PR100

Analysis and Technology Needs for Getting to 100% Renewable Energy

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

Dr. Murali Baggu, Laboratory Program Manger – Grid Integration, National Renewable Energy Laboratory

Invited talk for 2022 ISGT Europe Novi Sad

Authors

Dozens of talented researchers from the six participating national laboratories are contributing to the PR100 Study. This presentation was authored by:

- **National Renewable Energy Laboratory (NREL):** Robin Burton, Murali Baggu, Jill Rhodes, Nate Blair, Tom Harris, Manajit Sengupta, Clayton Barrows, Haiku Sky, Jaemo Yang, James Elsworth, Paritosh Das, Patrick Duffy, Gabriel Zuckerman, Jeremy Stefek, Prateek Joshi
- **Argonne National Laboratory (ANL):** Lawrence Paul Lewis, John Murphy
- **Lawrence Berkeley National Laboratory (LBNL):** Peter Cappers, Jeff Deason
- **Oak Ridge National Laboratory (ORNL):** Yilu Liu, Bandana Kar, Shih-Chieh Kao
- **Pacific Northwest National Laboratory (PNNL):** Marcelo Elizondo, Xiaoyuan Fan, Patrick Maloney, Vishvas Chalishazar, Patrick Royer, Fernando Bereta Dos Reis
- **Sandia National Laboratories (SNL):** Amanda Wachtel, Matthew Lave, Olga Epshtein Hart, Christian Birk Jones, James Ellison, Cody Newlun
- **Additional Team Members:** Michele Chait (Michele Chait LLC); Harvey Cutler and Martin Shields (Colorado State University)

Acknowledgements

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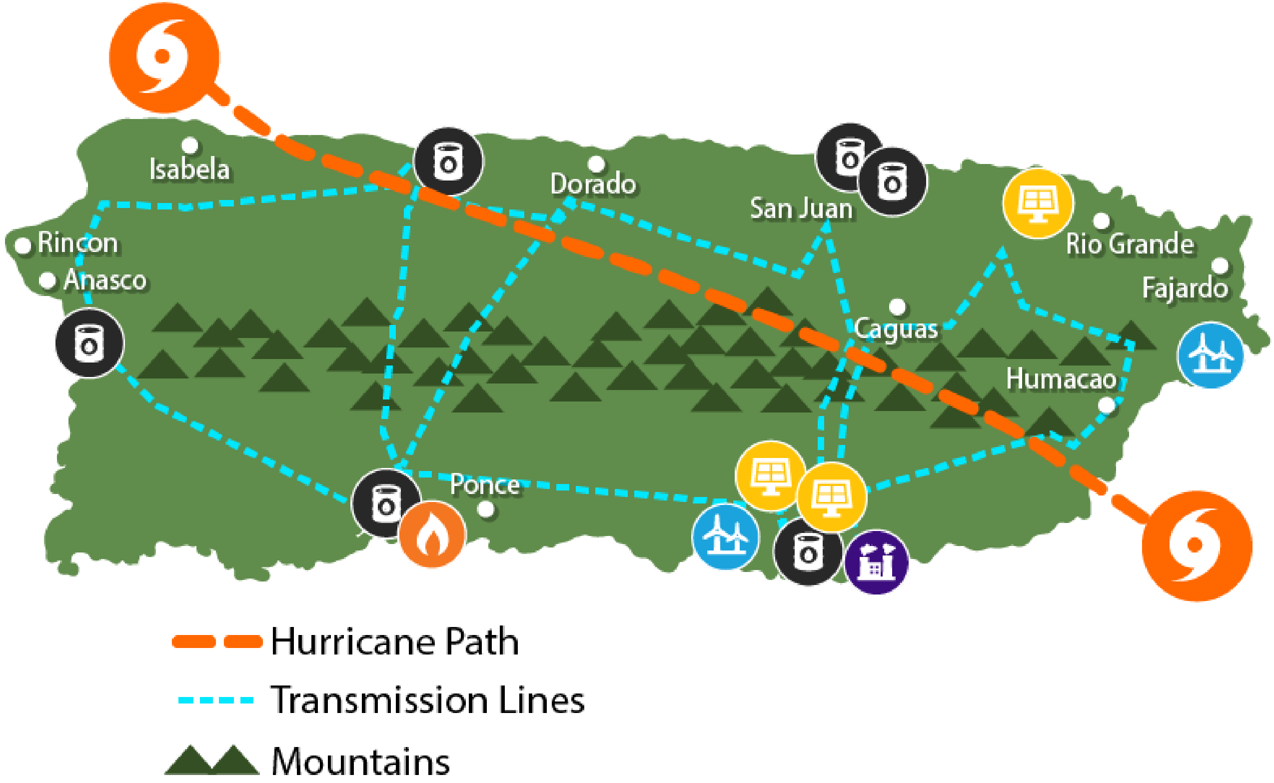
- This presentation was prepared by the PR100 multilab team, led by NREL with support from ANL, LBNL, ORNL, PNNL, and SNL.
- We appreciate the voluntary participation of more than 80 members of our Advisory Group, whose input ensures the process and results will reflect their priorities and perspectives.
- Thank you to the DOE's Puerto Rico Energy Recovery Team, Marisol Bonnet, Eric Britton, Ernesto Rivera-Umpierre, and Elizabeth Arnold for their leadership.
- Thank you also to Adam Warren and Juan Torres with NREL for providing technical review of this presentation, and Moriah Petty, Sarah Hauck, Fred Zietz, and additional members of the NREL communications team for their contributions to the project and this presentation.

Overview of the Storms

- Hurricane Irma hit the island on Sept. 6, knocking out power to almost a million customers.
- Two weeks later Hurricane Maria hit, crossing almost the entire island from southeast to northwest.
- Puerto Rico Electric Power Authority (PREPA) was still restoring power to hundreds of thousands of customers knocked out by Irma when Maria hit and caused a systemwide collapse.
- The double punch knocked out 80% of Puerto Rico's electric grid.
- This resulted in the largest blackout in U.S. history and the second largest in the world.

Path of Hurricane Maria



Impact of Storms on Grid Assets

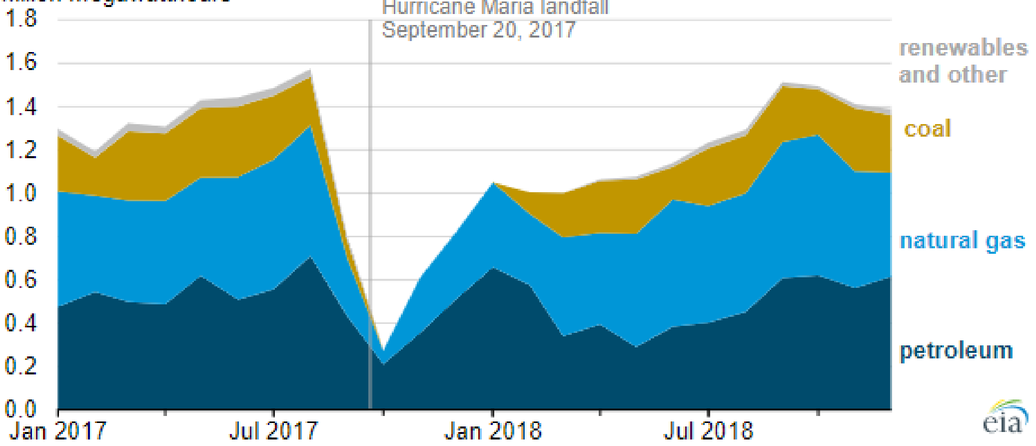
- The two hurricanes that hit Puerto Rico two weeks apart in 2017 resulted in a systemwide collapse and a U.S.- and global-record-setting blackout.
- Damage occurred to all elements (generation, distribution, and transmission) of Puerto Rico's already fragile energy system.
- FEMA allocated $3.2 billion for direct assistance and coordinated electricity grid restoration.
- Making a bad situation worse, a 2020 earthquake damaged the island's largest generation plant.

Generation Restoration

NOVEMBER 25, 2019

Puerto Rico electricity generation returned to pre-2017 hurricane levels one year later

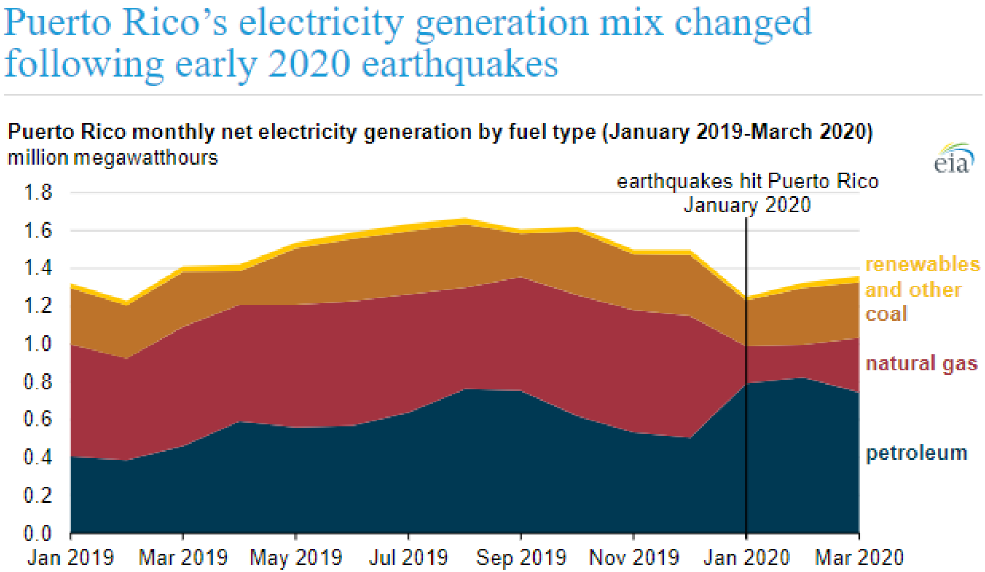
Monthly Puerto Rico net generation by fuel type (Jan 2017-Dec 2018)
million megawatthours



Source: U.S. Energy Information Administration, Form EIA-923, *Power Plant Operations Report*

Earthquake Aftermath

- **Costa Sur, the island's largest power plant, was severely damaged.**
- Costa Sur was producing roughly 40% of Puerto Rico's electricity.
- Power was restored to 99% of customers within a week, but the earthquake affected the energy mix of the entire island.



Source: U.S. Energy Information Administration, Form EIA-923M, *Power Plant Operations Report*, data for 2019 and 2020 are preliminary

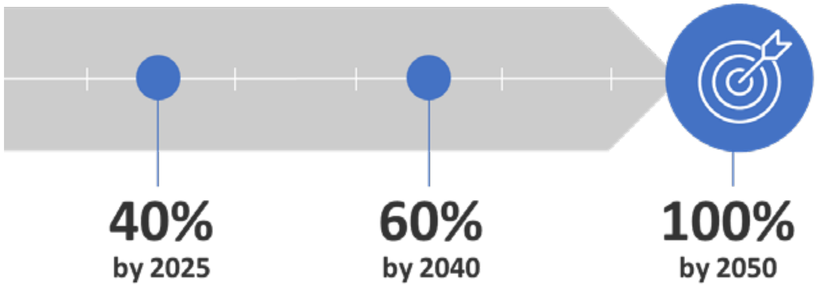
Energy Sector Recovery: Funding Sources

FEMA Hazard Mitigation Grant Program	FEMA Public Assistance	Housing and Urban Development (HUD) Community Development Block Grant (CDBG)-Disaster Recovery (DR): Electric Grid	Other HUD CDBG-DR and CDBG Mitigation disaster assistance programs
Amount: $832.5 million **Purpose**: Improve the resilience of disaster-damaged or undamaged facilities. **Recipient**: Central Office for Recovery, Reconstruction and Resiliency (COR3) **Subrecipient**: PREPA (and LUMA Energy as an agent)	**Amount**: $9.5 billion **Purpose**: Restoration and hazard mitigation for disaster-damaged public utilities. **Recipient**: COR3 **Subrecipient**: PREPA (and LUMA Energy as an agent)	**Amount**: $1.9 billion **Purpose**: Unmet needs after FEMA funds, insurance, and other federal or private sources are accounted for. Mitigate risks and improve resilience, sustainability, and financial viability for electrical power systems. **Recipient**: Puerto Rico Department of Housing (PRDOH) **Subrecipients**: Grantees of PRDOH Grant Programs, including local agencies, authorities, trusts, and governing boards; municipalities and local governments; private, for-profit entities; nonprofits, and homeowners.	**Community Energy and Water Resilience Installations ($300 million):** Support resilient design and improvements that incorporate modern technology for life-sustaining purposes. R3 eligible. **Community Energy and Water Resilience Installations ($500 million):** Same as above, but from CDBG-MIT with broader eligibility **City Revitalization Program ($1.29 billion):** Funding directly to municipalities for repairs of urban centers

Changes in Puerto Rico's Energy Public Policy

Act 17 of 2019

- **Increase generation from renewable energy resources:**



- **Reduce energy use by 30%** by 2040
- **Replace 100% of public lighting with LED** by 2030
- **Eliminate coal-fired generation** by 2028
- **Comply with the Integrated Resource Plan (IRP)**

2020 IRP

- Retire a significant number of oil-fired thermal units in the next 5 years
- Retire Aguirre diesel-fired combined cycle units 1 and 2 by 2030
- Limit the development of new gas turbine peaking units to 81 MW
- Integrate renewable generation projects to achieve the renewable portfolio standard in Act 17

Puerto Rico Energy Prices

Puerto Rico sets 7th electric rate increase in just a year

June 29, 2022

SAN JUAN, Puerto Rico (AP) — Officials in Puerto Rico announced another electric rate increase Wednesday, the seventh in a year amid continuing power outages and the U.S. territory's economic crisis.

For a client that consumes 800 kilowatt hours, the new rate will be 33 cents per kwh, compared with the previous 29 cents. The average U.S. electric rate is 14 cents per kwh, according to the U.S. Energy Information Administration.

What is the PR100 Study?

- A comprehensive analysis of possible pathways for Puerto Rico to achieve its goal of 100% renewable energy by 2050, based on extensive stakeholder input.

- A coordinated effort led by FEMA, DOE and NREL, leveraging the unique tools and capabilities of five additional national laboratories.

PR100 Scope

In scope

In this study, the project team will:

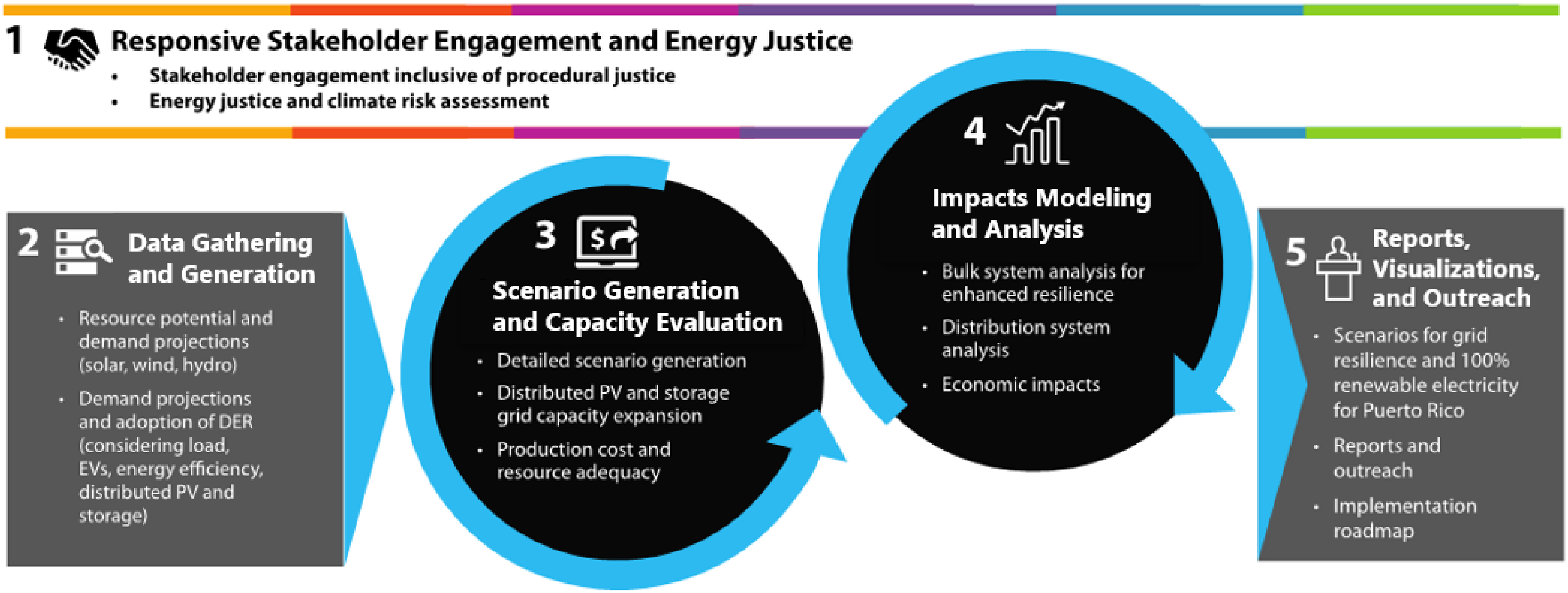
- Model pathways and analyze impacts
- Conduct analysis to inform potential investment decisions
- Produce a roadmap with recommended near- and long-term actions to transition to renewable resources
- Facilitate stakeholder interaction and information exchange to create foundation for future implementation
- Publish and disseminate results, including high-resolution datasets and open-source models.

