale solar, land-based wind, and offshore wind, among other technologies. Results for utility-scale solar are represented in the land use scenario variation (Figure 7, page 9).

The resource data are used to determine the renewable energy technical potential of a given technology to define its achievable energy generation given system performance, topographic, environmental, and land use constraints. Technical potential is the total amount of a resource that could be deployed; it is only limited by physical constraints (e.g., rooftop area, available land area, and technical efficiency), and does not indicate likely deployment. Figure 9 shows the 25-year average solar irradiance by global horizontal irradiance (GHI) for Puerto Rico, and Figure 10 shows the 20-year mean wind speeds, wind direction at 160 meters, and terrain height for Puerto Rico. Appendix C provides instructions on how to access the data.

[8] In our modeling, we include only generation technologies that meet the definition of renewable energy in the Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico Act (Act 82 of 2010, as amended). Consistent with this policy, technologies considered in PR100 include solar energy, wind energy, hydropower, marine and hydrokinetic renewable energy, ocean thermal energy, and combustion of biofuel derived solely from renewable biomass.

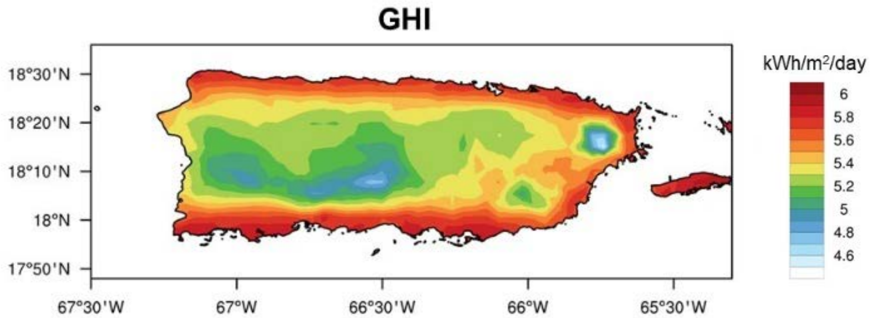

Figure 9. Map of 25-year average GHI for Puerto Rico

This map shows daily average GHI for 25 years of data using 4-km and 30-min resolution National Solar Radiation Database (NSRDB)[9] data sets.

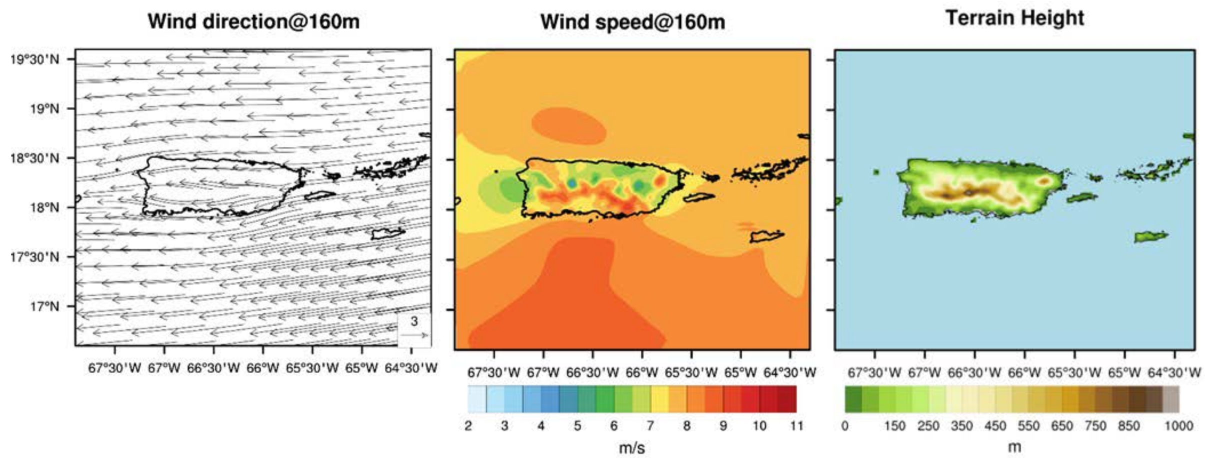

Figure 10. Maps of 20-year mean wind speeds, wind direction at 160 m, and terrain height for Puerto Rico

We found that while the Less Land variation provides sufficient developable area to meet annual load, the reduced land area is anticipated to result in the development of a greater number of smaller solar PV and land-based wind plants that are more dispersed across Puerto Rico, while the More Land scenario is more likely to result in larger but fewer plants. Due to the reduced economies of scale and increase in required infrastructure (e.g., access roads, interconnections, etc.) the costs associated with deployment under the Less Land scenario are higher on average than the More Land scenario across all modeled years and technology scenarios. In summary, more utility-scale solar PV capacity is available for each site at a lower levelized cost of electricity (LCOE) on average in scenarios where more land is available for development than less land ($75/MWh PPOA LCOE[10] and 44.67 GW for More Land and $79/MWh and 14.22 for Less Land in 2030 for expected levels of technology innovation) (Figure 11).[11]

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[9] https://nsrdb.nrel.gov/data-sets/how-to-access-data

[10] Using cost and financing assumptions derived from public power purchase and operating agreements (PPOAs) in Puerto Rico, the capacity expansion modeling team developed a process for calculating LCOEs under Annual Technology Baseline technology future scenarios (https://www.nrel.gov/analysis/data-tech-baseline.html).

[11] For a detailed discussion of these findings including the PPOA LCOE model and technology scenarios see the *PR100 Final Report*.

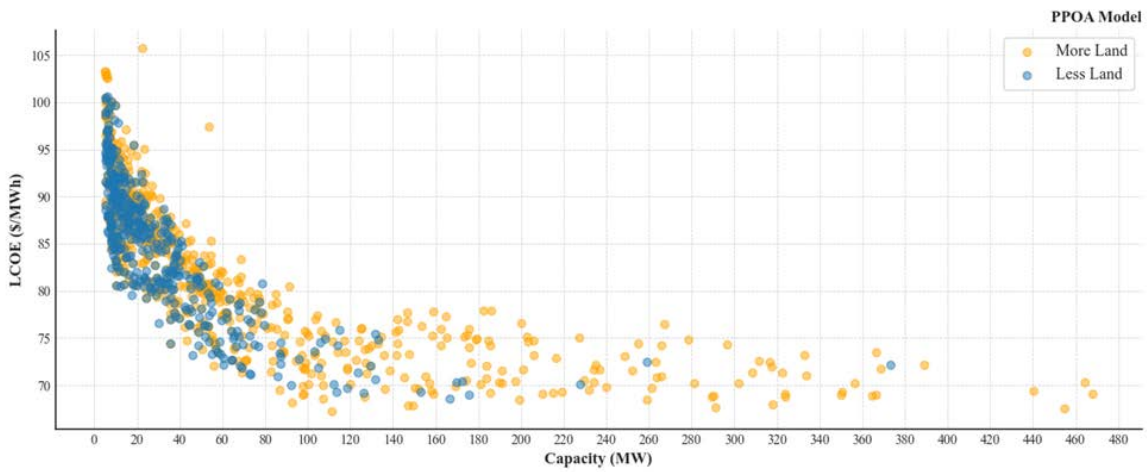

Figure 11. Total LCOE by plant capacity in 2030 for expected levels of technology innovation

We used results of an NREL analysis conducted by Mooney and Waechter (2020) to assess (1) how rooftop solar potential in Puerto Rico is distributed geographically, by income group, building type, and tenure of the building occupants and (2) how much electrical consumption can be offset by rooftop solar. The analysis processed 2015–2017 light detection and ranging (lidar) scans covering 96% of Puerto Rico's building stock. The lidar data were intersected with Census demographics tables of household counts by income, tenure, and building type. Solar generation was simulated for each roof plane using NREL's PVWatts and was aggregated at the tract and county level. Figure 12 illustrates the methodology. Results show the potential annual generation for all residential buildings is 24.6 TWh/year with potential capacity of 20.4 GW-dc. For low- and moderate-income households the potential annual generation is 11.9 TWh/year with potential capacity of 9.8 GW-dc.

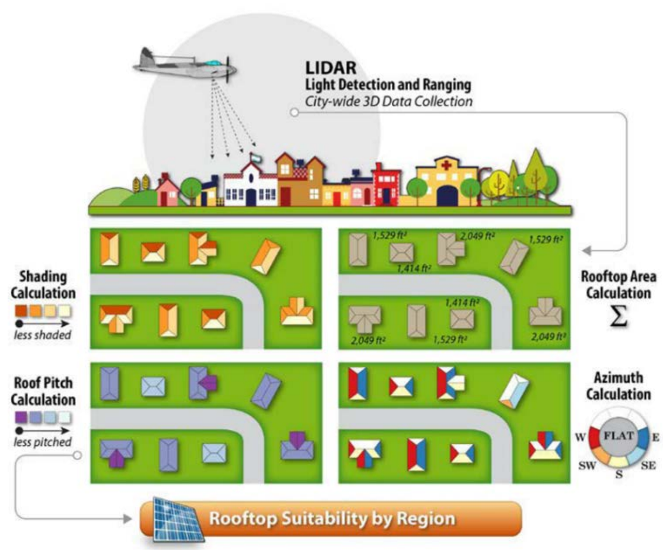

Figure 12. Summary example of rooftop PV analysis methodology

Source: Mooney and Waechter (2020)

We found that renewable energy resource potential assessed for Puerto Rico exceeds by more than tenfold what is required to meet the current and projected total annual loads through 2050 (Figure 13, page 14). Moreover, electric load can be met with mature technologies, such as distributed PV, utility-scale PV, utility-scale wind, storage, and reciprocating engines running on biofuels. A key finding from this analysis is that utility-scale PV deployment on nonagricultural land is sufficient to meet total annual electric load to 2050 in our scenarios. Achieving the 100% target would not require any technological breakthroughs. Emerging technologies could further diversify the technology mix in the future.

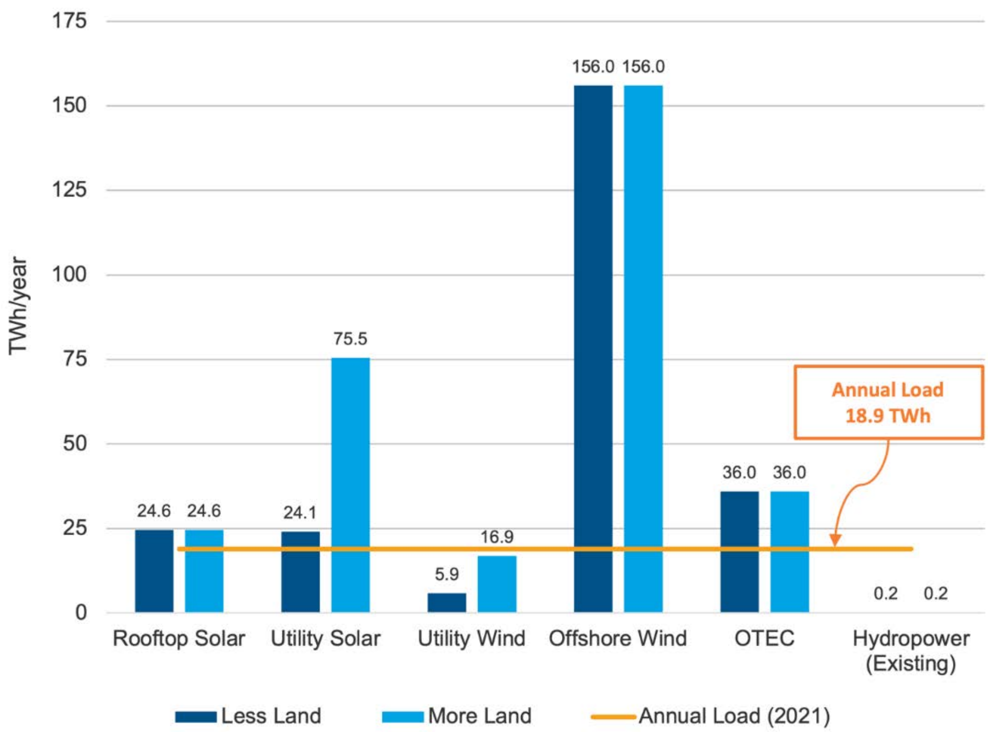

Figure 13. Potential annual generation in TWh of various renewable technologies compared to annual load in Puerto Rico in 2021

Key Findings

- Renewable energy potential assessed for Puerto Rico exceeds the current and projected total annual loads by more than tenfold through 2050.
- The technical potential of *mature* technologies—utility-scale PV, distributed PV, and land-based wind—is sufficient to achieve Puerto Rico's renewable energy goals.
- Emerging technologies may further diversify the technology mix in the future.
- Utility-scale solar PV potential capacity on nonagricultural land is sufficient to meet total annual electric load to 2050 in our scenarios.
- More utility-scale solar PV developable capacity per site is available at a lower LCOE on average in scenarios where more land is available.