Out of scope

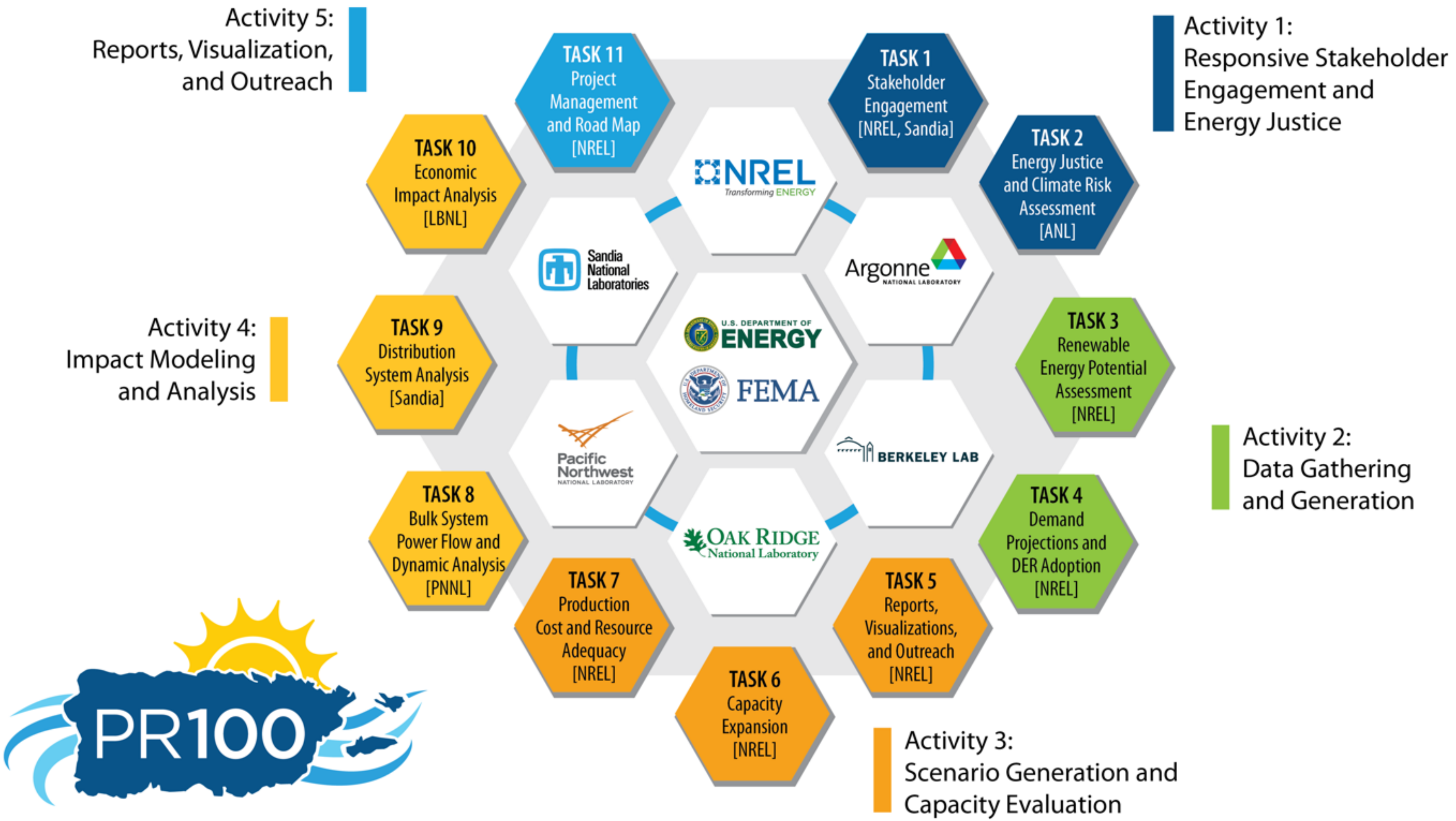
The study will not:

- Make policy recommendations
- Develop a detailed implementation plan
- Make specific investment recommendations
- Replace regulatory mandated capital investment planning processes such as the Integrated Resource Plan.

Activities in the Puerto Rico 100% Renewable Energy Study



Graphic by NREL

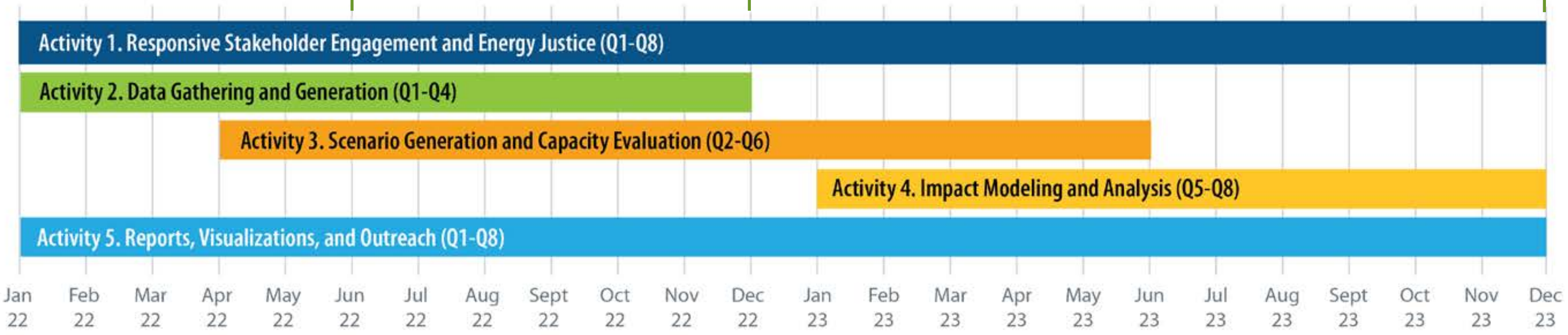

Activity 5:
Reports, Visualization, and Outreach
Activity 1:
Responsive Stakeholder Engagement and Energy Justice
Activity 4:
Impact Modeling and Analysis
Activity 2:
Data Gathering and Generation
Activity 3:
Scenario Generation and Capacity Evaluation
TASK 11 Project Management and Road Map [NREL]
TASK 1 Stakeholder Engagement [NREL, Sandia]
TASK 2 Energy Justice and Climate Risk Assessment [ANL]
TASK 3 Renewable Energy Potential Assessment [NREL]
TASK 4 Demand Projections and DER Adoption [NREL]
TASK 5 Reports, Visualizations, and Outreach [NREL]
TASK 6 Capacity Expansion [NREL]
TASK 7 Production Cost and Resource Adequacy [NREL]
TASK 8 Bulk System Power Flow and Dynamic Analysis [PNNL]
TASK 9 Distribution System Analysis [Sandia]
TASK 10 Economic Impact Analysis [LBNL]
NREL Transforming ENERGY
Sandia National Laboratories
Argonne NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY
FEMA
Pacific Northwest NATIONAL LABORATORY
BERKELEY LAB
OAK RIDGE National Laboratory
PR100

PR100 Timeline

6 Months (by June 2022):
Established stakeholder group meets monthly to inform scenarios
Defined four initial scenarios to achieve Puerto Rico's goals.

Year One (by December 2022):
- High-resolution data sets for wind and solar resource for 10 years
- Three feasible scenarios with high-level pathways.

Year Two (by December 2023):
- Comprehensive report and web-based visualizations
- Outreach and public engagement.



TASK 1: Stakeholder Engagement

Task Leads: Robin Burton, NREL and Matt Lave, SNL

Lead Labs: NREL and SNL

Supporting: ANL, ORNL

Advisory Group Formation and Engagement

- Convened Advisory Group of 80+ members from academia, public and private sectors, community-based and environmental organizations, and other sectors.
- Facilitated monthly Advisory Group meetings from February–June 2022 (four remote and one hybrid); bi-monthly or quarterly meetings to be held through December 2023.
- Received member input on the following topics and iterated on initial scenario framework generation for PR100:
  - Priorities for Puerto Rico's energy future
  - Scenario frameworks and electricity demand levels
  - Energy justice priorities
  - Data inputs including land use and technology cost.

Presentation during hybrid Advisory Group meeting held in San Juan, Puerto Rico in May 2022. Photo by Robin Burton, NREL

Advisory Group Formation and Engagement

hispanicfederation

- Partnered with Hispanic Federation in Puerto Rico for group facilitation and stakeholder engagement support, including:
  - Provide advice to the project team on additional stakeholders to include in the advisory group and general approach to conduct public outreach for dissemination of project deliverables;
  - Coordinate logistics for advisory group meetings;
  - Coordinate development and distribution of meeting materials in English and Spanish; and
  - Facilitate meetings and capture participant input.

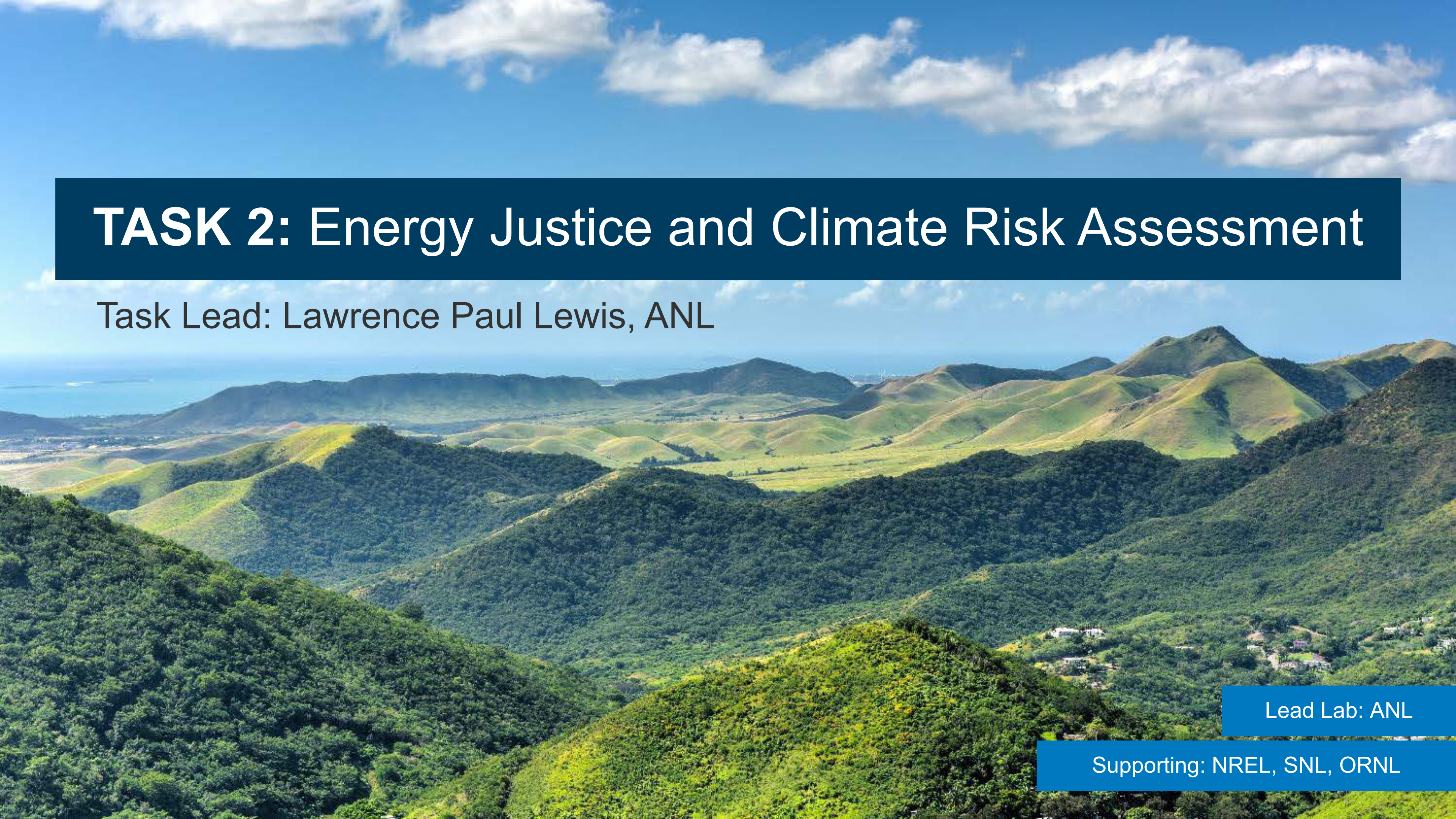
- Enlisted the expertise of the University of Puerto Rico – Mayaguez (UPRM) to:
  - Advise the PR100 team on the development of methods, inputs, and assumptions to accurately represent rooftop solar resources across models;
  - Produce new data through a comprehensive survey to improve the PR100 team's understanding of residential solar systems; and
  - Assist in the development of energy justice metrics based on outage restoration data from Hurricane Maria.

Additional Stakeholder Input

- Multiple Advisory Group members have submitted additional feedback in the form of memos or letters, some undersigned by other members or community groups
- Topics have included:
  - Land use considerations
  - How resilience will be incorporated and modeled in the study
  - Various considerations regarding the study including:
    - Benefits of rooftop solar
    - Vulnerabilities of centralized transmission and distribution
    - Equitable access to solar and storage
    - Additional analyses to consider including
    - Energy efficiency and demand response

TASK 2: Energy Justice and Climate Risk Assessment

Task Lead: Lawrence Paul Lewis, ANL



Lead Lab: ANL

Supporting: NREL, SNL, ORNL

Energy Justice in PR100

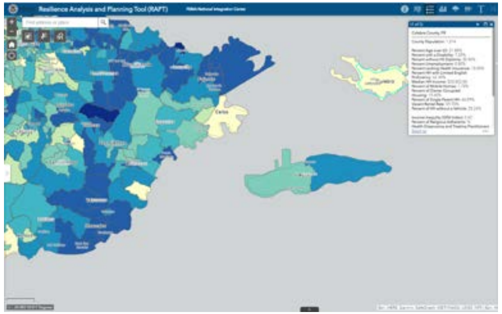
- **Metrics-based Energy Justice Analysis:**
  - Evaluate societal "cost" of long-duration outages and disparities in social burden
  - Evaluate energy justice impacts of modeled scenarios.

- **Infrastructure Interdependency Assessment:**
  - Identify and characterize electric power interdependencies of other critical infrastructure (i.e., communications, IT, transportation, water, and wastewater), community lifeline assets, etc.
  - Evaluate the extent to which energy injustices have resulted in other resource justice concerns.

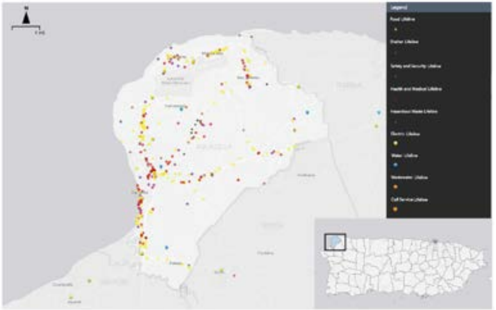
- **Climate Risk Assessment and Adaptation Strategies:**
  - Project where changing climate conditions will present future risks to infrastructure and the communities it supports
  - Inform siting and operational needs of infrastructure to avoid premature obsolescence.