Electric Load

As discussed in the Scenarios section above, we modeled projected changes in electric load in Puerto Rico by modeling end-use load parameters, such as future population size, changes to manufacturing employment, gross domestic product, and climate, as well as load impacts from electric vehicle (EV) adoption and energy efficiency. End-use loads are items in a building that use electricity, such as air conditioning, refrigeration, cooking equipment, lighting, plug loads and industrial loads. In this analysis, we took existing hourly end-use loads to determine if in the future these profiles would increase or decrease from year to year. As noted above, we found that end-use loads are anticipated to decrease across Puerto Rico by 2050 in the Mid case trajectory, based primarily on population and economic forecasts, so we developed a second trajectory called the Stress load which assumes the combination of end-use loads and energy efficiency will result in flat annual electricity sales and, due to the addition of EV loads, load trajectory increases.

In our energy efficiency analysis, we modeled the trajectory necessary to achieve Puerto Rico's goal of 30% energy efficiency by 2040 (Puerto Rico Legislative Assembly 2014, 57), as well as a second trajectory where the energy efficiency increases based on the annual consumption of each end use, the projected increase in efficiency of the relevant technology, and the estimated annual percent of technology stock turnover. In the bottom-up analysis we modeled the hourly impact of future energy efficiency adoption on the electricity load forecast. The savings are from natural turnover and codes and standards as well as programs. A key finding from these two approaches is that achieving the 30% goal is ambitious as compared with the bottom-up analysis results which show an 18% increase by 2050.

We also projected adoption of light-duty as well as medium- and heavy-duty EVs (MHDEVs) and the contribution to electric load. We based our estimate of the number of light-duty EVs in Puerto Rico from now until 2050 on U.S. Census and open-source road network GIS data to estimate driving energy consumption and charging locations. For MHDEVs we estimated travel patterns of existing medium- and heavy-duty vehicles in Puerto Rico and then determined the amount and geographical distribution of energy required to charge the MHDEV population assuming the adoption trend follows an S-curve, based on a 5% annual replacement of existing vehicles in the fleet, with the fraction of EVs growing by 4% every year between 2025 and 2050. We then applied charging schedules for the different end uses of MHDEVs to driving patterns to construct electric load shapes. A key finding is that 25% of light-duty vehicles and 47% of medium- and heavy-duty vehicles were estimated to be electric by 2050.

The Mid case and Stress load results of the electric load scenario variation (Figure 8, page 10) represent the combined contributions of three components. Figure 14 and Figure 15 show the contributions of these three components in the Mid case and Stress load variations. Based on LUMA data, total electricity sales for Puerto Rico were 16,282 GWh in FY22. In the Mid case variant, sales were projected to decline to 14,240 GWh in FY30 and to 13,192 GWh in FY51, with EVs accounting for 2% of electricity sales in FY30 and 16% in FY51.

In the Stress variant, electricity sales are projected to rise to 16,537 GWh in FY30 and to 18,422 GWh in FY51, with EVs accounting for 2% of sales in FY30 and 12% in FY51. Total EV electricity sales are slightly higher in FY51 in the Stress variation; however, EV sales account for a lower percentage of total sales in FY51 compared to the Mid case variation because end-use loads are significantly higher in the Stress variation.

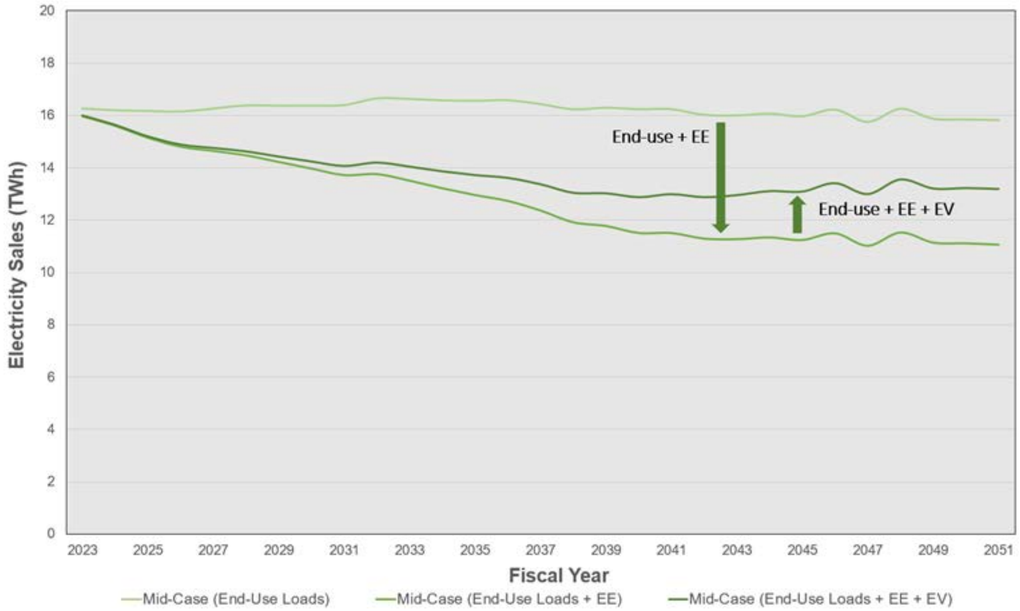

Figure 14. Annual electric load projections: Mid case variation, FY 2023–FY 2051

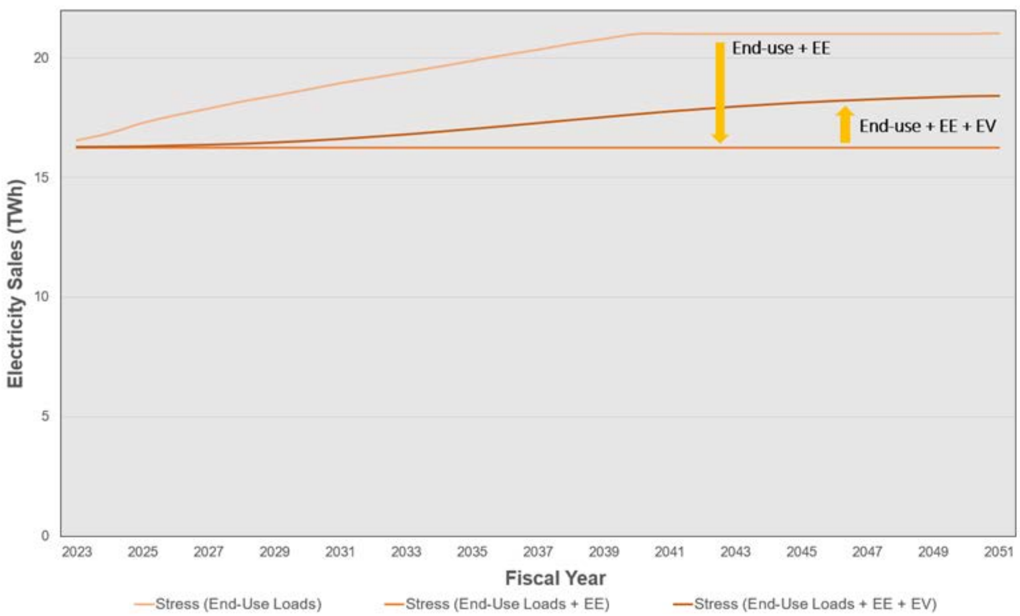

Figure 15. Annual electric load projections: Stress variation, FY 2023–FY 2051

Key Findings

- End-use loads are anticipated to decrease across Puerto Rico by 2050 in the Mid case trajectory, based primarily on population and economic forecasts. This trajectory of downward electricity demand is unlike most electric systems, which anticipate increasing loads even with increased energy efficiency.
- End-use loads into the future are uncertain and might not decrease, assuming other scenario changes (significant investment in the electric system resulting in a reliable grid); therefore, we examined a range of load trajectories (Mid case and Stress) anticipating that actual loads would be captured within this range.
- The current energy efficiency goal of 30% by 2040 is shown to be aggressive compared with results of our bottom-up analysis which show 18% energy efficiency by 2050. Currently, very limited resources are available for energy efficiency improvements in Puerto Rico.
- A total of 47 % of medium- and heavy-duty vehicles (MHDVs) were estimated to be electric by 2050.
- Light-duty EVs (LDEVs) are modeled to reach 25% of the overall fleet stock by 2050. This will have implications for the overall load and impact on the retail rates and other factors.

Distributed Solar Photovoltaics (PV) and Storage Adoption

We modeled the adoption of distributed solar PV and storage for each scenario using NREL's Distributed Generation Market Demand (dGen™) model.[12] We modeled six scenario variations—each of the three main scenarios combined with the load variations—because we assumed that variation in land use policies does not impact deployment of distributed generation (but rather, the adoption trajectory of distributed generation impacts how much additional renewable capacity is needed at the utility scale). As such, the range of distributed PV adoption for each scenario reflects the load trajectories in the Mid case and Stress load variations (Figure 8, page 10). The results can be summarized as follows:

- The Scenario 1 results represent the economic deployment of distributed PV based on bill savings to building owners combined with a monetized value of backup power and with adoption rates governed by historical consumer adoption behaviors (for residential, commercial and industrial buildings) and for critical services such as hospitals, fire stations, and grocery stores. By 2050, the economic adoption of distributed PV results in 2,500 to 3,300 MW of capacity (4,000 to 5,300 TWh of generation). These levels of distributed PV are 370% to 490% higher than the 680 MW in 2023.
- For Scenario 2, in which distributed PV deployment is expanded to meet the critical loads of low-income and remote communities, results show that an additional 11%–14% of distributed PV capacity beyond Scenario 1 is deployed (for a total of 2,800 to 3,600 MW of capacity or 4,600 to 5,900 TWh of generation).
- Finally, Scenario 3, which models further expanding rooftop PV and storage to all suitable rooftops to meet critical loads across Puerto Rico, results in a total rooftop PV capacity of 5,200 to 6,100 MW by 2050 (or 8,500 to 9,900 TWh of generation), more

[12] https://www.nrel.gov/analysis/dgen/

than 100% more that of Scenario 1. Similarly, a study conducted in support of the Queremos Sol proposal, with which Scenario 3 was designed to compare, previously found that the deployment of rooftop PV and storage systems on all residential and commercial rooftops, while a somewhat different set of buildings from those modeled in PR100, would result in 5,000 MW of distributed PV capacity (Vila Biaggi, Kunkel, and Irizarry Rivera 2021).