Metrics-Based Energy Justice Analysis

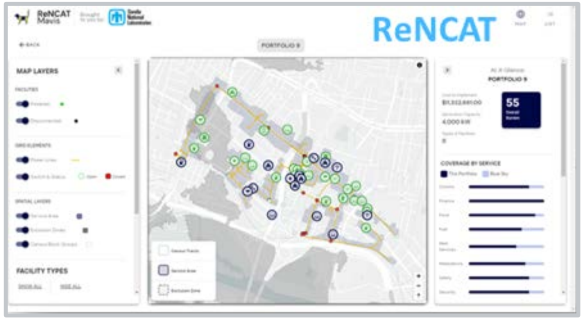
- Community resilience assessment (RAPT and Multi-Criteria Decision Analysis):
  - Capture municipal- and census tract-level demographic data related to overall community resilience as well as the proximity and availability of community lifelines to communities
  - Apply indicators derived through social statistics and best-in-class community resilience indicators to determine how underlying characteristics may influence energy justice concerns.
- Social burden analysis (ReNCAT):
  - Quantifying census block groups' ability to access critical services (fuel, food, other services) both historical and across future scenarios
  - Evaluating populations' relative ability to access such services during disasters, given natural hazard risk profiles that affect power systems.



Community resilience indicators in RAPT (graphic from Argonne)



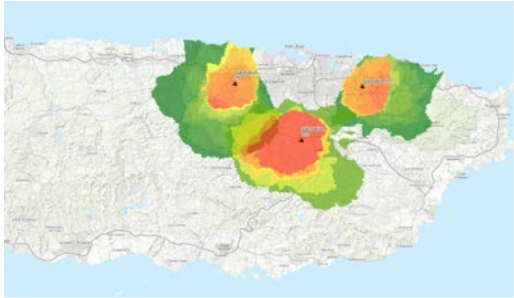
Identification of community lifelines in RAPT (graphic from Argonne)



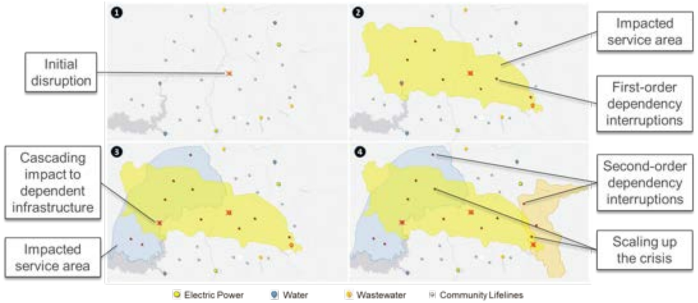
Social burden analysis in ReNCAT (graphic from Sandia)

Infrastructure Interdependency Assessment

- Infrastructure interdependency assessment (PRIIA):
  - Identify and characterize electric power dependencies of other critical infrastructure through a network analysis of their overlapping and dependent service area connections
  - Assess the criticality of substations and loads (i.e., other critical infrastructure) throughout communities based on simulations of potential cascading failures across dependent assets that might scale up the consequences of disruption.
- Progress running the PRIIA model:
  - Completed modeling of service areas for electricity-dependent critical infrastructure across Puerto Rico (i.e., all 38-kv substations, cellular transmission towers, water treatment plants, and wastewater treatment plants)
  - Developed GIS dataset and visualization of critical infrastructure dependencies for each distribution substation
  - Finalizing dataset and GIS visualization widget for sharing across PR100 and with local stakeholders.



Service areas modeling results in PRIIA (graphic from Argonne)

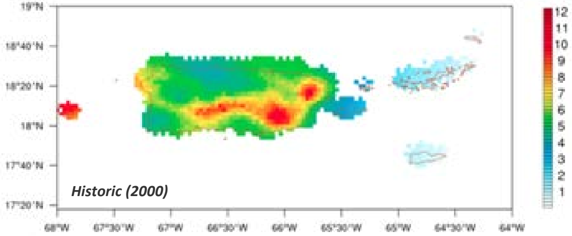


Notional illustration of a cascading electricity failure impacting water and wastewater service in PRIIA (graphic from Argonne)

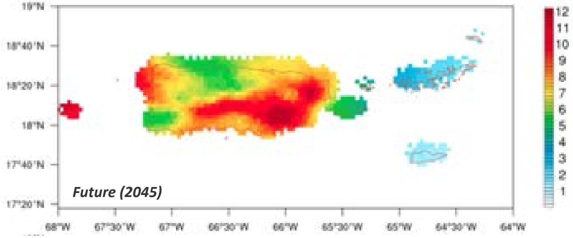
Result for modeled cascading failure in PRIIA (graphic from Argonne)

Climate Risk Assessment

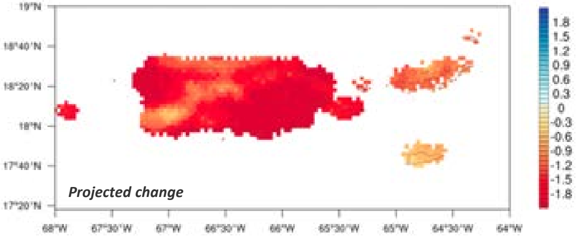
- Downscaled climate modeling:
  - Leveraged climate modeling capabilities to develop 4-km grid and dataset for a range of climate variables projected for mid-century and end-of-century, including:
    - Surface parameters (e.g., accumulated total precipitation, daily minimum and maximum temperatures, etc.)
    - Atmospheric parameters (e.g., wind speeds, cloud fraction, relative humidity, etc.)
    - Soil parameters (e.g., soil temperature, moisture, liquid water, etc.)
    - Hydrologic parameters (e.g., sea level rise, inland waterway level rise, etc.).
- Progress on downscaled climate modeling:
  - Completed first modeling decadal tranche of historic (2000-2010) and mid-century (2040-2045) variables
  - Currently processing second tranche of historic (2010-2020) and mid-century (2045-2050) variables, with end-of-century (2090-2100) up next.



Preliminary downscaled modeling of historic annual daily average precipitation amount (mm/day) (graphic from Argonne)



Preliminary downscaled modeling of future annual daily average precipitation amount (mm/day) (graphic from Argonne)



Preliminary downscaled modeling of projected climate-driven change to annual daily average precipitation amount (mm/day) (graphic from Argonne)

TASK 3: Renewable Energy Potential Assessment

Task Lead: Manajit Sengupta, NREL

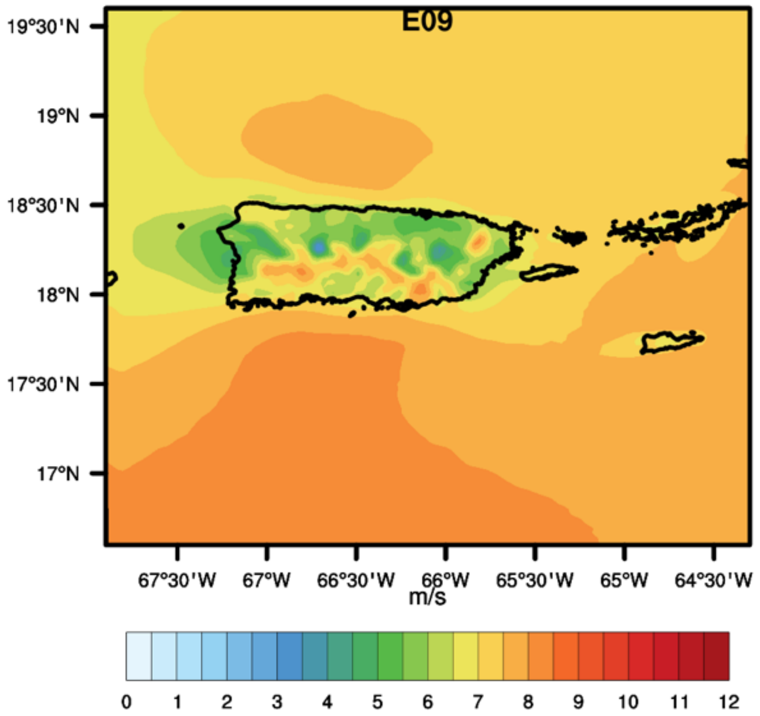
Lead Lab: NREL

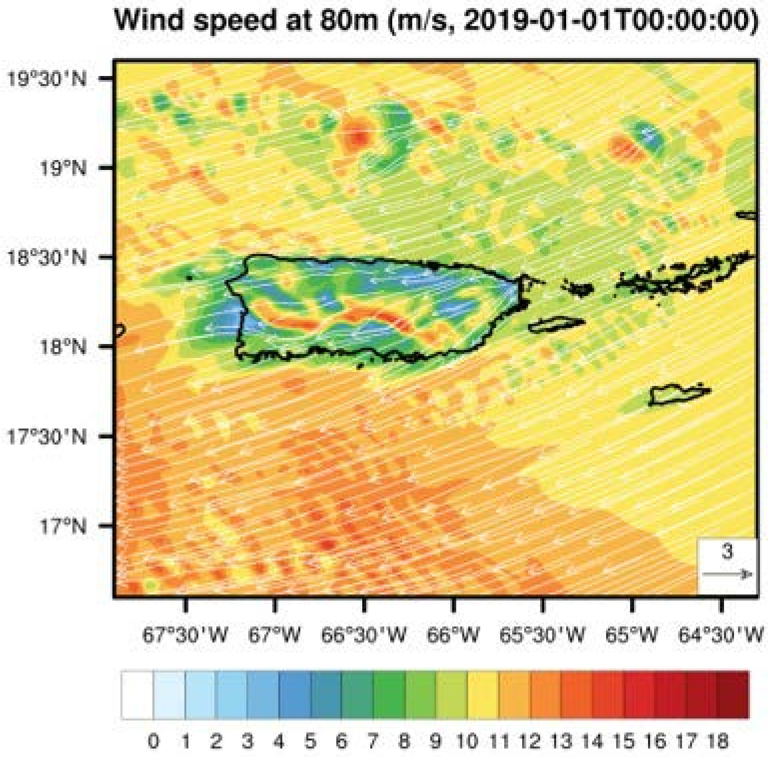
Wind Resource Assessment

Development of high-resolution wind resource datasets

Wind Resource Data

2019: 1-yr averaged wind speed@80m

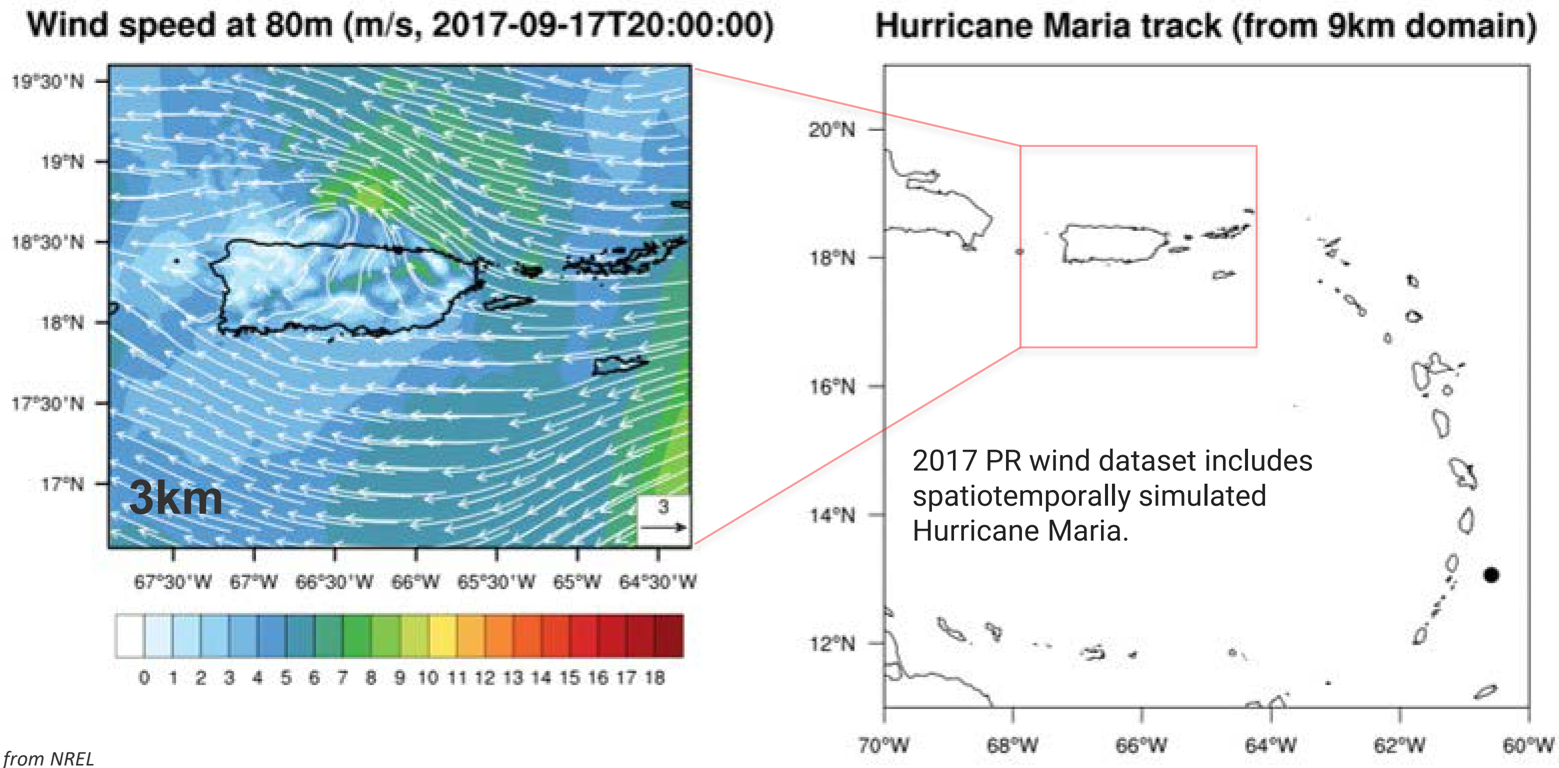




20 years of high-resolution offshore and onshore wind data was developed.

Map from NREL

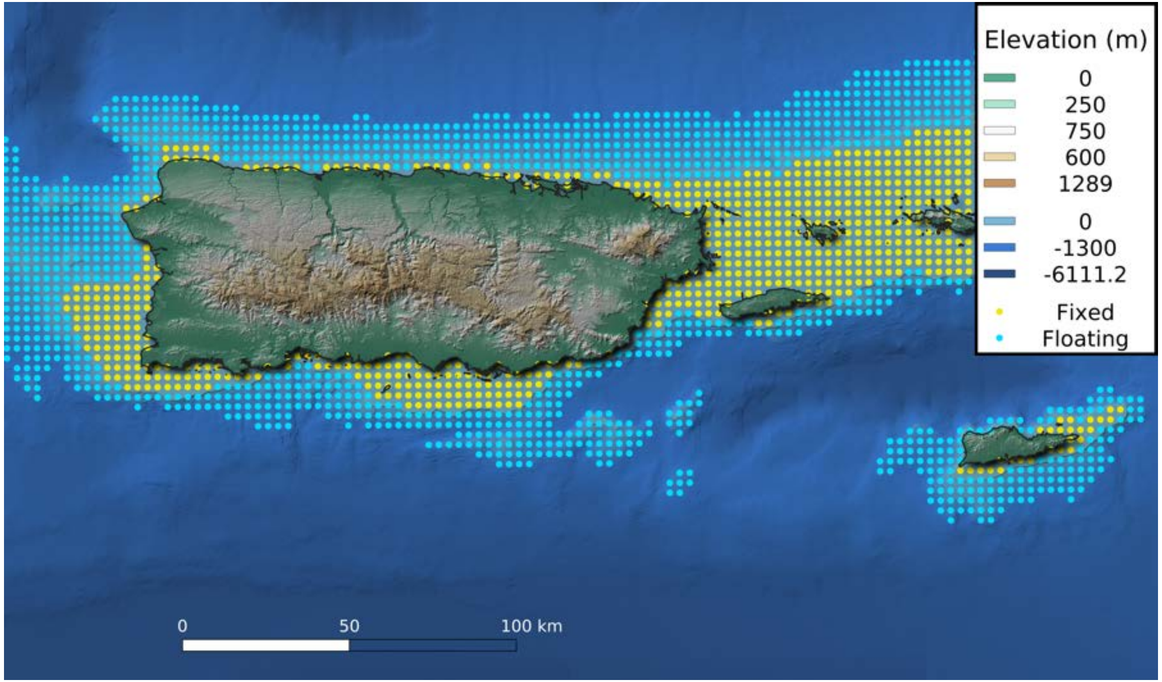
Representing Severe Weather



Map from NREL

Extreme weather events bring utmost challenges to power system reliability and resilience due to their multifaceted impacts on renewable generation resources, demand, and power system outages.