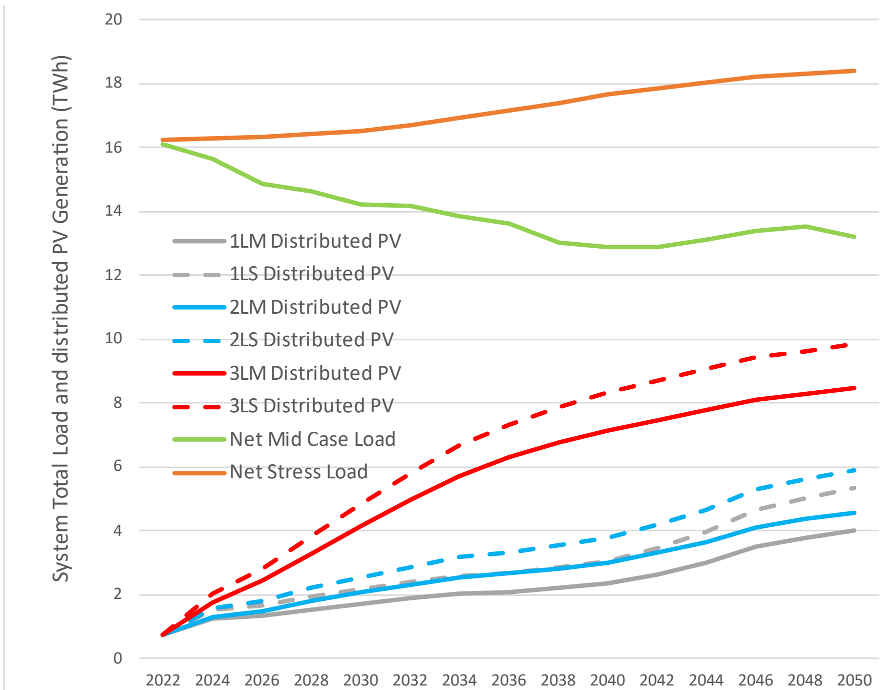

Figure 16. Rooftop PV generation across scenarios and Puerto Rico load forecasts plotted to demonstrate the fraction of annual load met by distributed generation

Figure 17, Figure 18 and Figure 19 (page 19) show rooftop PV capacity per customer by municipality for each scenario by 2050. A comparison of the three maps shows increasing capacity of rooftop PV per customer from Scenario 1 to Scenario 3. For Scenario 2, as illustrated by comparison with the small map (bottom right) of municipalities we defined as remote (see Scenarios section for discussion), Scenario 2 results in more capacity per customer in remote municipalities than Scenario 1.

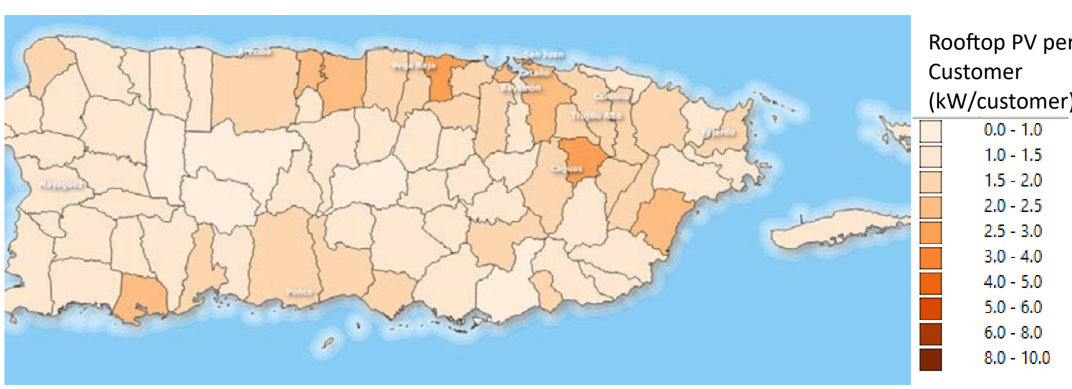

Figure 17. Year 2050 rooftop PV capacity per customer for Scenario 1 with Mid case load (1LM)

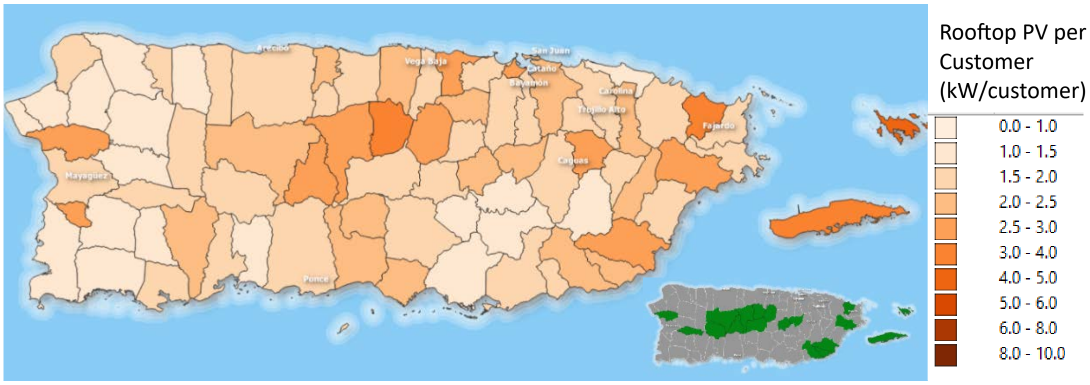

Figure 18. Year 2050 rooftop PV capacity per customer for Scenario 2 with Mid case load (2LM)

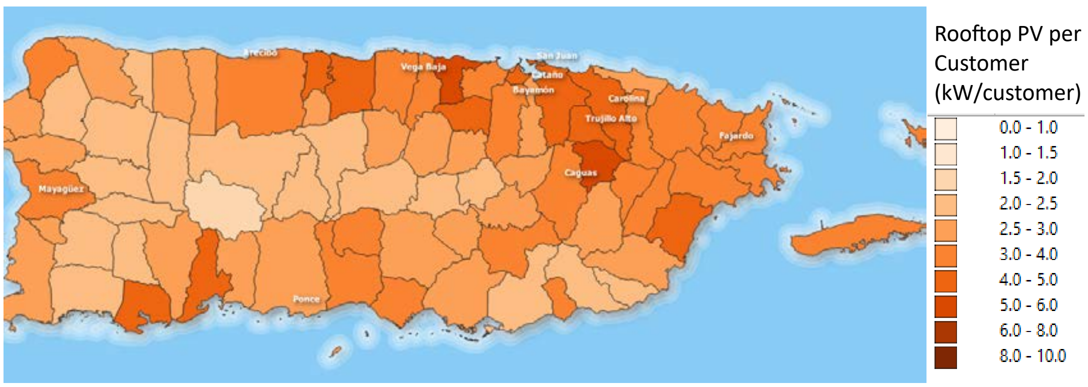

Figure 19. Year 2050 rooftop PV capacity per customer for Scenario 3 with Mid case load (3LM)

Our modeling assumes continuation of the current net metering compensation program out to 2050.[13] Under this framework, consumers are assumed to adopt behind-the-meter, distributed storage that is used for backup power during outages, which in 2021 occurred seven times more frequently on average in Puerto Rico than in the 50 U.S. states (FOMB 2023a). In this study, we did not model participation in demand response programs.

There is uncertainty around rooftop PV and battery costs for Puerto Rico, with some evidence pointing to lower costs than we used in the modeling. Lower system costs would increase and accelerate the adoption of rooftop PV and storage capacity in Scenario 1 because rooftop PV and storage would be more economic compared to utility rates; adoption would increase in Scenario 2 for the same reason. The Scenario 3 results would not be affected because rooftop PV and storage adoption is imposed on all suitable rooftops in that scenario rather than relying on economics.

[13] "The rate of the compensation provided is ten (10) cents per kilowatt-hour or the amount resulting from the subtraction of the adjusted fuel fee based on the variable costs incurred by PREPA exclusively for the purchase of fuel and energy from the total price PREPA charges its customers, converted into kilowatt hours, whichever is greater" (Puerto Rico Legislative Assembly 2007).

Key Findings

- Under all scenarios (Scenarios 1, 2, 3) and variations, the amount of rooftop PV capacity and storage capacity deployed in Puerto Rico by 2050 will be significant both in aggregate (2,500 to 6,100 MW) and in the instantaneous power supplied back to the grid during the day.
- Model results indicate that rooftop PV and storage deployment will continue even as the grid becomes more resilient because of economics and the ongoing desire for local generation and backup power. As battery and PV costs continue to decrease, the deployment of rooftop PV and batteries might result in extra capacity toward 2050 if significant utility-scale renewables are built in the near term.

Integrated Capacity Investment

We conducted capacity expansion modeling to find the lowest-cost system[14] for each scenario while meeting load, Act 17, and scheduled plans for resource procurement and retirement. We began by establishing the levelized cost of electricity (LCOE) for existing and new technologies. LCOE of technologies included in modeling results for 2035 are shown in Figure 20.

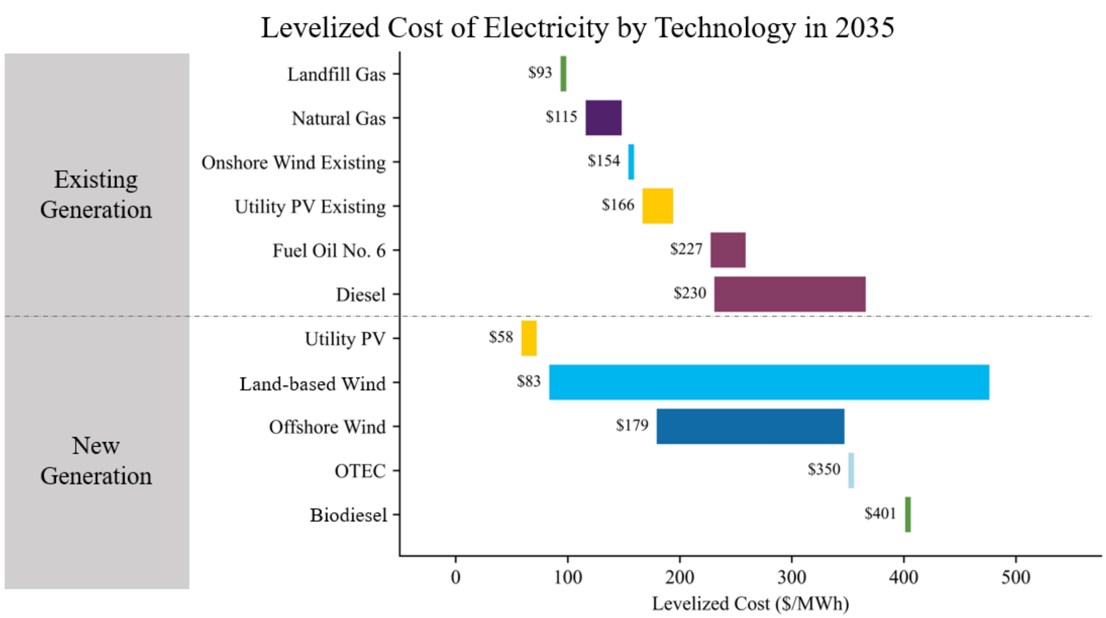

Figure 20. Levelized cost of electricity by technology in 2035 (costs in 2021 real dollars)

[14] By "lowest cost," or "least-cost" we mean the lowest-cost combination of resources (generators, wires, etc.) that together have the energy production capacities to meet system electricity demand at all times. Some stakeholders pushed back against this approach because it does not account for complexities such as social or environmental costs.

We then evaluated the system adequacy of these optimizations and augmented expansion results to achieve acceptable levels of system adequacy. By that, we mean that this analysis focused on the adequacy[15] and operational reliability[16] of future systems to minimize outages which have been so impactful in Puerto Rico. There are other reliability measures that we have not included in this project.[17]

We found that additional generation capacity is needed immediately—on the scale of hundreds of megawatts—to achieve system adequacy and minimize outages. Indeed, even if all six tranches of PREPA's Renewable Energy Generation and Energy Storage Resource Procurement Plan (PREB 2020) successfully result in capacity additions as planned, a significant investment in additional generation capacity would still be needed to achieve acceptable reliability performance.

As shown in Figure 21, to achieve 40% renewable energy, the optimal expansion planning results include 2,600–3,500 MW of utility-scale PV capacity, depending on the scenario, along with approximately 700 MW of 4-hour-duration utility-scale batteries, 260–400 MW of long-duration storage, and 170–340 MW of land-based wind. These utility-scale capacity additions augment the capacity added from the distributed PV and storage adoption results described in the previous section that were used as fixed inputs in the capacity expansion model. Much of the roughly 4-GW of existing fossil-fueled generation remained on the system in this phase. We observed that the current pace of utility-scale deployment is likely too slow to result in 40% renewable energy by the 2025 statutory deadline and a reliable grid in the near term.

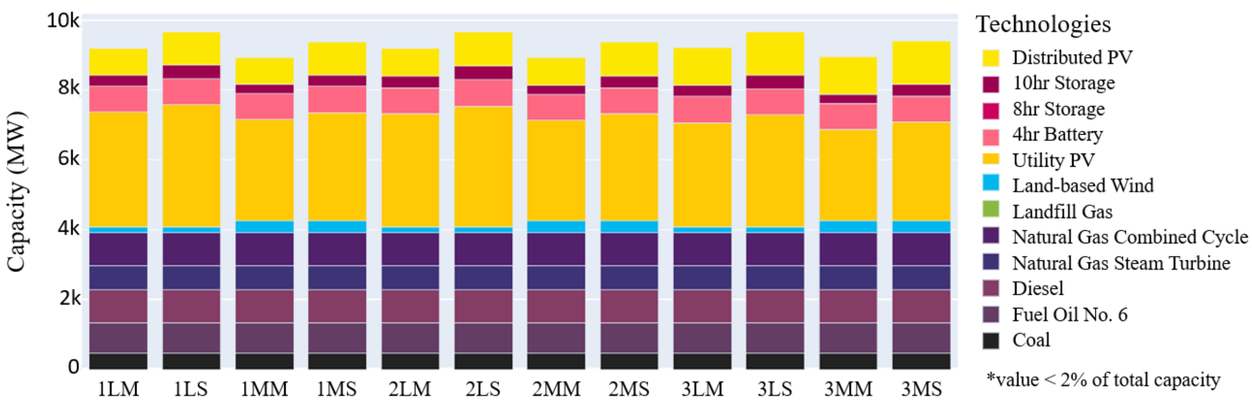

Figure 21. Total capacity to achieve 40% renewable energy

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[15] Adequacy is the ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. https://www.nerc.com/AboutNERC/Documents/Terms%20AUG13.pdf

[16] Operating reliability is the ability of the bulk power system to withstand sudden disturbances, such as electric short circuits or the unanticipated loss of system elements from credible contingencies, while avoiding uncontrolled cascading blackouts or damage to equipment.
https://www.nerc.com/AboutNERC/Documents/Terms%20AUG13.pdf

[17] Reliability measures include but are not limited to pole replacements; transformer monitoring/replacement; recloser installation; conductor inspection and replacement; animal guards; fault location, isolation, and service restoration, etc. These are not addressed in this study.

The scenario modeling results for 2050 (Figure 22) show the generation mix on the system when 100% generation by renewables is achieved (and the system maintains the reliability requirements achieved at 40%). All fossil-fueled plants are retired by 2050. The optimal mix of resources includes the addition of energy storage and biodiesel engines to serve system energy demands during periods of low wind and solar output. Once all fossil-fueled plants are retired the system requires some biodiesel engine capacity (or a similar alternative resource) that can operate for prolonged periods. Biodiesel was chosen by the model from several flexible generation options including hydrogen because it was the lowest cost option to fill in these time periods and provide reliable capacity beyond energy storage.

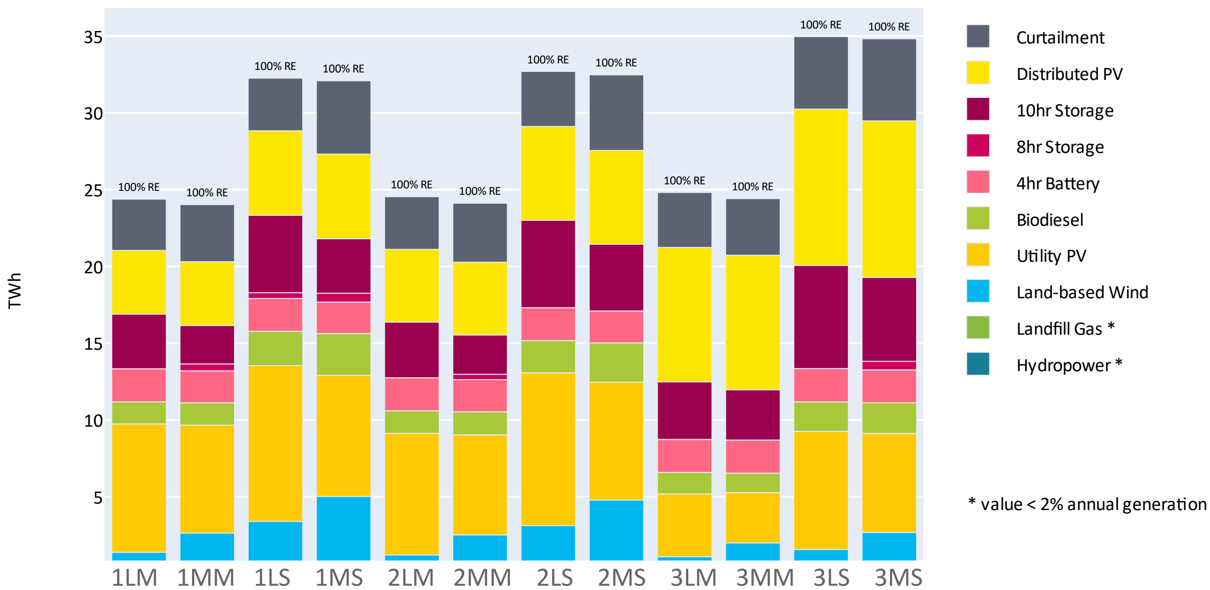

Figure 22. Total annual electricity generation by scenario to meet 100% renewable generation requirements for study year 2050

Despite modeling several additional technologies,[18] the results for all scenarios show a path to 100% renewable energy driven by solar PV at both the distributed and utility scales. Land-based wind is also built in all scenarios, to a smaller degree in the Less Land scenario variations than in the More Land scenario variations. Other resources were not shown to be cost- and performance-competitive. This predominance of solar, both distributed and utility-scale, necessitates storage and/or flexible generation to ensure that load from residential as well as commercial and industrial customers can be met reliably. Because solar generation occurs during the day, the system needs both energy and capacity at night as well. Of the renewable resources available to build, this need is most effectively met by storage and flexible generation. Other resources, such as hydrogen storage, could be deployed to meet this need if they emerge as the least expensive options.

[18] Generation technologies included in future scenarios include distributed PV, utility-scale PV, land-based utility-scale wind, offshore wind, hydropower, landfill gas, biodiesel engines, ocean thermal energy conversion (OTEC), and hydrogen production and storage.

Several additional observations can be made about the electric system model results for 2050. First, generation levels vary greatly with load: The Mid case load scenario variations generally need less generation than the Stress loads. There is additional variation among the Stress load scenario results because some generation moves through storage systems before being used. Additionally, we observe that restricting the amount of land available for renewable energy development does constrain the amount of land-based wind capacity deployed in the Less Land scenario-variation results. Finally, curtailment of solar in 2050 is notable. The expectation is that variable sources of renewable energy are curtailed somewhat regularly to balance the system; this is a common finding in 100% renewable energy studies and is still the least-cost system solution.

Key Findings

- To meet the near-term 40% RPS goal by 2025 as well as resource adequacy needs, the capacity expansion model's optimal solution includes multiple GW of solar and storage, and some land-based wind, by 2025.
- Across the scenarios, we do not see deployment of additional offshore wind, ocean thermal energy conversion (OTEC), or hydrogen in the model due mostly to a lack of current and projected cost-competitiveness.
- Relative costs of wind, solar, batteries, and biodiesel generators are critical drivers of the integrated capacity investment results.
- Distributed PV deployment in the future leads to some utility-scale curtailment in the model because of earlier build-out of utility PV—especially in Scenario 3—and mechanisms are needed to assess that post-2024.

Bulk Power System Operational Scheduling

This section focuses on the hour-to-hour operation of projected future bulk power systems resulting from distributed resource adoption and optimal capacity expansion. We simulated optimal scheduling of the projected bulk power system components including utility-scale generation and high-voltage transmission (38-kV and above) to meet an aggregated representation of energy demands and distributed generation to evaluate the ability of projected future energy systems for Puerto Rico to produce and transport enough electrical energy to meet electrical demand at all times. In total, we analyzed 84 years of hourly production cost model results (1 year of hourly optimal operational schedules for each capacity expansion scenario-variation and study year (2025, 2028, 2030, 2035, 2040, 2045, and 2050)).

Production cost model results indicate that with substantial changes to operational scheduling practices all projected scenario-variation systems can manage expected forecast errors to meet energy demand at all times throughout the study horizon. Even with updated scheduling practices, the lower voltage (38-kV) transmission network is found to be insufficient to support the projected system buildouts. With solar resources dominating the distributed and utility-scale generation expansions, our results show there is relatively little need for additional cross-island transmission capacity. However, the number of new generation interconnections and amount of distributed generation capacity significantly alters the flow patterns on the local transmission infrastructure that is predominantly served by 38-kV assets.

Figure 23 (page 24) shows the total magnitude of violations simulated in each scenario and year without restricting the 38-kV transmission line flow limits. Our results show that careful generation interconnection siting, transmission expansion, and other possible mitigating actions are required to avoid frequent and debilitating 38-kV network overloads even at 40%–50% renewable energy, regardless of scenario that would limit the renewable power production capabilities of some regions.