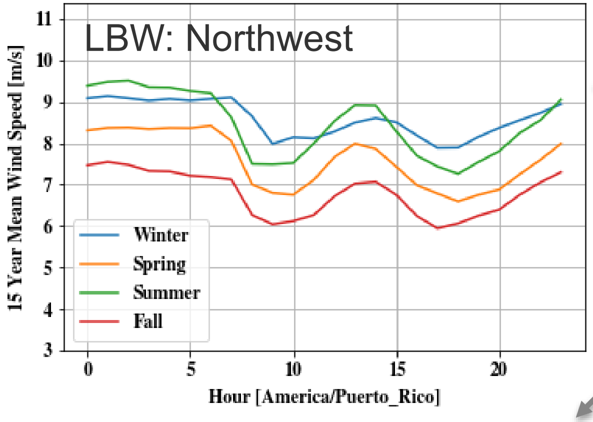
Offshore Assumption Development: Fixed vs. Floating Offshore Wind

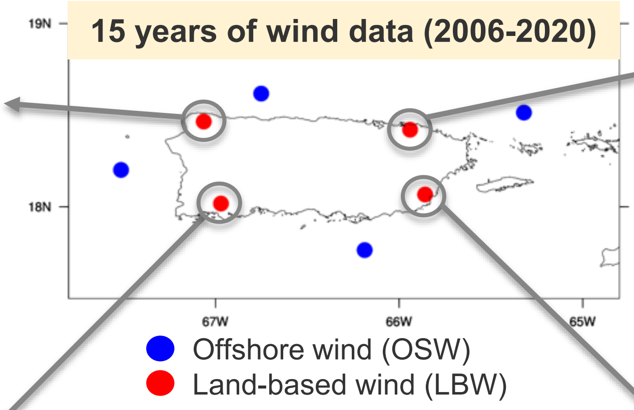


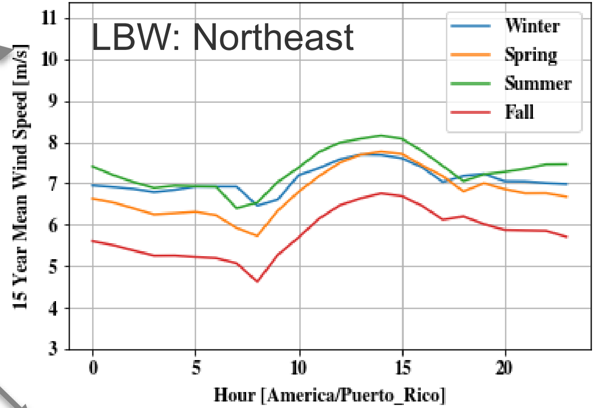
- When modeling offshore wind, we assume fixed-bottom foundations are cost effective until 60m water depths based on recent market trends (yellow dots).
- Floating substructures are assumed to be cost effective up to 1,300m with current floating technologies (blue dots).

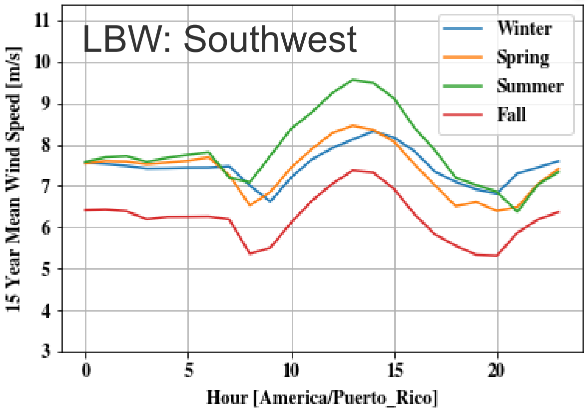
Graphic from NREL

Diurnal Analysis of Wind Data: Onshore

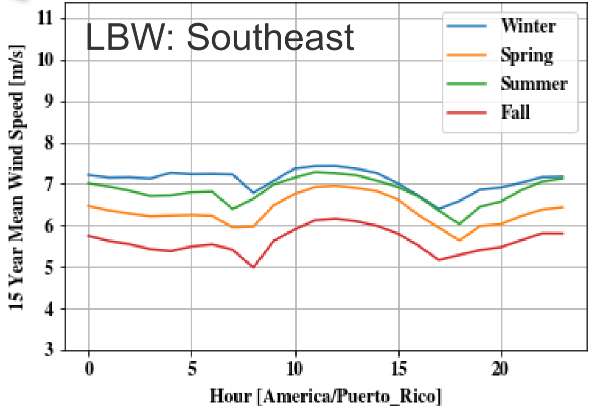






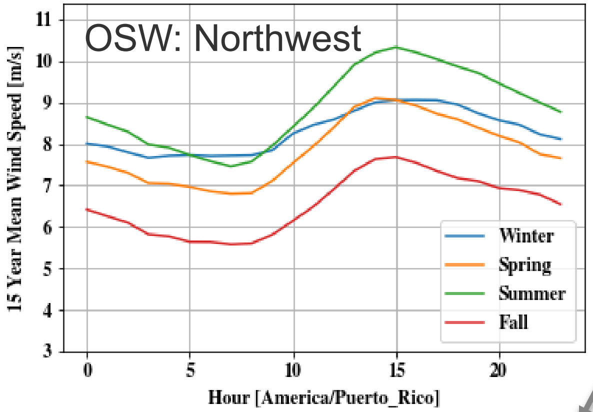


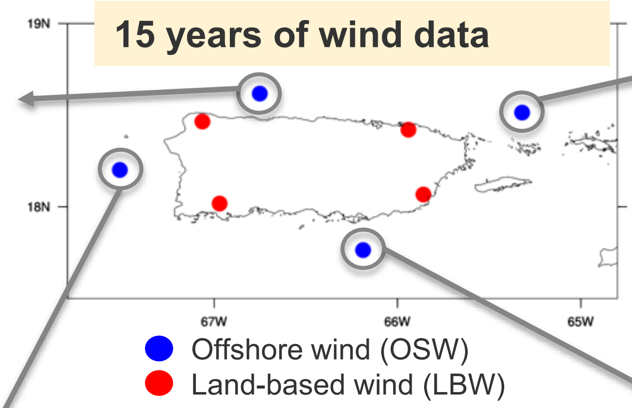
- Seasonal wind speeds feature similar patterns among four sites with increase around noon (e.g., because of strong sea breeze during daytime).
- Wind speed is higher in summer/winter than in spring/fall.

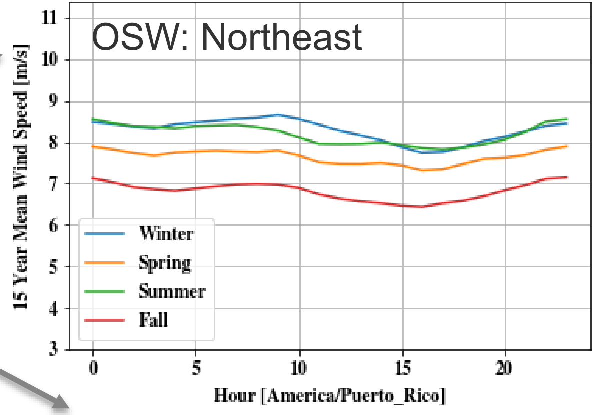


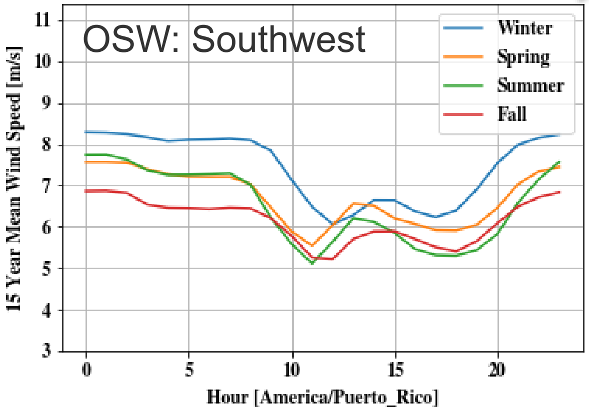
Graphics from NREL

Diurnal Analysis of Wind Data: Offshore

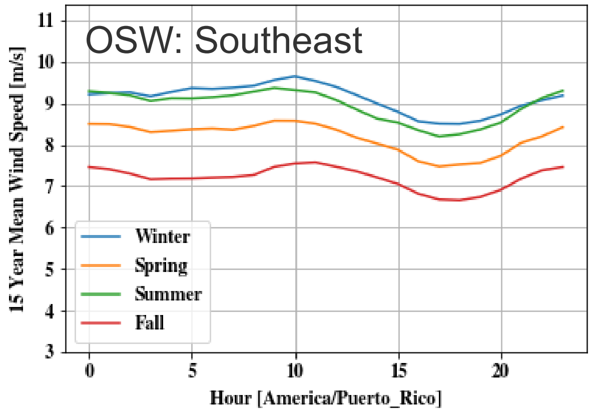








- Northwest site shows high wind magnitude during daytime. Potentially good signal for supporting high demand of energy in summer.
- The other sites show higher wind speeds during nighttime. Potential complementarity between solar and wind generation.

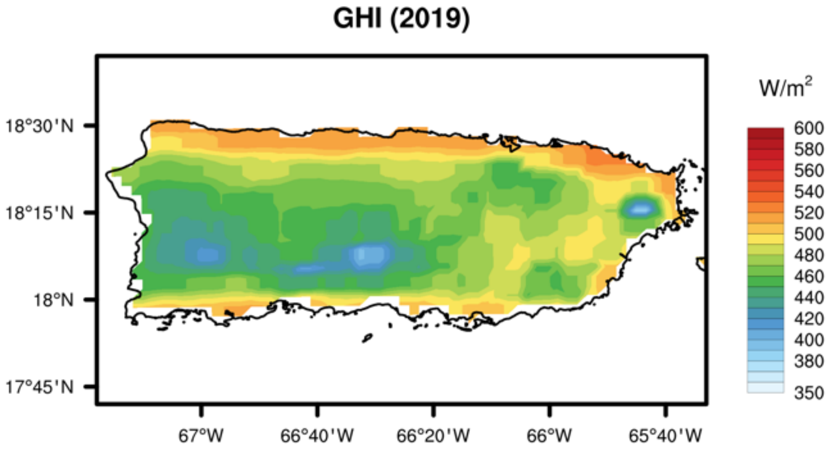


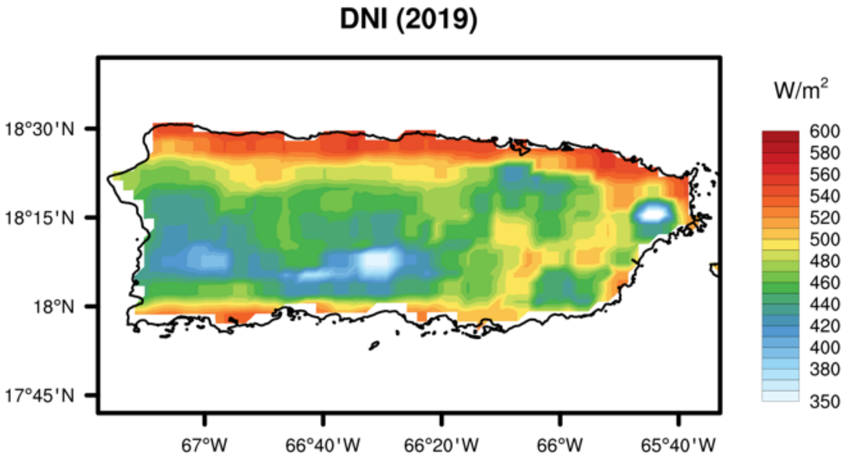
Graphics from NREL

Solar Resource Assessment

Development of high-resolution solar resource datasets

Solar Resource for Recent Years





Solar datasets are being added for 2018-2020. Average Global and Direct Solar Radiation for 2019 shows that most of the island including the coastal regions have high solar resource.

Maps from NREL

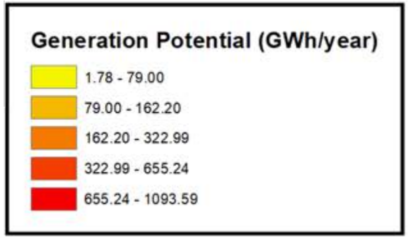
Rooftop Solar Assessment

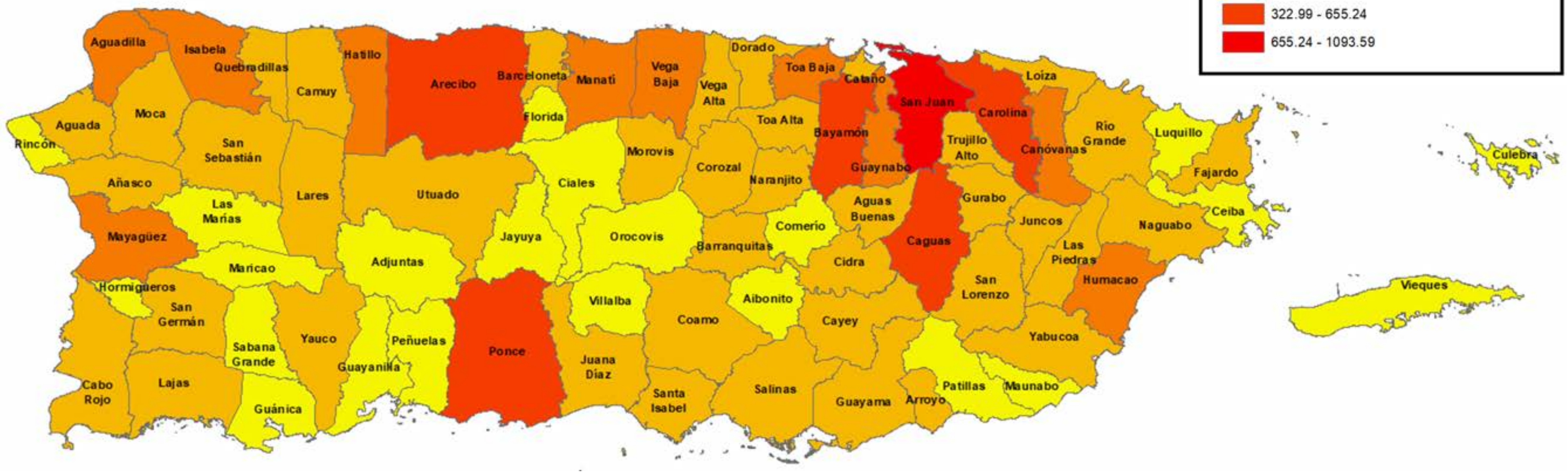
- This study processes LiDAR scans (<0.35 nominal resolution) of Puerto Rico's building stock (96% of Puerto Rico building stock).
- LiDAR data intersected with Census demographics tables of household counts by income, tenure, and building type.
- A statistical model, trained on LiDAR tracts, is used to impute building stock characteristics (area, orientation, shading, etc.) for 4% of building stock without sufficient LiDAR data.
- Finally, simulate solar generation for each roof plane using NREL PVWATTS and aggregate at the tract and county level.

Sources: Mooney et al. (2020), Puerto Rico Low-to-Moderate Income Rooftop PV and Solar Savings Potential (NREL Presentation); Mooney et al (2020), Puerto Rico Solar-for-All: LMI PV Rooftop Technical Potential and Solar Savings Potential (NREL-Produced Datasets)

Residential Rooftop Solar Potential by County

Distributed PV resource exceeds 20 GW of capacity potential.