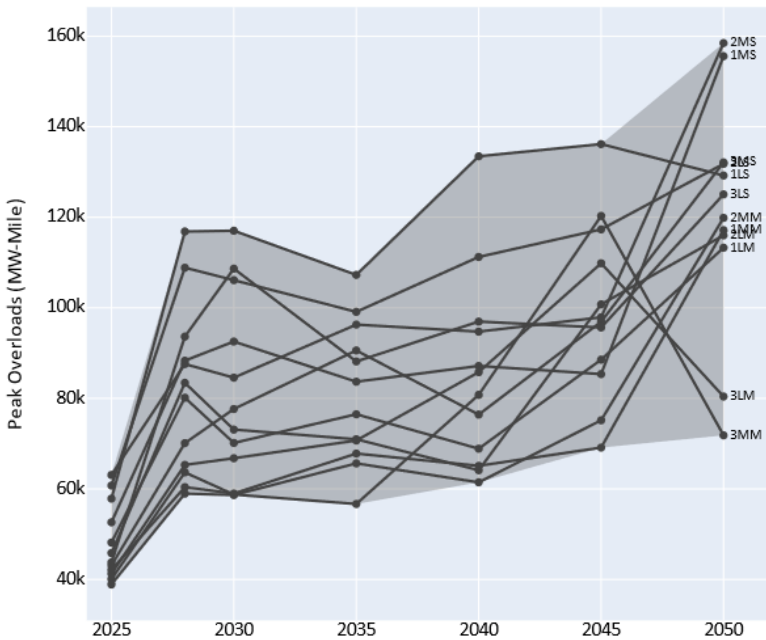

Figure 23. The 38-kV line overloads for 40% and 100% renewable energy

> *Key Findings*
>
> - The lower-voltage (38-kV) transmission network components are insufficient to handle the projected system transitions.
> - The projected system build-outs have sufficient generation, storage, and transmission resources to manage forecast errors and maintain reliable service under normal operating conditions.
> - While managing forecast errors will be possible, the lack of resource diversity in the projected systems will require significant operational scheduling changes to do so.

Bulk System Power Flow, Dynamic, and Resilience Impact Analysis

This section focuses on modeling and analysis of the physics of the Puerto Rican power grid to assess system reliability and resilience. The bulk power system impact analysis in PR100 comprises eight main aspects:

1. Alternating current (AC) power flow analysis to evaluate the needs for additional voltage control equipment to maintain voltages within limits and manage voltage fluctuations from the variable output from distributed and utility scale renewables;

2. Grid strength analysis to identify potential need for protection system upgrades, stability concerns, and need for synchronous condensers or equivalent equipment to resolve these concerns;
3. Model tuning to improve dynamic grid models for a better baseline of analysis;
4. Electromagnetic transient (EMT) stability analysis for very near term for highest resolution modeling of renewable generation and BESS with grid supporting functions in grid following (GFL) mode;
5. Stability analysis for 100% instantaneous penetration and grid-forming (GFM) controls in battery energy storage systems (BESS) and solar PV to be able to operate the system;
6. Load dynamics and DER modeling to capture interactions between DER and loads that may cause unwanted disconnections of DER potentially compromising reliability;
7. System black start using GFM battery energy storage system to begin considering replacement of fossil fuel resources that currently provide black start service; and
8. Resilience analysis to estimate possible damage to generation and transmission and distribution (T&D) infrastructure from hurricane events as well as studying the ability of future system to recover from severe hurricane damage. The corresponding eight subsections in the full report describe the methodologies, results, and considerations.

In this summary, we highlight two aspects of this analysis: grid strength and energy storage.[19] First, low grid strength is indicative of potential need for protection system upgrades and possible stability problems. As a representation metric of grid strength, Figure 24 (page 25) shows the buses in red that are the most likely to experience stability problems and needs of protection system upgrades (as indicated by largest percentage change in short-circuit megavolt-amperes (SCMVA)). As renewable energy generation increases from 40% to 100%, high-voltage buses and legacy (fossil-fueled) generator locations show the greatest decrease in SCMVA and therefore have the least grid strength (and therefore potential stability issues and needs of protection upgrades) as the system switches to renewable energy. Remote and rural locations show little change despite having more dispersed utility-scale PV and wind in those areas. In the future, grid strength will need to be improved in areas with retired plants. Improved grid strength can help with protection coordination and avoid potential stability problems.

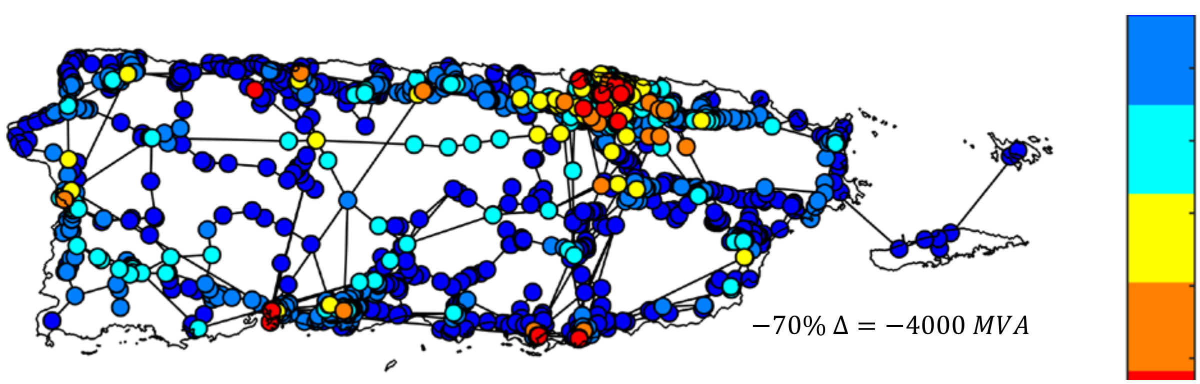

Figure 24. Percentage change in SCMVA from 40% to 100% renewable energy

[19] All eight aspects of this analysis are described in detail in Section 10 of the *PR100 Final Report*.

Second, results show that installing energy storage equipped with advanced grid supporting controls will be key for improving grid reliability and resilience as Puerto Rico transitions to high levels of renewables. Grid supporting controls can include primary frequency control, automatic voltage regulation, secondary automatic generation control, GFM control, and black start. GFM inverters can establish grid voltage and frequency, including in momentary conditions where all resources are renewable (instantaneous 100% inverter penetration); on the other hand, grid-following inverters (currently widely used) need other resources to establish grid voltage and frequency before contributing grid support. GFM functionality will be key for reliable operation of the Puerto Rico grid with high levels of renewables.

Modeling in PR100 showed improved stability, maintaining frequency and voltages within acceptable performance after sudden generation outages, transmission faults, and undesired DER disconnections. GFM inverters are shown to be necessary for 100% instantaneous inverter penetration, and the model performed well for GFM in all BESS with fast frequency controls with 1% droop; simulations also showed that additional GFM controls in PV improves the performance further. Additionally, for system resilience, GFM inverters can contribute to black-starting the grid after hurricanes (grid-following inverters cannot provide black start services); modeling showed how a single BESS can energize the 230 kV transmission system, providing an important step for black start and system restoration. Location of energy storage systems are also very important for efficient grid recovery after hurricanes; grid recovery simulations show faster resources that can support recovery, like BESS, are available in more locations.

Key Findings

- Modeling results show that to operate the system in moments of 100% inverter conditions, advanced grid supporting functions like GFM inverters are key; in addition, synchronous condensers (1,600-megavolt-ampere [MVA] total needed to bring grid strength to about current levels) or equivalent equipment are needed to increase grid strength for adequate protection and to avoid potential stability problems.
- Results indicate that to mitigate large frequency deviations and contribute to black start and grid recovery, 300 to 800 MW of battery energy storage with GFM functionality and the ability to set up fast frequency response (1% droop) will be key for the short term. Simulations show significant stability improvement with acceptable frequency deviations for cases with 40% and 100% instantaneous inverter penetration conditions.

Distribution Grid Impacts

In PR100, we simulated impacts related to increasing amounts of distributed PV connected at the distribution system level. Distribution feeder power flow modeling was conducted on a set of representative distribution feeders from across Puerto Rico. The modeling looked at power flow, voltage, and loading impacts on feeder operation with the PV penetrations modeled under Scenarios 1, 2, and 3. It was additionally noted that some feeders, as they exist in Puerto Rico today, already operate beyond the American National Standards Institute Range A standard voltages (Kersting 2018), even with no solar PV generation, such as during nighttime periods. This was found primarily to be caused by high feeder head voltage setpoints and always-on capacitors which increased system voltage, even when voltage was already high. For this study of renewable energy impacts to distribution feeders, we assumed that these feeders were corrected to operate within American National Standards Institute Range A prior to adding any simulated PV systems. Corrections would include for the utility to change voltage setpoints and remove or replace always-on capacitors with controllable capacitors.

Figure 25 shows the percentage of feeders with backfeeding under Scenarios 1, 2, and 3. Backfeeding means that during midday periods there was more generation on the feeder from distributed PV than there was load consumed by customers on that feeder. Distribution systems in Puerto Rico cannot currently accommodate any backfeeding due to existing system settings which do not allow reverse power flow and which are not easily changed. To address backfeeding and other possible voltage and loading concerns from high levels of distributed PV on the distribution system, we evaluated mitigation strategies including PV grid support functions (Volt/VAR and Volt/Watt), utility-controlled storage located on the distribution feeders, and participation of customer-owned storage in a grid-interactive way (e.g., charging during midday periods). Combinations of these strategies working together were found to eliminate nearly all negative impacts of high levels of distributed PV.

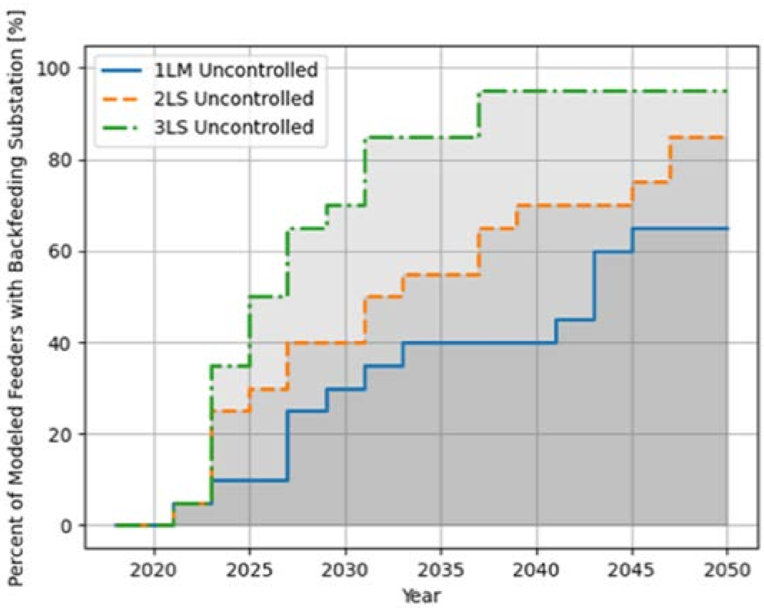

Figure 25. Percentage of feeders with back-feeding substations

Key Findings

- Some feeders as they exist in Puerto Rico today operate beyond the American National Standards Institute Range A standard voltages even when there is no PV power production (e.g., at night). To isolate the impact of adding renewables, these feeders were assumed to be fixed to operate within standard voltages prior to adding any simulated PV systems.
- Uncontrolled distributed PV capacity under PR100 Scenarios 1, 2, and 3 was found to exceed 65%–95% of the studied distribution feeders' hosting capacities, due to issues such as backfeeding and PV-caused voltage violations.
- Combinations of mitigation strategies including utility-controlled storage, PV grid support functions, and use of customer-owned storage in a grid-interactive way were found to eliminate nearly all negative impacts of high distributed PV penetrations.

Economic Impact Analysis

We conducted an analysis of the economic impacts associated with Puerto Rico's energy transition. We employed three types of economic impact analyses to answer questions about how much the energy transition will cost the citizens and businesses of Puerto Rico, and how citizens will be financially impacted: (1) retail rate analysis, (2) gross macroeconomic impact analysis, and (3) net macroeconomic impact analysis. See the *PR100 Final Report* for a detailed discussion of all three analyses.