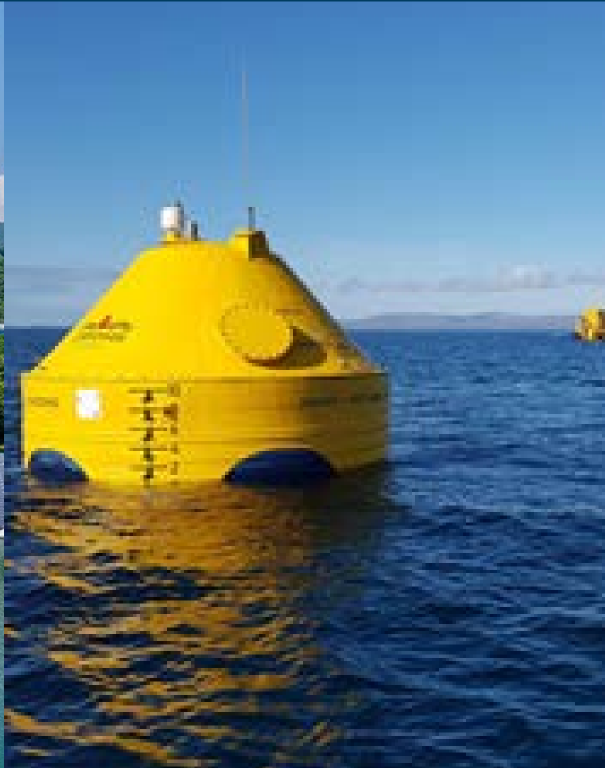


Data Sources: Visualization generated using NREL's Distributed Generation Market Demand (dGenTM) model; Residential rooftop solar PV potential for Puerto Rico from Mooney and Waechter (2020), Puerto Rico Low-to-Moderate Income Rooftop PV and Solar Savings Potential

Additional Resource Potential Assessments in Progress or Under Consideration

Resource Potential Assessments in Progress or Under Consideration

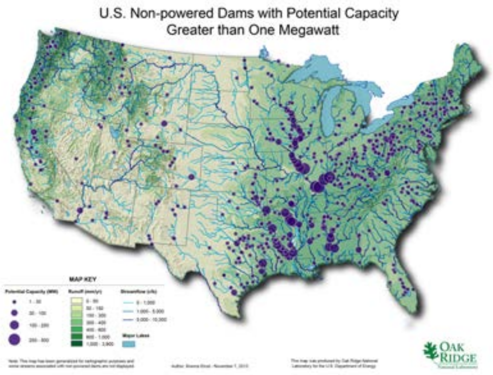


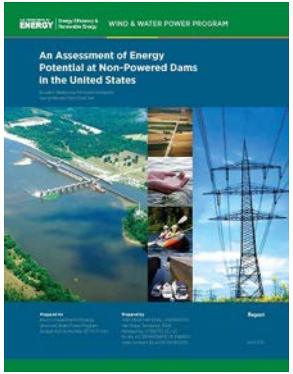


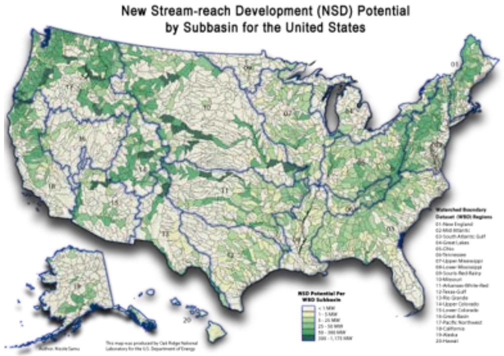
Through year one and into year two, the team will evaluate hydropower and pumped hydro storage, marine energy, and may address additional technologies such as floating PV, bioenergy, and ocean thermal technology conversions (OTEC).

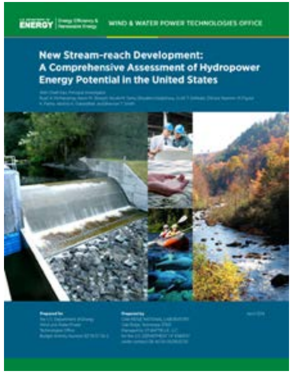
Hydropower Resource Assessment

- Provide estimates of new hydropower capacity, energy, and cost for:
  - upgrade/expansion of existing hydropower fleet
  - non-powered dam development
  - new-stream reach & conduit (TBD)
- Provide daily streamflow analysis from 1950–2014 to support the evaluation of water availability, flow duration curves, and other water resources applications.
- Provide supply curves for capacity and energy expansion models to project hydropower growth in Puerto Rico.









Expanding nationwide hydropower resource assessments to include Puerto Rico. Source: https://hydrosource.ornl.gov/

Assessment of Capacity Increases at Existing Hydropower Facilities

- Black and Veatch completed a feasibility study of the hydro electric system on behalf of PREPA in February 2021.
- From the study:
  - Maximum capacity of the 10 facilities is 94 MW.
  - Current total active capacity is approximately 39 MW.
  - Four of ten facilities active.
  - Results of Black and Veatch study indicate that it is feasible to increase generation and improve the capacity factors.
  - Repairs/upgrades required to reach a capacity factor of 0.28 from current 0.06.
- PR100 study will include the possibility that hydroelectric capacity is maximized, and reservoir operational curves are optimized.

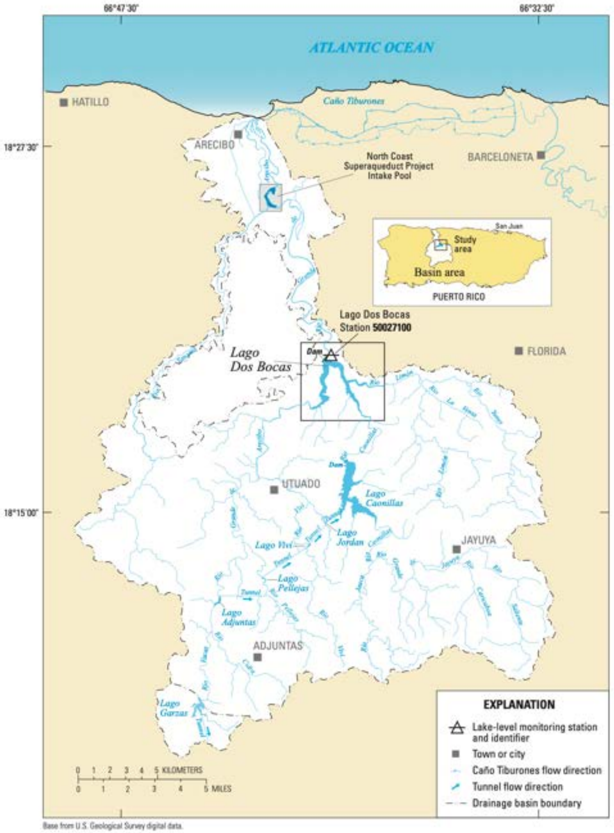
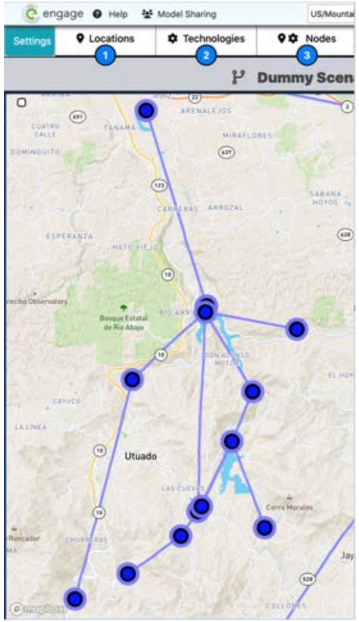


Figure 1. Location of Lago Dos Bocas within the Río Grande de Arecibo basin.

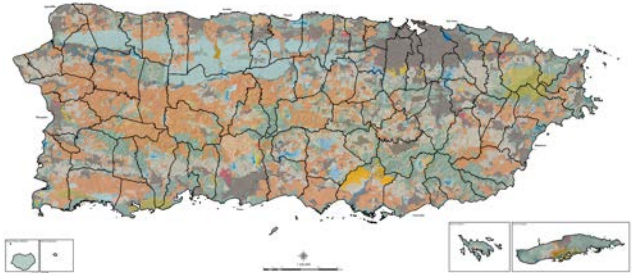


Source: Black & Veatch, [Feasibility Study for Improvements to Hydroelectrical System](#) (submitted as a motion by PREPA to the Puerto Rico Energy Bureau under Case Number CEPR-AP-2018-0001)

Graphics from NREL. Images illustrate how the Engage model will represent and evaluate hydroelectric resources.

Marine and Land Exclusions

- These assessments provide an estimate of the technical resource potential for various renewable energy technologies in Puerto Rico. Once marine and land use exclusions are applied, the feasible utility-scale potential will be much lower.
- Possible exclusions identified to date include:
  - Geographic exclusions are areas determined to be excluded from potential utility-scale renewable energy development.
  - Onshore exclusion layers, including terrain, protected areas, water bodies, roads and building, etc., are being considered.
  - Offshore exclusion layers include Unexploded Ordinance Zones, Protected Areas, Danger Zones, Ocean Disposal Sites.
  - Offshore wind may be limited due to rapid increase of ocean depth near the shore.
- Land use and potential exclusions has been a topic of interest for the Advisory Group, which we will continue to explore.



Puerto Rico Land Use Plan adopted by the Planning Board in 2015 (2019 and 2020 versions have been legally challenged)

TASK 4: Demand Projections and DER Adoption

Task Lead: Nate Blair, NREL

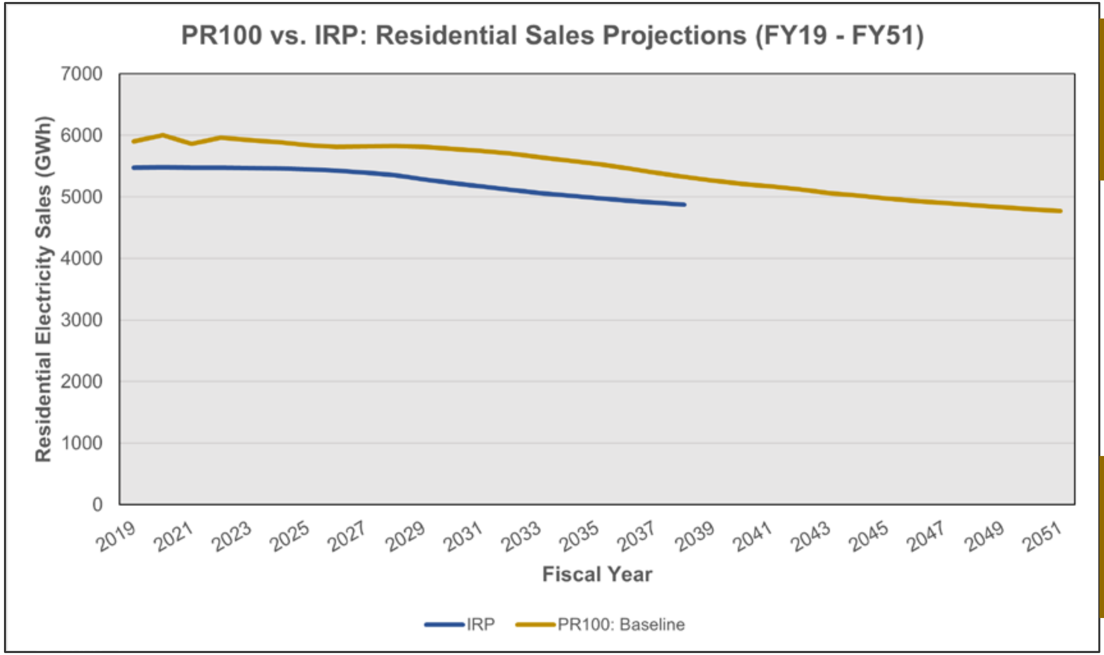
Lead Lab: NREL

Supporting: ANL, LBNL, SNL

Demand Impacts

- The end-use electric usage is based on prior methods with updated data.
- The electric usage will be reduced by energy efficiency improvements.
- The electric usage will be increased by modeled electric vehicle adoption.
- The electric usage will be reduced by adoption of distributed solar and storage.
- The remaining (net) electric usage will be met by large solar, wind, and other RE sources.

Baseline Projections: Residential Sector



Graph from NREL

PR100: New Input Data
Population
Real GNP
CDD

IRP: Old Input Data
Population
Real GNP
CDD

↓ ↓

IRP: Linear Regression Equation
Historical Data from 2000–2017

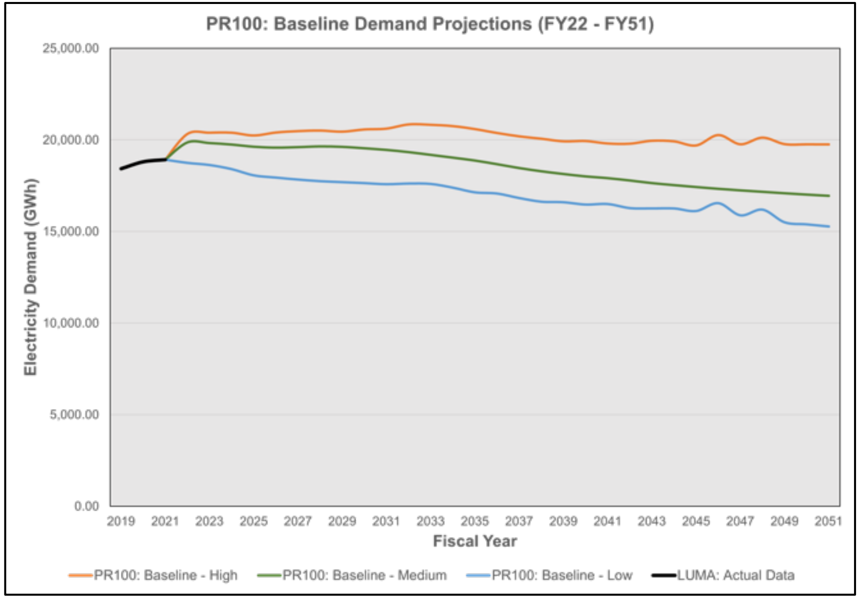
↓ ↓

PR100: New Projection
Residential Sector
Electricity Sales
(FY 2019–FY51)

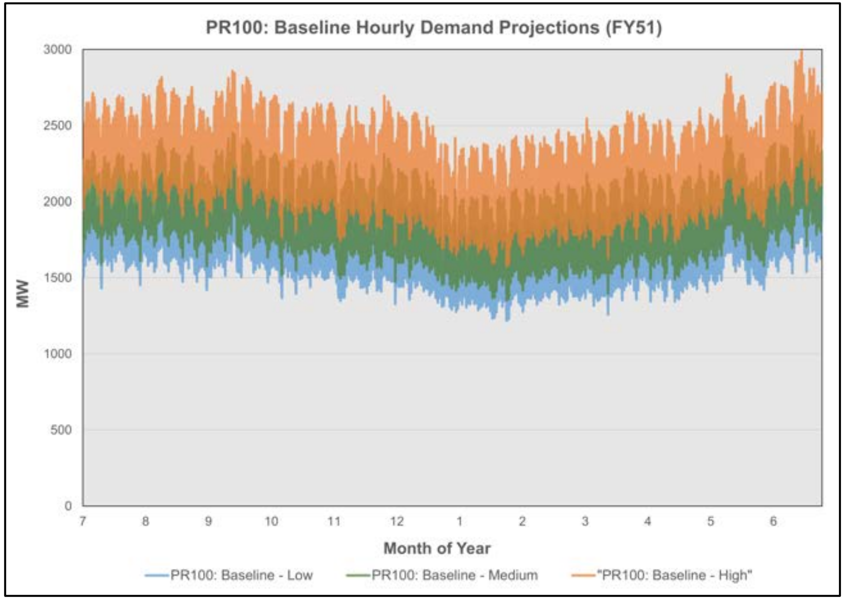
IRP: Old Projection
Residential Sector
Electricity Sales
(FY 2019–FY 2038)

Baseline Projections: Hourly Demand

Annual Projections for FY 2022–FY 2051



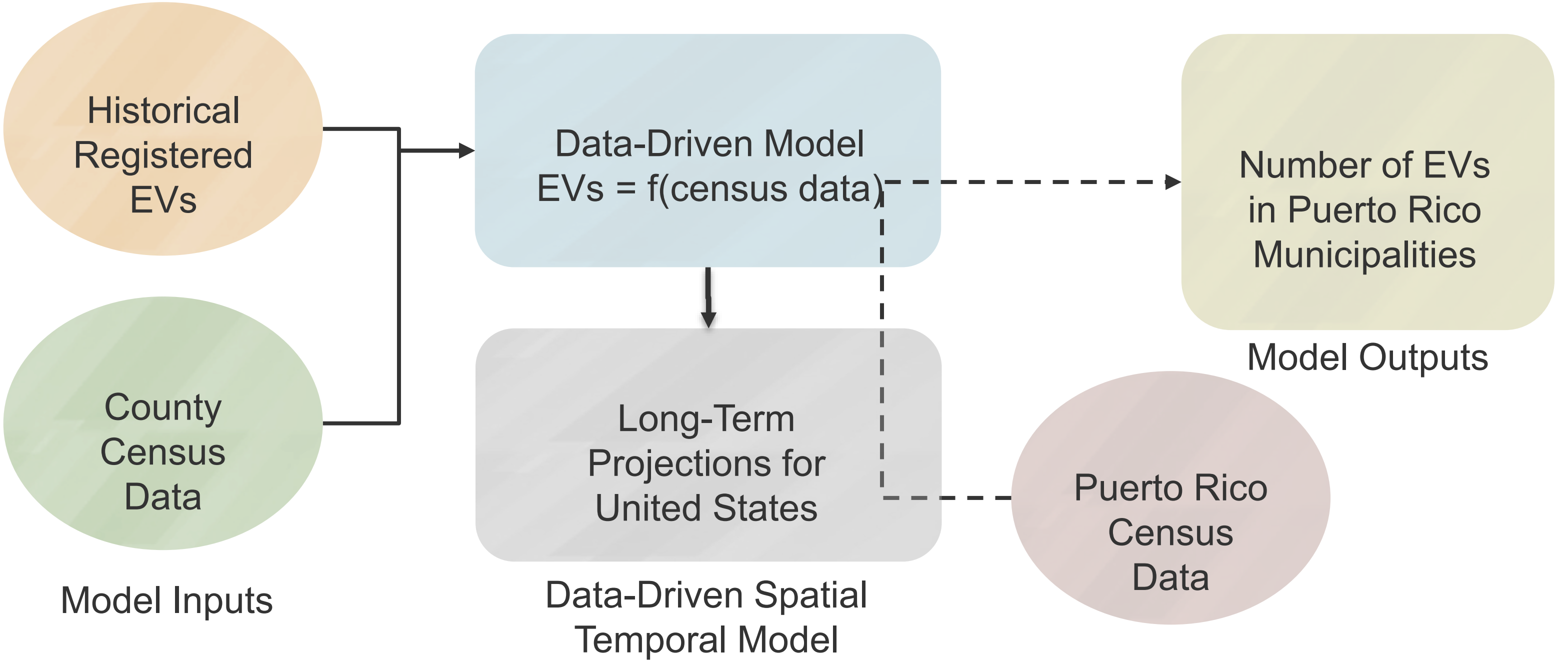
Hourly Projections for FY 2022–FY 2051



Graphs from NREL

Electric Vehicle Adoption Projections

The EV adoption model will utilize a national model (based on national adoption trends) combined with local demographics to model future EV adoption in Puerto Rico.



Energy Efficiency Savings Sources

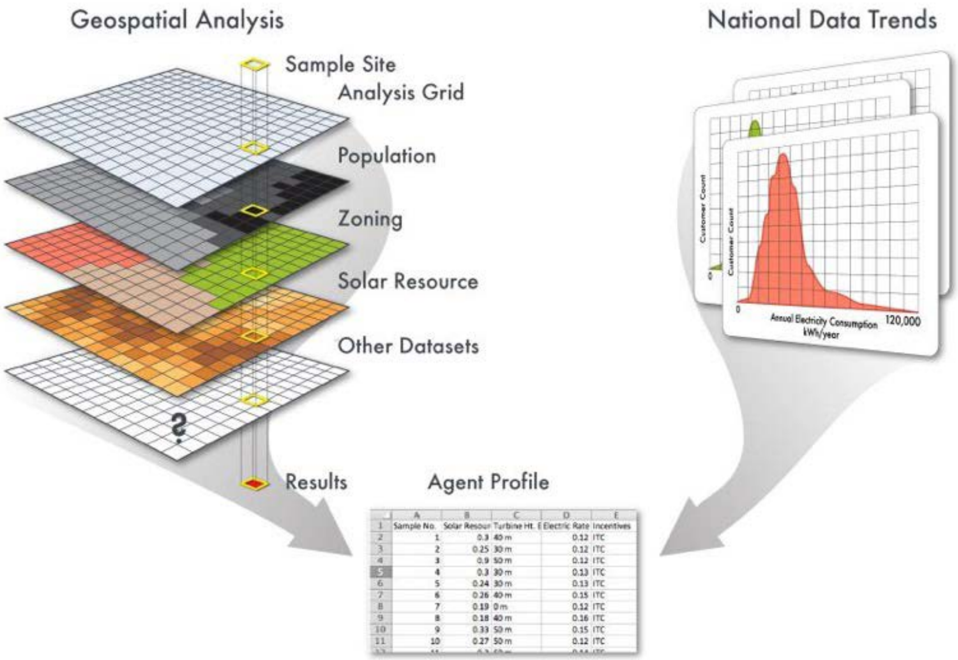
Source of energy efficiency savings	Default	Stress
Programs	Programs (both transition period and permanent) are implemented as contemplated in current energy efficiency proceedings	No new programs are implemented, likely due to a lack of available funding for the planned programs
Building energy codes	Puerto Rico adopts increasingly stringent building energy codes and enforces them sufficiently to produce savings	Little to no savings from codes, either because Puerto Rico does not adopt more stringent codes or is unable to enforce them sufficiently
Appliance and equipment standards	Puerto Rico receives savings from the implementation of increasingly stringent federal standards	Same as default except that federal standards adoption is somewhat slower, reducing savings
Net impact	Energy efficiency decreases load	Energy efficiency is only sufficient to offset demand, resulting in flat net load

Energy efficiency in the default and stress scenarios

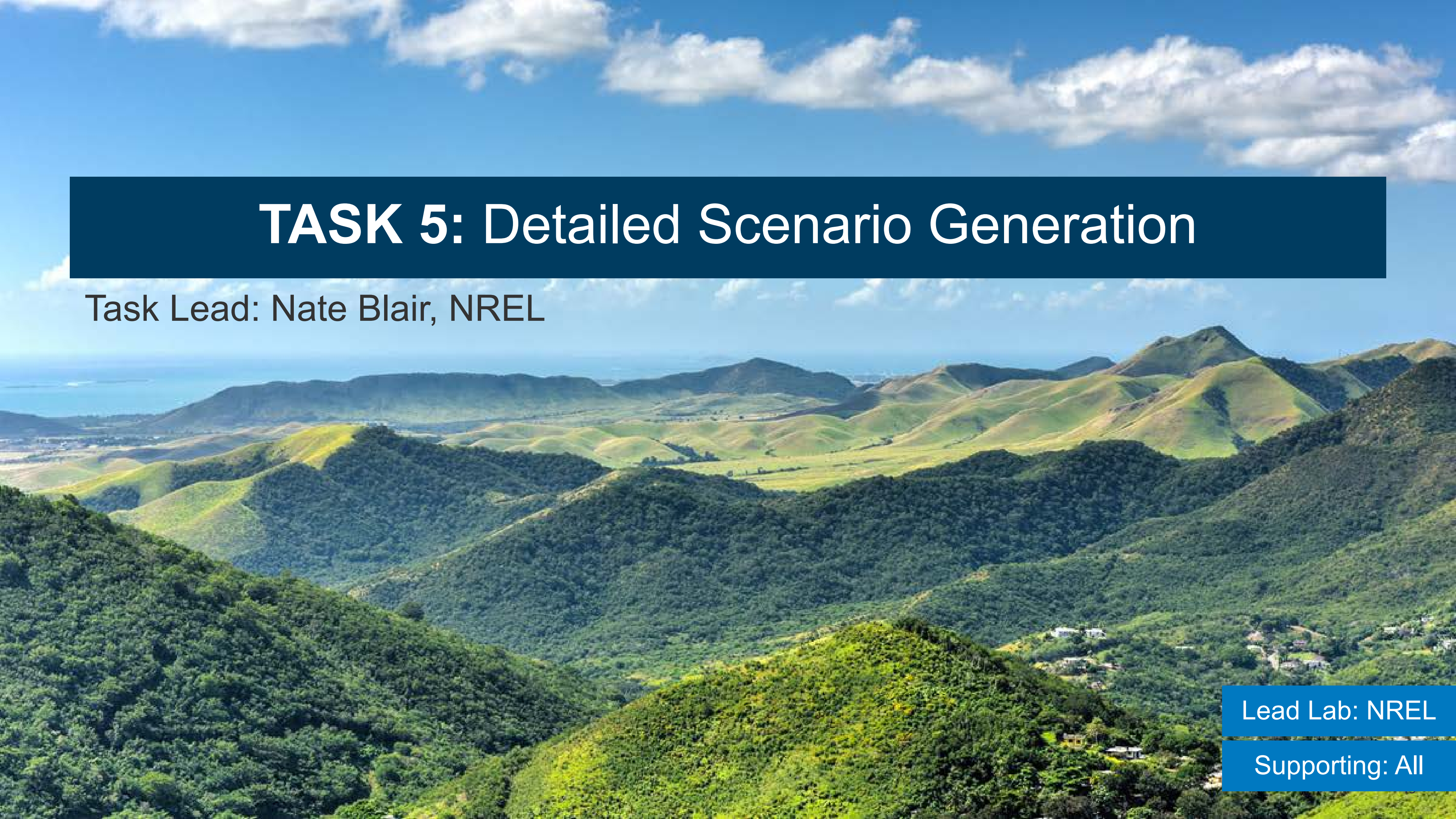
DER Adoption

About the Distributed Generation Market Demand (dGen^{TM}) model:

- Agent-based model simulates consumer decision making
- Forecasts adoption of distributed solar by sector and state through 2050
- Incorporates detailed spatial data to understand geographic variation (see Task 3)
- Agent characteristics derived from population-weighted sampling to create a comprehensive and representative database of the analysis population



Website: www.nrel.gov/analysis/dgen/
Documentation: www.nrel.gov/docs/fy16osti/65231.pdf



TASK 5: Detailed Scenario Generation

Task Lead: Nate Blair, NREL

Lead Lab: NREL

Supporting: All

Initial Scenario Definition

- The project team worked closely with the Advisory Group during the first six months of the study to define four initial scenarios to model.
- The primary distinction between the four scenarios is varying levels of distributed energy resources, such as rooftop solar and energy storage.
- Variations of load and land use will also be applied to select scenarios. More detail is provided in the Task 5 update herein.

Similar Examples:

PR100 modeling is based on a research standard, but it is not a one size fits all. Different communities have different priorities, conditions, and local legislation.

Oahu, Hawaii

- ✓ High energy consumption
- ✓ Land availability
- ✓ Competing maritime interests

LA100

- ✓ Compliance with CA Senate Bill
- ✓ Transmission focus
- ✓ Biofuel opportunities
- ✓ Customer electricity demand

Solar Futures Study

- ✓ Changes in policy
- ✓ Deep decarbonization
- ✓ Increased electrification

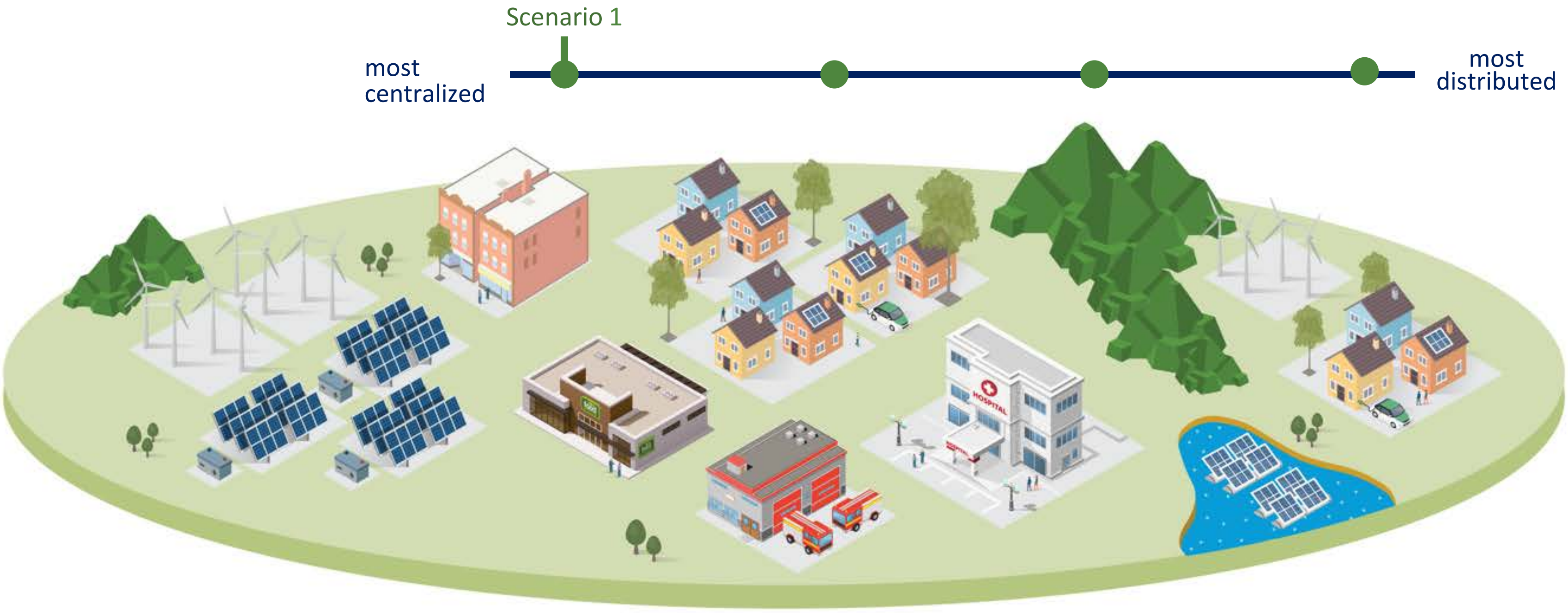
PR100

- ✓ Grid recovery
- ✓ Resilience in extreme storms
- ✓ Land availability

Images left to right: Dennis Schroeder / NREL 57777, Microsoft Images, Dennis Schroeder / NREL 40820, Werner Slocum / NREL 53641

Scenario 1. Economic Adoption of Distributed Solar PV and Storage

Electricity system is modeled to achieve 100% renewable energy by 2050



Scenario 2. Deployment of Distributed Energy Resources for Critical Services

Distributed energy resources installed beyond Scenario 1 for critical services like hospitals, fire stations, and grocery stores

Graphic by NREL

Scenario 3. Equitable Deployment of Distributed Energy Resources

Installation of distributed energy resources is prioritized beyond Scenario 2 for remote and low- and moderate-income households

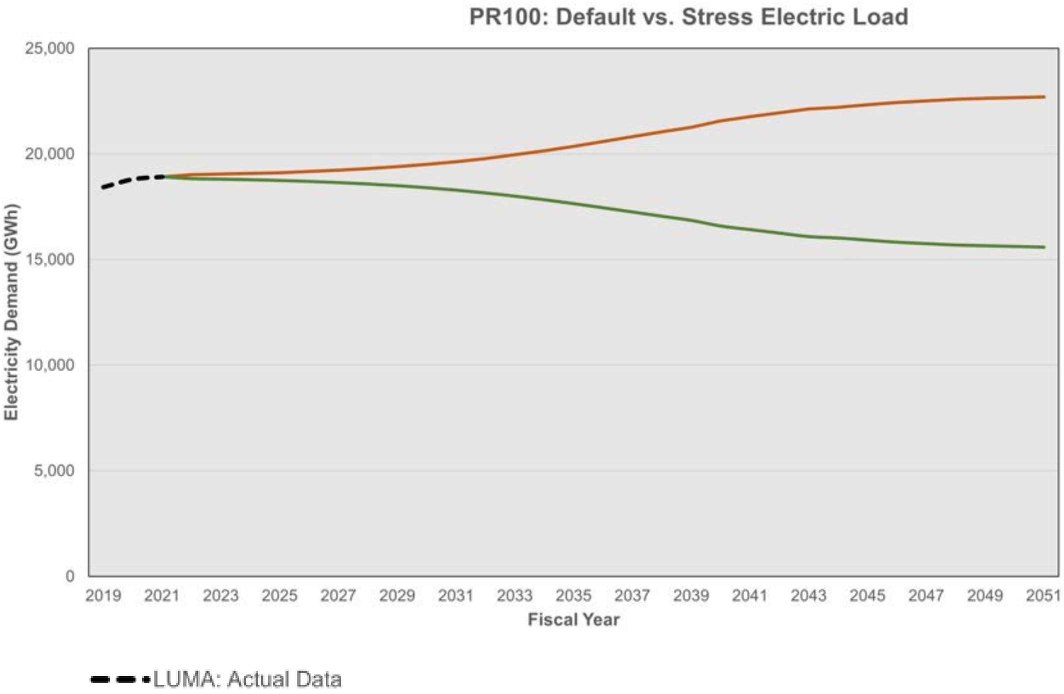
Graphic by NREL

Scenario 4. Maximum Deployment of Distributed Energy Resources

Distributed solar and storage is added to all suitable rooftops

Graphic by NREL

Potential Electric Load Options



NOTE: Place-holder data used for energy efficiency and EV adoption to illustrate potential impacts to default electric load.