We found that the utility-incurred costs to transform Puerto Rico's electric grid to one that is reliable will be significant regardless of the mix of generation technologies. Because the cost variation is more meaningful over time than by scenario, we examined two scenario variations to demonstrate cost changes over time: 1LS (Scenario 1, Less Land, Stress load) and 3LS (Scenario 3, Less Land, Stress load).

Figure 26 shows the revenue that the utility must collect to cover its costs, known as a revenue requirement, for each scenario along with the resulting all-in average retail rate (i.e., revenue per unit of retail electric sales) over time. Despite incurring roughly similar costs regardless of the level of distributed PV adoption, the utility must charge substantially higher all-in average retail rates in Scenario 3LS (right) than Scenario 1LS (left) because the former has 20% less utility-sold electricity than the latter.

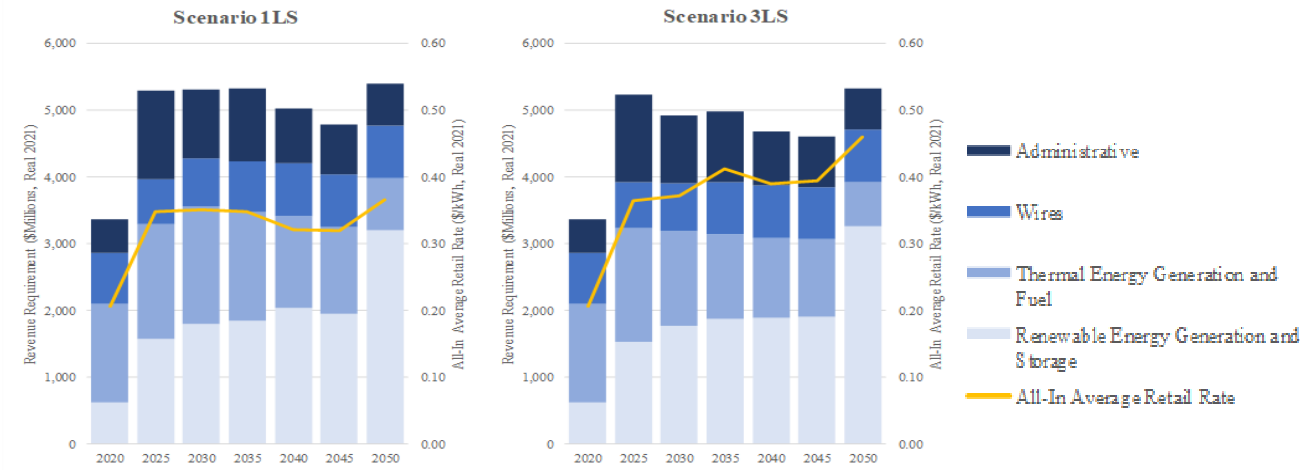

Figure 26. Revenue required by the utility to cover its costs for two scenario variations

Our results show that between 2020 and 2025, the large increase in utility-incurred costs was driven by three key factors: investments to achieve an adequate generation fleet, the costs of new energy efficiency programs, and PREPA's exit from bankruptcy resulting in repayment of legacy debt and pension obligations (FOMB 2023b). Importantly, as above, significant investments in generation are needed in the near term simply to achieve resource adequacy as the Commonwealth currently suffers from regular outages due to shortfalls in energy availability. Because our modeling assumes the system meets the Act 17 requirement of 40% renewable by 2025, this investment is made in renewable resources.[20] After this period, costs are relatively stable through 2025–2045 as renewable energy generation gradually replaces fossil fuel-fired generation, leading to a reduction in associated costs such as for fuel.

Our results show that between 2045 and 2050, the system experiences notable cost increases that would be incurred by any system moving from already high levels of renewable energy to 100% renewable energy. This is due to the requirement to retire existing fossil fuel units and replace the firming and balancing function they perform at high levels of renewable energy (i.e., supplying energy only on an as-needed basis when renewable generation is low and storage reserves are exhausted, for example during periods with several cloudy days in a row). However, note that the costs of energy and fuels in 2050 are highly uncertain because many aspects could change during this period.

Both the cost of electricity and the investment into the electric system are important factors for Puerto Rico's economy. Our analysis examined the impact of the transition to 100% renewable energy on the economy overall, including the net impact on real household income. In the initial years of the transition (Epoch 1 in Figure 27), the increased investment during this time promoted expansion in the broader Puerto Rico economy but the retail rate increases eroded those gains resulting in a net decline in real household income. During the middle and end periods of the transition (Epochs 2 and 3), local investments in renewable energy and reductions

[20] For comparison, we ran a sensitivity that relaxed the 40% RPS requirement but still incurred generation-related investments to achieve a more reliable grid by 2025. The utility's generation-related costs as well as the overall revenue requirement were comparable to those incurred when the 40% RPS requirement was imposed.

in fossil fuel purchases generally lead to net increases in household income. Additional macroeconomic results, including employment impacts, can be found in the *PR100 Final Report*.

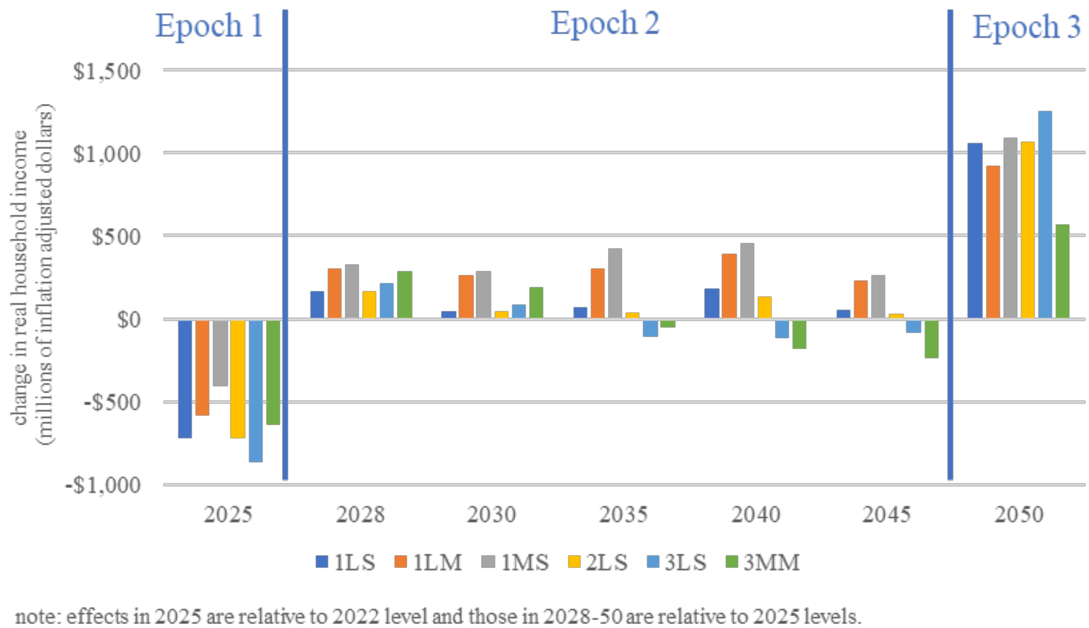

Figure 27. Real household income changes (millions of dollars) over scenarios for all years

Key Findings

- Modeling results showed a substantial increase in the utility's revenue requirement (48%–57%) between 2020 and 2025 to achieve a more reliable and stable energy system that also met the 40% renewable energy RPS requirement, resulting in large all-in average retail rate growth (66%–83%).
- Between 2025 and 2045, the utility experienced a decline in its revenue requirement (9%–24%) which when combined with the positive macroeconomic benefits from investments and expenditures in renewable energy resulted in increases in real household income.
- To fully achieve the 100% RPS requirement between 2045 and 2050, the utility experienced an increase in its revenue requirement (4%–16%), resulting in modest average retail rate growth (11%–17%).
- Increases in retail rates adversely affect the bills of nonadopters of rooftop PV.
- Very low-income households (earning $15K/year or less) were particularly vulnerable to large retail rate increases, especially if they were more likely to be nonadopters of rooftop PV, resulting in energy justice implications.

Implementation Actions

In the PR100 Implementation Roadmap ("Roadmap"), we identify implementation actions stakeholders can take to progress toward a more robust, reliable, renewable, resilient, and equitable energy system for Puerto Rico. These actions are based on the results of our analysis in PR100, observations about Puerto Rico's current energy system made while performing the PR100 analysis, and our knowledge of industry best practices. Actions are highlighted throughout the *PR100 Final Report* and are aggregated and discussed in the Roadmap. Here we summarize high-level action items which are combinations of multiple specific actions listed in the Roadmap. For the full Roadmap which contains more details on these action items see Section 15 of the *PR100 Final Report*.

Here and in the Roadmap we organize implementation actions into the following temporal phases, shown in :

- ***Immediate actions*** to build a more robust electricity system and lay the foundation for high levels of renewable energy
- ***Near-term*** actions to achieve 40% renewable energy while moving toward industry accepted system performance and increasing resilience
- ***Mid-term*** actions to achieve 60% renewable energy to gain operating experience and be adaptive in system design
- ***Long-term*** actions on the road to 100% renewable energy where effective deployment and operation of the complex system is achieved
- ***Recurring actions*** to continually maintain and improve the system and associated planning processes.

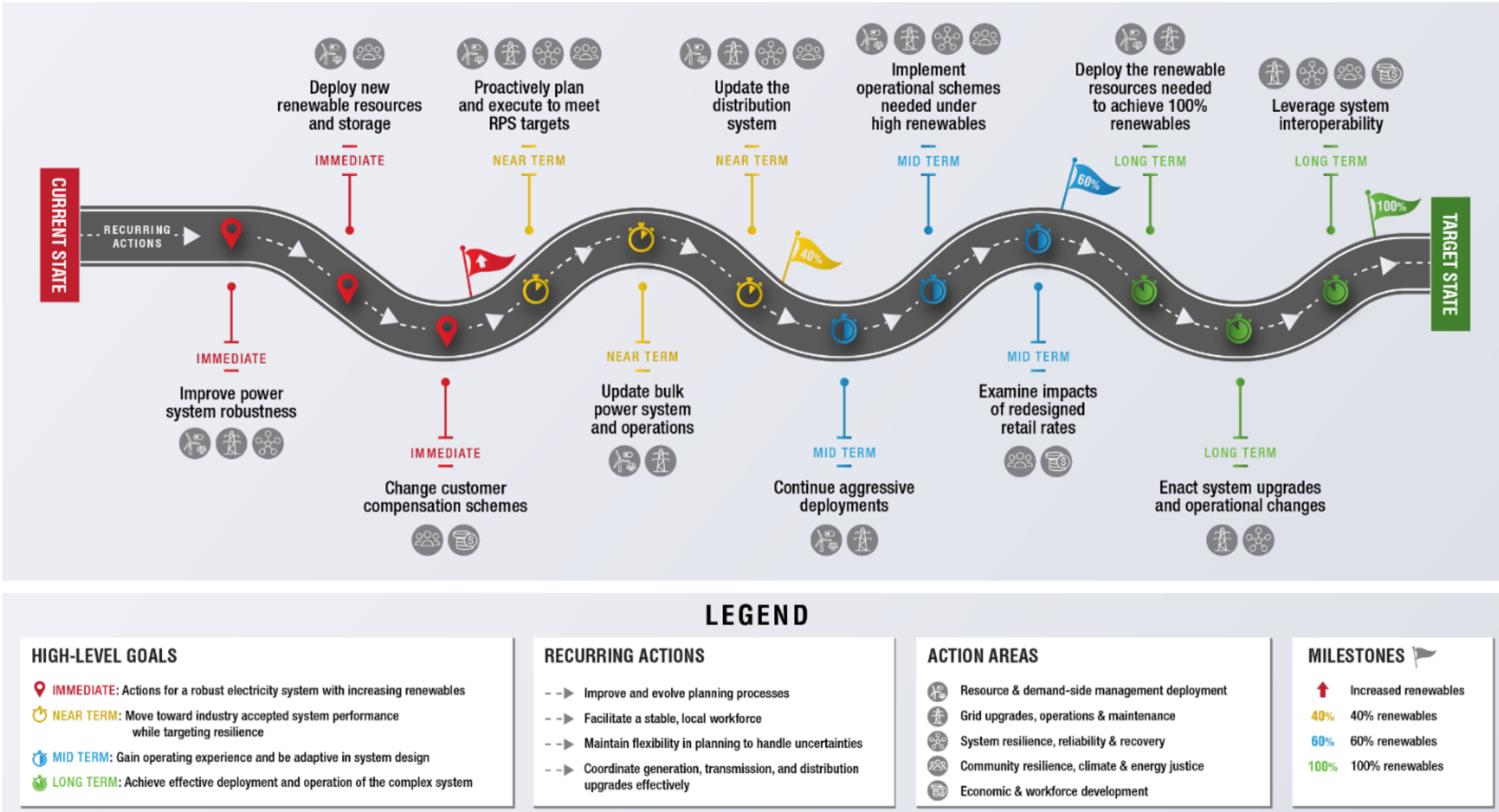

Figure 28. The temporal organization of the PR100 Implementation Roadmap

Actions are additionally categorized by topic areas ("action areas") and stakeholder groups to organize the actions and to help identify responsible parties for executing each action. Action areas and their associated icons are shown in Figure 29.

Figure 29. Implementation Roadmap action areas

The four stakeholder groups identified in the Roadmap as having a role to play in the implementation of Puerto Rico's energy future are:

- Utility and grid operators
- Renewable developers
- Energy regulators
- Customers and communities.

Immediate Actions for a Robust Electricity System with Increasing Renewables

PR100 results across all scenarios indicate that increased capacity is needed immediately to achieve a robust electricity system. New renewable resources will both increase system capacity and contribute to Puerto Rico's near-term goal of 40% renewable energy. The table below describes the immediate implementation actions identified in PR100. These actions could be undertaken right away to help position the electric system to achieve a future state that will increase system robustness and enable integration of a high level of renewable energy.

Table 1. Immediate actions identified by PR100

High-Level Actions	Action Areas	Stakeholders
Improve power system robustness by increasing capacity and making urgent repairs		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Energy Regulators
Deploy new renewable resources and storage via stakeholder-driven pathways		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Customers and Communities
Change customer compensation schemes to incentivize temporal-based charging and discharging among stakeholders		✓ Utility and Grid Operators ✓ Energy Regulators

Rationale for Actions

Improve power system robustness by increasing capacity and making urgent repairs

The power system in Puerto Rico requires immediate upgrades to improve performance to acceptable levels. The power system is considered fragile across all levels—generation, transmission, and distribution systems—which manifests as poor reliability, inefficient operations, and vulnerability to extreme weather events and other natural hazards (e.g., hurricanes, floods, and earthquakes). There is an immediate need to make the system robust by building new capacity and updating transmission and distribution system operations, controls, and hardware, as legacy infrastructure is reconstructed and new resources are deployed.

Deploy new renewable resources and storage via stakeholder-driven pathways

PR100 results confirm an immediate need for new resources on the current system to stabilize the grid and alleviate current generation shortfalls, including rapid deployment of utility-scale and distributed renewable resources and significant amounts of storage to address current system issues and contribute to the near-term Act 17 goals. Consider stakeholder priorities and concerns and follow stakeholder-driven pathways to enable the accelerated deployment needed to overcome generation capacity shortfalls and meet Act 17 goals.

Change customer compensation schemes to incentivize temporal-based charging and discharging among stakeholders

PR100 results point to long-term impacts of current customer compensation in Puerto Rico. Specifically, there is no incentive for customers to use their batteries in a grid-interactive fashion, and there can be equity concerns around electric rates paid by those customers who own distributed energy systems versus those that do not. To stave off near-term distribution hosting capacity concerns and long-term rate concerns, there is an immediate need to incentivize temporal-based charging and discharging of customer-owner storage systems to increase hosting capacity and better align compensation for customer generation with its value to grid operations. The Battery Emergency Demand Response Program piloted by LUMA is an initial effort that can be leveraged and built upon to address this immediate action (LUMA 2023a).

Near-Term: Move Toward Industry Accepted System Performance while Targeting Resilience (Transitioning to 40% Renewables)

In the near term, the primary goal is to improve the system performance to an industry accepted level while targeting resilience. Listed in Table 2 are actions directly supported by PR100 findings which can help achieve the near-term phase of implementation, which is to reach 40% renewable energy generation.

Table 2. Near-term actions identified by PR100

High-level Actions	Action Areas	Stakeholders
Proactively plan and execute to meet RPS targets, including installing multiple GW of renewable resources and storage and rapidly designing and implementing energy efficiency to achieve Act 17 goals.		✓ Utility and Grid Operators ✓ Energy Regulators ✓ Renewable Developers ✓ Customers and Communities
Update bulk power system and operations: establish updated operational strategies, establish requirements for grid-forming inverters, study and upgrade lower voltage (38kV) transmission network, plan for future renewable penetrations, and deploy storage.		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Energy Regulators
Update the distribution system: upgrade control schemes including voltage regulation, deploy storage at critical points, and prioritize upgrades on vulnerable feeders.		✓ Utility and Grid Operators ✓ Energy Regulators ✓ Customers and Communities

Rationale for Actions

Proactively plan and execute to meet RPS targets

Across all scenarios, significant deployment is immediately necessary to achieve 40% renewable energy. Several resource deployment activities are already underway, including procurement tranches for implementation of the 2019 IRP (PREB 2020) at the utility scale and actions through the Puerto Rico Energy Resilience Fund, [21] which incentivizes distributed solar and storage for very low-income households and households that include a family member with an energy-dependent disability.

Re-evaluation of the RPS in Act 17 may be needed, in alignment with a proposed regulation from PREB regarding regulation of renewable energy certificates compliance with the RPS, which would establish annual targets starting in 2024 and procedures and penalties for non-compliance (PREB 2023a). Actions to consider in re-evaluation include adding more interim targets to keep deployment on schedule, setting goals in energy (MWh) to match procurement requirements, providing clear guidance on renewable energy certificates to include the measurement of distributed PV in RPS requirements, and clearly defining impacts for missing RPS targets to increase accountability.

[21] "Puerto Rico Energy Resilience Fund," DOE Grid Deployment Office. https://www.energy.gov/gdo/puerto-rico-energy-resilience-fund

Update bulk power system and operations

As highlighted in Figure 23 (page 24), action is necessary to mitigate the modeled level of low-voltage transmission overloads on the 38-kV network which will emerge with more renewables. This could require various enhancements from non-wires alternatives, reactive power support solutions, installing new renewable resources and storage at optimal locations to mitigate the violations, and additional lines to improve current management. A detailed modeling study of the 38-kV system to identify specific investments could be conducted by LUMA as part of the IRP process or as a standalone effort. Additional efforts to update the operational strategies and forecasting techniques can also be taken to prepare for a system with high renewable penetrations.

PR100 has also identified that storage will play a key role in supporting the energy transition and mitigating several issues on the grid in the near term. Deploying utility-scale storage with advanced controls on both the transmission and distribution grid in the near term can eliminate voltage and reliability issues experienced under high renewable scenarios. Larger storage systems are also important for occasional multiday discharges. Utilizing distributed storage to support the grid, including during outages, is also critical.

Update the distribution system

Starting the process immediately to improve hosting capacity generally is important as distribution system hosting capacity needs to be increased to accommodate accelerating deployment of rooftop solar. Inverter controls could help increase that capacity, as could improvements to distribution infrastructure and deployment of utility-controlled battery storage on feeder lines. Additionally, transparent and up-to-date data about hosting capacity from the utility is crucial for continued solar adoption.

Best Practices

In addition to the action items directly supported by PR100 findings listed in the table above, several action items to follow best practices were indicated directly or indirectly by PR100 findings. Resilience will be a key focus in the near term as renewable energy penetration can allow for increased resilience if operated effectively, such as utilization for black start and microgrid adoption. To support resilience, rooftop PV systems could be integrated into microgrids. To support blue-sky operations, virtual power plants can be operated. Additional sensing across distribution and transmission systems will support identification of outages and problem areas and will enhance modeling and simulation efforts.

Mid-Term: Gain Operating Experience and Be Adaptive in System Design (Operating with 40-60% Renewables)

The primary goal in the mid term is for stakeholders to gain operating experience and be adaptive in system design as future uncertainties are realized. Actions inspired by PR100 which support the implementation phase from 40% to 60% renewable energy are shown in Table 3.

Table 3. Mid-term actions identified by PR100

High-Level Actions	Action Areas	Stakeholders
Continue aggressive deployment of renewable resources including significant amounts of storage.		✓ Utility and Grid Operators ✓ Energy Regulators ✓ Renewable Developers ✓ Customers and Communities
Implement operation schemes needed under high penetrations of renewables including advanced forecasting, operating reserves, and protection coordination schemes.		✓ Utility and Grid Operators ✓ Customers and Communities
Examine impacts of redesigned retail rates and distributed generation compensation schemes and modify as needed to achieve efficient system operation and support equitable solution.		✓ Utility and Grid Operators ✓ Renewable Developers

Rationale for Actions

Continue aggressive deployment of renewable resources

Continuing to deploy renewables at an aggressive pace is expected to promote a smooth buildout across all timescales. Particularly important during the mid term will be installing and utilizing storage. Larger storage systems become important during the mid term, as occasional multiday lulls in renewable resource generation (e.g., multiple cloudy days in a row) can cause disruptions to power supply at the penetrations seen in the mid term. Additionally, distributed storage to support the grid, including during outages, remains very important during the mid term. Installing storage and renewable generation with grid-supportive controls will help overcome new challenges to system stability. An additional consideration that becomes important in the mid term is to spread generation across the territory to avoid large impacts from single-point failures.

Implement operation schemes needed under high penetrations

In the mid term and extending into the long term, it will become important to update and test procedures for operating reserves and scheduling to operate the system as it becomes more complex due to the addition of variable renewable generation. Part of this will be implementing advanced forecasting and dispatch technologies to inform battery charging and discharging cycles, and to control loads via demand response as applicable. There will be a need to perform studies to identify the correct protection coordination concerns such as reverse power flow and line overloading on both distribution and lower-voltage transmission networks as the renewable penetration increases.

Examine impacts of redesigned retail rates

By the mid term, there will be a significant amount of customer-owned generation under all PR100 scenarios. In the mid term, as the number of customers who own generation is of the same magnitude as those who do not, it will become critical to assess electric rate equity concerns. Under net metering as it exists today, PR100 results show that rates for customer electrical service will increase in the long term, and that lower income households are especially vulnerable to higher electricity prices. Lower income households may also have a more difficult time adopting rooftop PV and storage due to higher up-front costs and lack of access to financing. Ongoing efforts to provide equitable access to participate in the energy transition will ease these effects on lower income residents.

Best Practices

Inspired by the findings of PR100, in the mid term a best practice is for stakeholders to gain experience with new renewable energy technologies. Operators can deploy small and mid-scale emerging and resilient resources such as long duration storage, dispatchable renewables, and other currently unknown solutions to gain foundational knowledge of their operation and prepare for their large-scale deployment in the long term. Included in this will be an opportunity to identify and evaluate different dispatchable renewable energy solutions. At this mid-term stage, it will additionally be prudent to adapt to advances in renewable energy technology, changes in relative costs between different renewable energy types, and climate changes altering resources and threats.