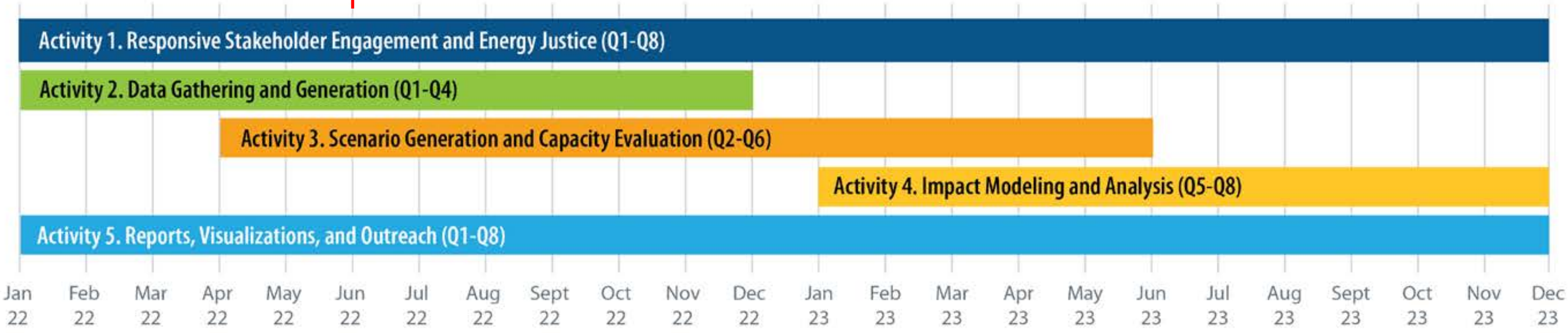
	Default	Stress
End Use Loads	Inputs include gross national product, population, cooling degree days, and manufacturing jobs	Combination of end-use loads and energy efficiency result in a flat net annual load
Energy Efficiency	Mid-case: Impact of reduced energy waste	
EV Adoption	Moderate EV adoption	High EV adoption (uncontrolled)

PR100 Timeline

6 Months :
Established stakeholder group meets monthly to inform scenarios
Defined four initial scenarios to achieve Puerto Rico's goals.

Next Steps -- Each scenario will be modeled to understand:

- What new capacity gets built, where, and at what cost?
- What are the fixed and variable costs of operating the system?
- Does reaching 100% mean big changes locally—like building new transmission lines or increasing hosting capacity of the distribution system?
- If Puerto Ricans adopt energy technologies like EVs, how might that change total demand for electricity?
- Are scenarios resilient under extreme weather events?
- What are the economic impacts, such as changes to retail rates?



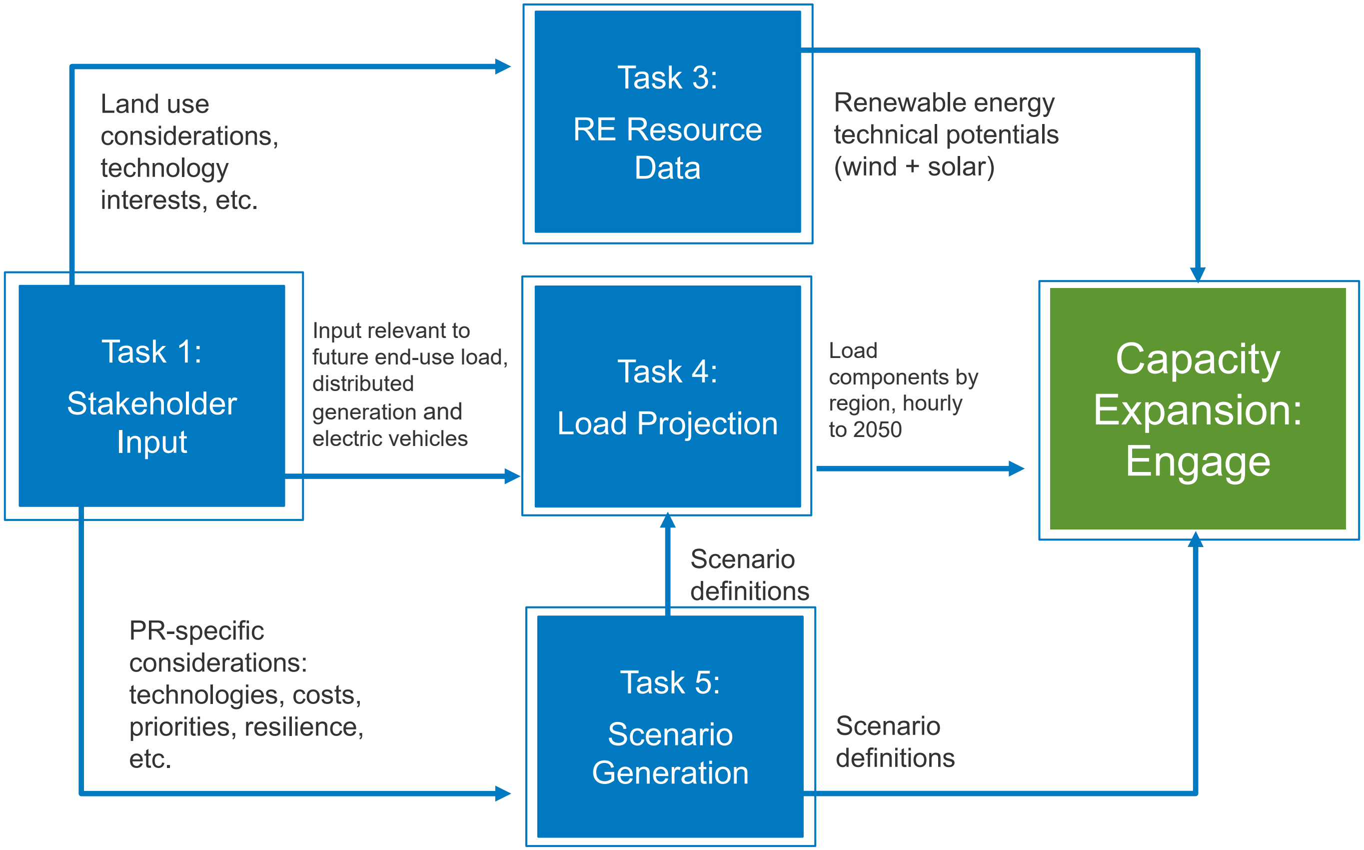
TASK 6: Capacity Expansion Modeling

Task Lead: Tom Harris, NREL

Lead Lab: NREL

Supporting: ANL, PNNL

Engage: Bringing it All Together *Quantitatively*



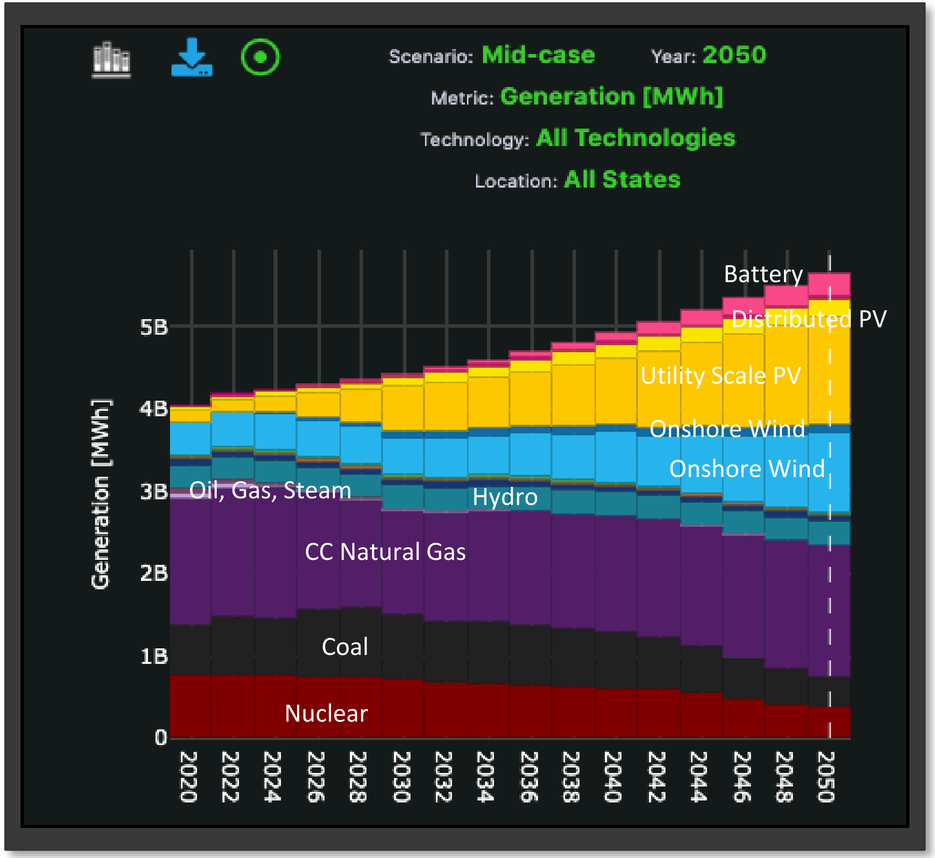
- Collected existing generation and transmission assets data from PREPA/LUMA.
- Created a data ingestion pipeline with placeholder data from Task 3 and Task 4 (loads).
- (Now) Characterizing additional existing system technologies (hydro) and future system technologies in the Engage model.
- Next, scenario modeling.

* Translation is from load, EV, EE municipality-level data to substation-level data for the electrical models.

Graphic from NREL

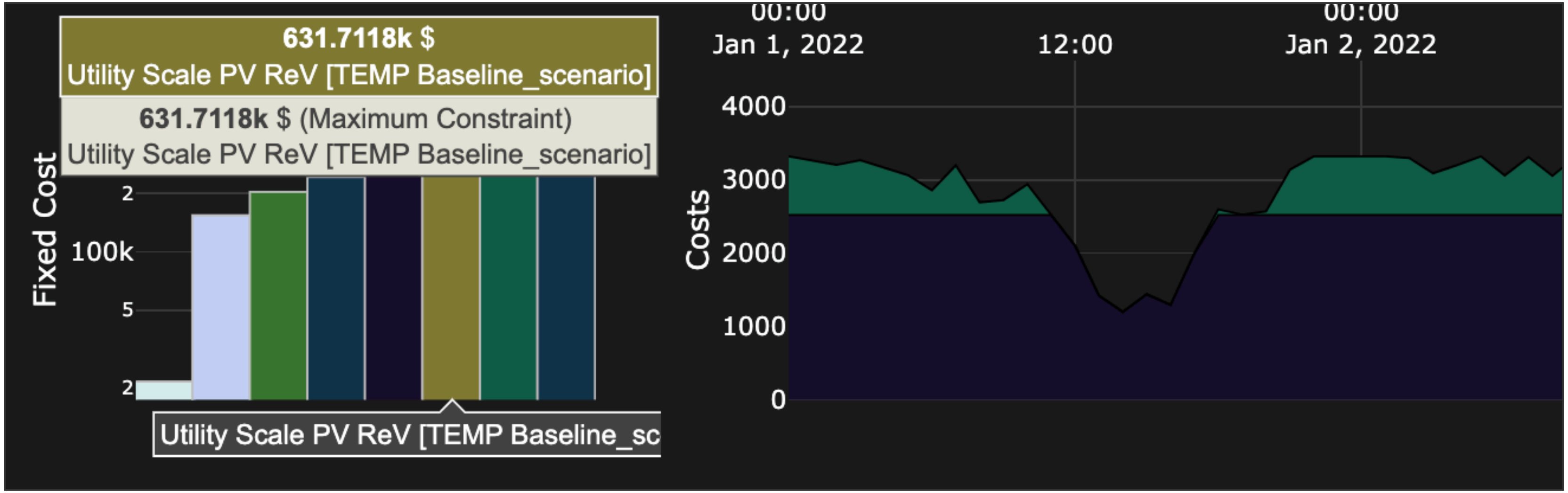
Engage Outputs

Generation build-out and retirement projections in the 50 states of the U.S. through the years



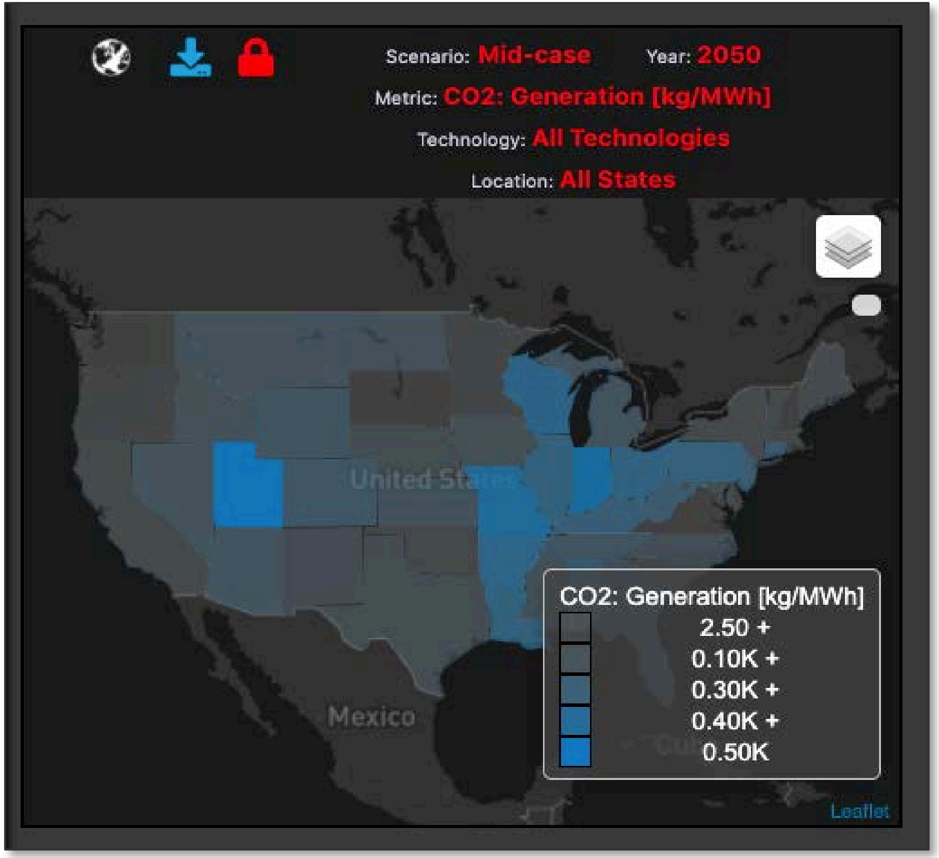
Engage Outputs

Investment Costs and Operating Costs

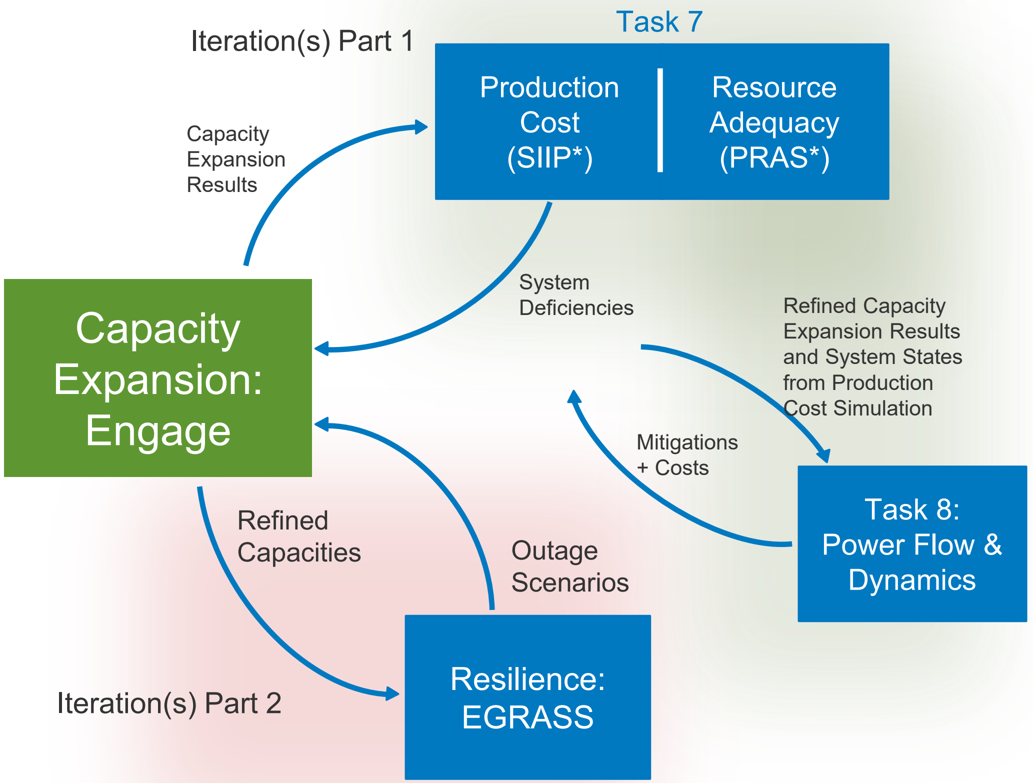


Engage Outputs

Emissions, land use, pollution projections



Engage in PR100 Context: Next Phase



Graphic from NREL

* SIIP: Scalable Integrated Infrastructure Planning, PRAS: Probabilistic Resource Adequacy Suite

TASK 7: Production Cost and Resource Adequacy

Task Lead: Clayton Barrows, NREL

Lead Lab: NREL

Supporting: ANL

Production Cost and Resource Adequacy: Tools and Workflow Coordination Progress to Date

Task 6: Capacity Expansion

- What resources are developed under each scenario assumption?