Long-Term: Achieve Effective Deployment and Operation of the Complex System (Approaching 100% Renewables)

The primary goals in the long term are to achieve effective deployment and efficiently operate the complex system as it approaches 100% renewables. Uncertainty in the later years is inherent in any study looking out several decades. There are likely to be changes in technology availability (e.g., long-duration storage), resource capital costs, network topology, and other key factors. Detailed in Table 4 are considerations from the study that are relevant to the final phase from 60% to 100% renewable energy generation.

Table 4. Long-term actions identified by PR100

High-Level Actions	Action Areas	Stakeholders
Deploy the renewable resources needed to achieve 100% penetrations, including implementing long-duration storage and dispatchable renewable resources.		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Energy Regulators ✓ Customers and Communities
Enact system upgrades and operational changes to mitigate congestion issues from high-penetration renewable system with dispersed generation; enable black start and recovery capabilities of all assets via GFM controls.		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Energy Regulators
Leverage system interoperability between loads such as increased electric vehicle adoptions and variable generation using advanced forecasting, dynamic rates, and export compensation schemes.		✓ Utility and Grid Operators ✓ Energy Regulators ✓ Customers and Communities

Rationale for Actions

Deploy the renewable resources needed to achieve 100% penetrations

To achieve 100% penetration, significant installations of mature and currently emerging technologies will be required. Deployment of utility-scale PV, distributed PV, wind generation, storage technologies, and dispatchable renewable resources are all required in the long term. PR100 identified the need for over 1,300 MW of biodiesel generation (or other equivalent "firm" generation), a dispatchable asset which provides flexibility for the highly renewable system. The study also found that distributed PV deployment is an essential building block towards reaching 100% penetrations and is especially needed to overcome many of the resilience challenges that Puerto Rico's grid could face; scenarios with more rooftop PV enabled much faster recovery than those with more centralized generation.

Enact system upgrades and operational changes

Substantial grid upgrades are required to accommodate the future resource mix. The future grid will require buildout of new protection equipment, transmission and distribution infrastructure, sensing, and more. The transmission system can be strengthened by enhancing distribution system management to accommodate very high distributed PV penetrations and deploying synchronous condensers. On the distribution system, battery storage capacities of up to 2x installed distributed PV capacities will be needed, though storage needs can be reduced if customer-owned storage is used interactively with grid operations. On the transmission system, the study identified a need for 1,600 MVA total capacity of synchronous condensers in eight locations to enable 100% renewable scenarios. Additionally, advanced forecasting and dispatch technologies will need to be capable of operating the energy system in the long term. Implementing black start and recovery capabilities via GFM controls can support full-scale combined use of energy storage, renewables, and microgrids to black start the entire Puerto Rico energy system.

Leverage system interoperability

In the long term, electric vehicle adoptions are projected to increase total system load by about 15% and can have a higher instantaneous contribution. Electric vehicle loads are projected to increase the nighttime system peak load while large amounts of PV generation will decrease the system daytime minimum load. This will require efficient operation and deployment of long-duration storage and dispatchable renewable generation. However, this also presents the opportunity to integrate controllable loads into system operations. Controllable loads including EVs can help consume load when generation is plentiful and can limit consumption when generation is scarce. This will help reduce storage capacity needs and congestion concerns.

Best Practices

Climate change and other evolving factors will affect management, operation, and maintenance of the energy system. This is particularly true in the long term, as future work on end-of-century climate projections may point to increasing impacts currently not captured by mid-century climate models. Utilities can mitigate these impacts by integrating climate awareness into grid planning processes and day-to-day utility operations. Adaptable disaster plans and resilience goals can evolve with the hazard landscape.

Recurring Actions – Continually Maintain the System and Improve Planning Processes

In addition to near-, mid-, and long-term action items, we identified several recurring actions for stakeholders to take throughout the energy transition, detailed in Table 5. Many of the recurring actions are not technical findings of PR100, but are best practices noted through stakeholder engagement and energy justice analysis conducted as part of PR100.

Table 5. Recurring actions identified by PR100

High-Level Actions	Action Areas	Stakeholders
Improve and evolve planning processes: Identify and pursue stakeholder-informed pathways for deploying new resources and storage, including consideration of land use and local resilience benefits.		✓ Utility and Grid Operators ✓ Renewable Developers ✓ Energy Regulators ✓ Customers and Communities
Facilitate a stable, local workforce to support installation, operations, and maintenance of the system across the entire planning horizon.		✓ Utility and Grid Operators ✓ Customers and Communities

Rationale for Actions

Improve and evolve planning processes

A key recurring action for stakeholders to consider is to continually improve and evolve grid planning processes. Involving a breadth of stakeholders to develop and implement meaningful processes for engaging communities, assessing potential impact, and interpreting land use policy can support deployment of large-scale renewable energy projects. Developing structures and processes that foster community and industry sector participation and take into consideration their unique and common perspectives can ensure broad and meaningful stakeholder participation in planning, decision-making, and implementation of Puerto Rico's energy future. Continually evaluating local resilience benefits, such as microgrids, will improve the resilience planning efforts across all time periods. Overall, this can help support a just and inclusive energy transition for Puerto Rico.

Facilitate a stable, local workforce

Developing and expanding job training and education programs could help prepare the Puerto Rico workforce to meet the estimated 25,000 jobs required for the transition to 100% renewables. Supporting workforce training within Puerto Rico has benefits for household and territory-wide economics, and for public knowledge and participation in energy system development. Other efforts to educate about the Puerto Rico energy system and energy efficiency programs are similarly useful for citizens.

Best Practices

There are likely to be changes in technology maturity (e.g., long-duration storage), resource capital costs, policies, and other key uncertainties as the system approaches 100%. This uncertainty is a reminder to maintain some flexibility in planning to be able to adjust as the future unfolds. Additionally, ensuring that grid planning processes and subsequent investment decisions are coordinated across the generation, transmission, and distribution systems will ensure a diversified energy mix at the least-cost options while addressing stakeholder priorities and system needs over the long planning horizon.

Conclusion

Achieving a robust, affordable, resilient, and equitable energy system for Puerto Rico powered by 100% renewable energy will not be fast or easy, but it is possible. The *PR100 Final Report* and website provides stakeholders in Puerto Rico a detailed set of results and an unprecedented view into the current energy system and possibilities for the future based on in-depth modeling and analysis. Deep engagement with members of our Advisory Group, Steering Committee, industry sectors, and communities across Puerto Rico by the PR100 project team informed our understanding of the experiences and priorities that motivate the people who are affected by and who will shape the energy system of the future. As we conducted the study, the landscape of energy policy, programs, projects, funding, incentives, costs, and other market factors continued to shift, including as Hurricane Fiona caused a systemwide blackout and frequent outages disrupted daily life.

Residential, commercial, and industrial customers in Puerto Rico have adopted rooftop solar and storage at a very fast pace in recent years. The role of electric cooperatives and community-based projects is expanding, and the level of interest in the energy transition across Puerto Rico is truly inspiring, though not surprising considering these topics are top of mind due to the widespread and devastating effects of past disruptions. It is an exciting time for the people of Puerto Rico to stand up and say what they want and do not want from the energy system of the future, and to contribute to the decisions that will affect their lives. As the PR100 study concludes, it is up to decision makers to review the study results, evaluate tradeoffs, and implement decisions to improve the energy system now and prepare for the transition to a reliable, resilient 100% renewable energy future.

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Appendix A. Scenarios and Variations Modeled in PR100

Table 6. Scenarios and Variations Modeled in PR100

Scenario Number	Scenario Short Name	Variation 1: Land Use	Variation 2: Electric Load	Scenario Identifier
1	Economic	Less	Mid	1LM
1	Economic	Less	Stress	1LS
1	Economic	More	Mid	1MM
1	Economic	More	Stress	1MS
2	Equitable	Less	Mid	2LM
2	Equitable	Less	Stress	2LS
2	Equitable	More	Mid	2MM
2	Equitable	More	Stress	2MS
3	Maximum	Less	Mid	3LM
3	Maximum	Less	Stress	3LS
3	Maximum	More	Mid	3MM
3	Maximum	More	Stress	3MS

Appendix B. Assumptions and Constraints

Following are a few assumptions made in PR100. Additional assumptions that underpin specific analyses are discussed in the relevant sections of the full report.

- All modeling and analysis in PR100 assumes compliance with Puerto Rico energy policy, including Act 17; the definitions of renewable energy assumed are in the:
    - Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico Act (Act 82 of 2010, as amended) (Puerto Rico Legislative Assembly 2010)
    - Puerto Rico Climate Change Mitigation, Adaptation, and Resilience Act (Act 33 of 2019) (Puerto Rico Legislative Assembly 2019, 33–2019)
    - Puerto Rico Electric Power Authority's (PREPA's) 2019 integrated resource plan (IRP) (Siemens Industry 2019; PREB 2020).
- In the modeling, we include only generation technologies that meet the definition of renewable energy in the aforementioned public policy. Consistent with Act 82 as amended, technologies considered in PR100 include solar energy, wind energy, hydropower, marine and hydrokinetic renewable energy, ocean thermal energy, and combustion of biofuel derived solely from renewable biomass. Of the other resources listed in Act 82, we do not include geothermal energy, renewable biomass combustion, or renewable biomass gas combustion.
- The retirement schedule for existing fossil-fueled generation units follows the retirements established in the 2019 IRP (Siemens Industry 2019; PREB 2020). Note that PREPA has stated that the planned retirements from the 2019 IRP are based on assumptions regarding renewable technology cost and electric load reductions and that the new renewable energy generation (with compliance with minimum technical requirements) is also assumed; therefore, retirements might change because those assumptions are not maintained on schedule.
- Transmission is identically represented in all 12 scenario variations using a linearized DC power flow model to represent lossless active power flow in the network. The production cost model is configured to enforce flow limits on lines rated at 115 kV and above, whereas flow limits are relaxed on 38-kV lines because of the uncertainties associated with specific renewable interconnection points and demand changes, so 38-kV overloads are expected.

Appendix C. How to Access Solar and Wind Resource Data

Solar Resource Data Sets

Users can access the solar resource data sets via the National Renewable Energy Laboratory's National Solar Radiation Database (NSRDB) website in three ways: the NSRDB Viewer, an application programming interface, or a cloud-based service.[22]

Wind Resource Data Sets

Twenty years of wind resource data (5-min and hourly temporal resolutions) are available on the Highly Scalable Data Service (HSDS). Users can refer to a GitHub repository with setup guidance for using a Jupyter notebook to access the HSDS data.[23] Users need to clone the repository to their computers and follow the instructions starting at "How to Use." Once users get a sample notebook to work with an HSDS data set, they can modify it to work with their own data set. If users install h5pyd[24] and execute hsconfigure, they should be able to test the connection by running the hsinfo. Then users can check the /nrel/directory by executing hsls. For example, users can run hsls /nrel/ to see what is in the directory.

The wind data sets for Puerto Rico are in:

1. Hourly data (puerto_rico_wind_hourly_yyyy.h5): /nrel/wtk/pr100/hourly/

2. 5-min data (puerto_rico_wind_5min_yyyy.h5): /nrel/wtk/pr100/5min/

[22] See "How to Access the Data," NREL, https://nsrdb.nrel.gov/data-sets/how-to-access-data.

[23] https://github.com/NREL/hsds-examples

[24] As shown in the instructions available at https://github.com/NREL/hsds-examples.

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