Task 7: Resource Adequacy

- How likely are failures in each scenario system?
- Are additional resources required to maintain reliability?

Task 7: Production Cost Modeling

- How well does each scenario system economically balance supply and demand?
- Are additional resources needed for balancing?

Progress to Date:

- Coordinated common reference data based on load flow case shared by LUMA
- Identified required metrics for downstream analysis in tasks 8 and 10
- Enabled key inter-model data hand-offs and translations required for accepting Capacity Expansion Model results as inputs and providing inputs to downstream tasks
- Developed initial base-case resource adequacy and production cost modeling datasets

What is coming in Task 7:

- Validated base case model results
- Expanded system scenario results and analysis:
  - Feedback on expanded system performance to identify additional resource requirements
  - System performance analysis of probability of lost load, total production costs, plant operations, transmission utilization, and reserve allocation
  - Impact analysis of emissions and wholesale electricity prices

TASK 8: Bulk System Power Flow and Dynamic Analysis

Task Lead: Marcelo Elizondo, PNNL

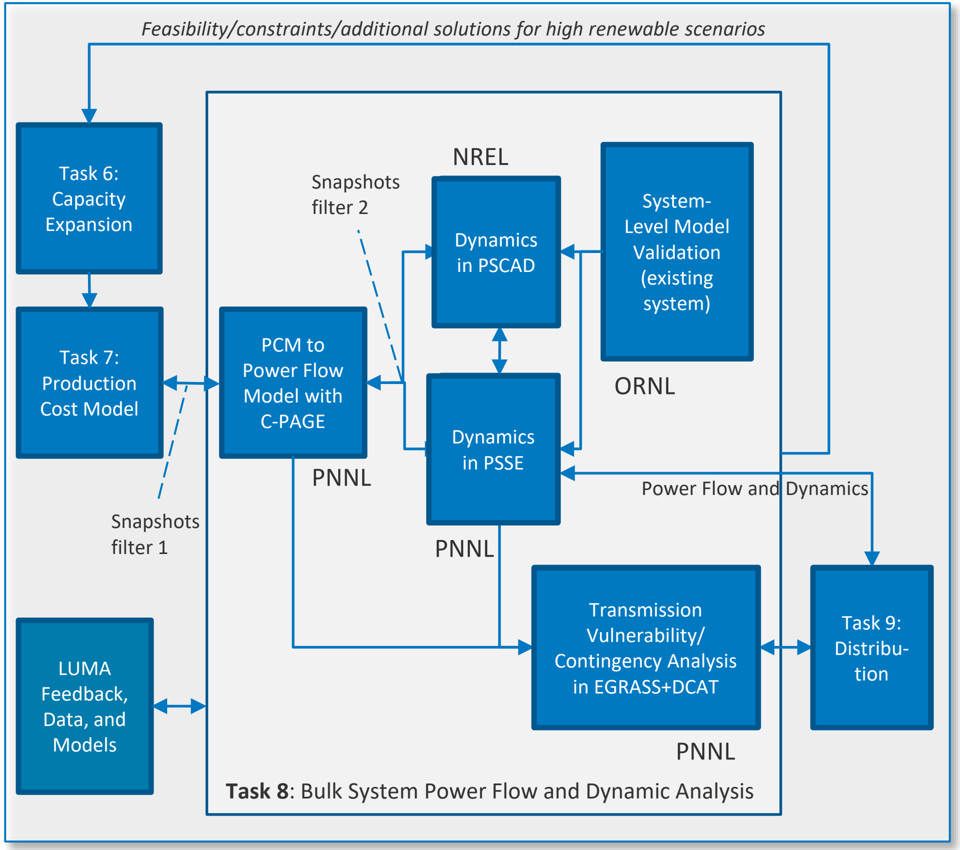
Lead Lab: PNNL

Supporting: ORNL, NREL

Bulk System Power Flow and Dynamics Analysis

Progress to Date

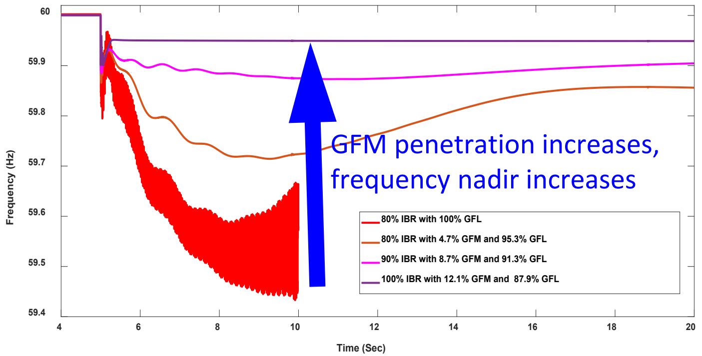
- AC Power Flow
  - ➢ LUMA provided 2021 Base Case
  - ➢ PNNL preparing a test case with high RE penetration case
- Dynamics (PSS/E, PSCAD)
  - ➢ PNNL adapted 2019 PSS/E dynamic model to 2021 case, and shared with NREL and ORNL
  - ➢ NREL built PSCAD model based on 2019 dynamics; currently building PSCAD model for tranche 1
  - ➢ PNNL working on PSSE DER and motor load models
- Sensor Data and Model Validation
  - ➢ LUMA shared new event data with Task 8 team
  - ➢ ORNL identified events of interest and working on analysis event data provided by LUMA
- Resilience Evaluation Consideration
  - ➢ Configured EGRASS-DCAT to run vulnerability assessment – hurricane N-k dynamic cascading analysis
  - ➢ EGRASS being adapted to inform capacity expansion (within task 6) – also adding distribution and solar PV
- Data and Model Coordination with LUMA, and Tasks 6, 7, 8, and 9



Bulk System Power Flow and Dynamics Analysis

What Is Coming in Task 8

- Validation of system-level dynamics
- Control and stability for high penetration of renewables: concerns → possible solutions
  - Low inertia → inverter control (e.g., fast frequency response), synchronous condensers
  - Weak grids → inverter control (e.g., grid forming), synchronous condensers
  - Balancing reserves → variability and uncertainty analysis
  - Monitoring, control, and coordination of distributed energy resources → distribution-level control, transmission-level control/coordination
- Scenario analysis
  - Analysis of various operating points
  - Control and stability impacts and solutions at transmission with aggregated behavior from distribution and solar PV
  - Vulnerability: hurricane N-k dynamic cascading analysis



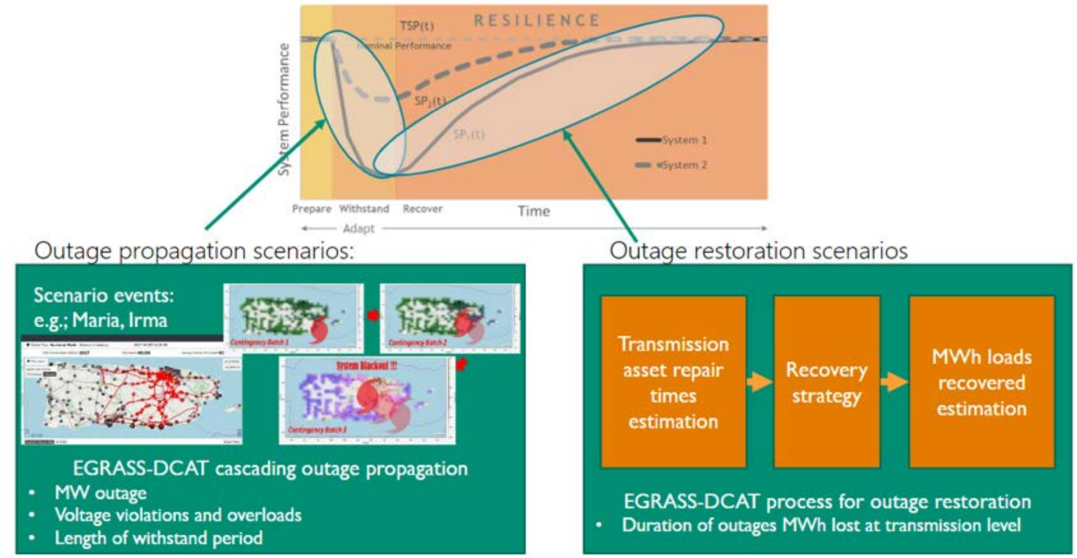
(Image from PNNL)

Question: How many grid-forming inverters (GFMs) are needed to maintain the stability of future inverter-based resource (IBR)-dominated systems? In 160,000-node min-WECC system with 10,000+ inverters:

- 12.1% in 100% IBR system
- 8.7% in 90% IBR system
- GFMs, if properly controlled, achieves better system reliability performance than conventional synchronous machines

Source: Du, W. "Transient and Dynamic Modeling and Droop-Controlled, Grid-Forming Inverters at Scale." Presented at UNIFI-Spring 2022 Seminar Series on Grid-Forming Technologies, Virtual, Washington. PNNL-SA-169855.

Hurricane grid resilience analysis



EGRASS updates for planning studies in PR100

- Adding PV fragility
- Added initial distribution feeder fragility

Outage restoration estimations, full-island initial results

- To inform capacity expansion and adequacy
- Figure uses preliminary output from capacity expansion in Engage tool

Images by PNNL

TASK 9: Distribution System Analysis

Task Lead: Matt Lave, SNL

Lead Lab: SNL

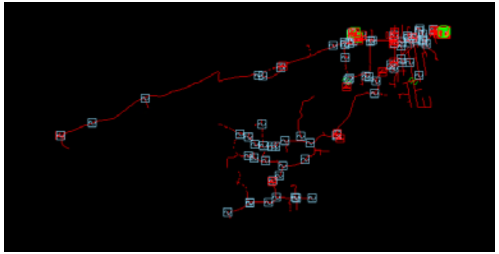
Supporting: NREL, PNNL

Distribution System Analysis

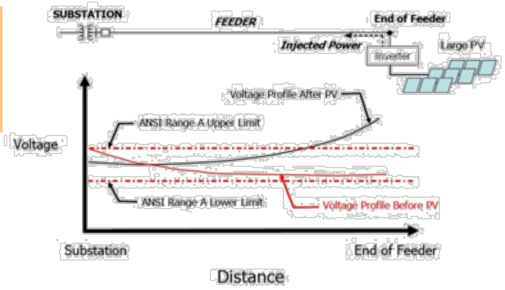
Progress to Date:

- Working on conversion of ~30 distribution feeders supplied by LUMA in Synergy to research platform OpenDSS
- Setting up hosting capacity analysis to understand DER capacities
- Engaging in crosscutting discussions with other tasks to set up control strategies, resilience metrics, etc.
- Refining hosting capacity analysis to account for controls, grid upgrades, or other mitigation measures
- Identifying and quantifying resilience benefits from large amounts of DERs and storage on distribution grids

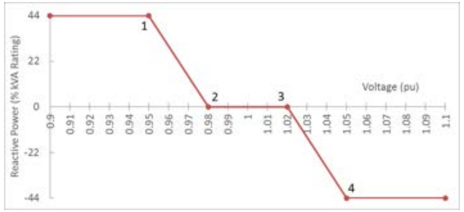
Synergy feeder example



Voltage impact from DERs



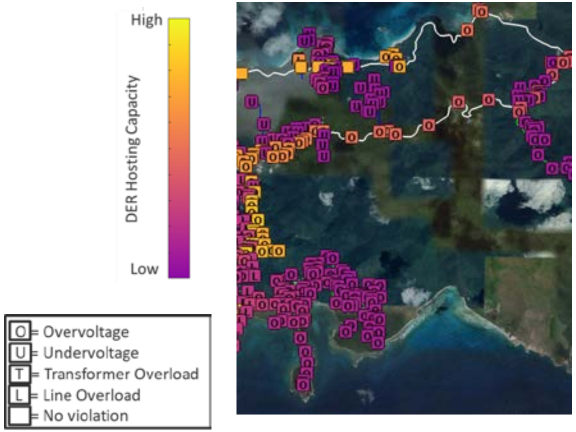
Mitigation strategy: volt/var controls

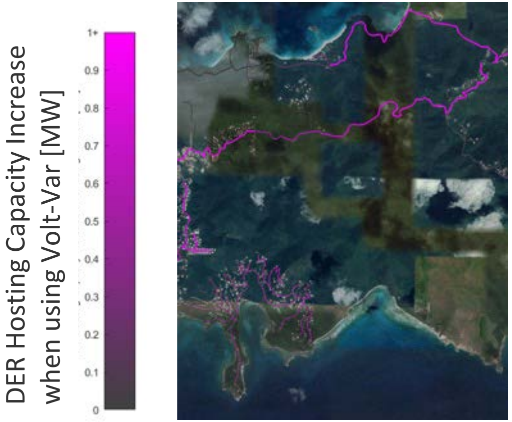


Graphics from Sandia

Distribution System Analysis

- In the next 6 months:
  - Detailed analysis to understand capacity for distributed renewables and limiting factors
  - Implement planned system upgrades into modeling
  - Quantify possible increases to capacity due to controls (e.g., volt-var)
- In the next 12 months:
  - Identify interdependencies between distribution and bulk system operations
  - Simulate vulnerabilities under high penetrations
  - Explore microgrid opportunities from high levels of DERs and resulting resilience benefits





Graphics from Sandia

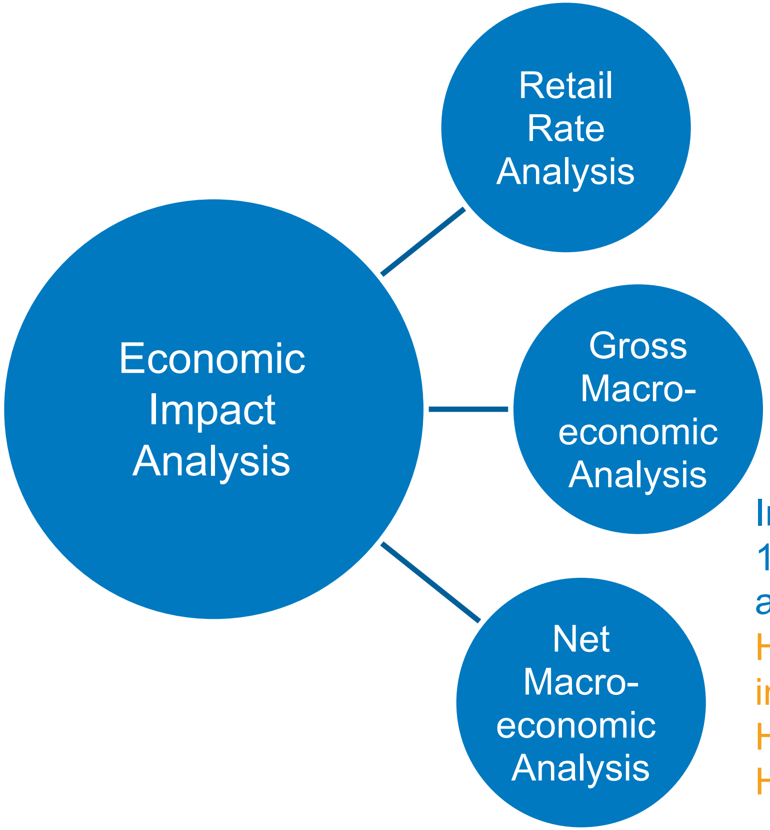
TASK 10: Economic Impact

Task Lead: Pete Capers, LBNL

Lead Lab: LBNL

Supporting: NREL

Task 10: Key Research Questions Summary



What are the impacts on annual electricity rates resulting from achieving Puerto Rico's transition to 100% renewable energy?

Regarding only the renewable energy generation investments needed to achieve the 100% goal
How will the Puerto Rico economy be impacted?
How many jobs will be created?

Incorporating all costs associated with the transition to 100% renewable energy, including transmission, reliability, and distribution investments
How will the Puerto Rico economy be directly and indirectly impacted?
How will changes in electricity rates affect consumers?
How will these impacts vary across regions in Puerto Rico?

Upcoming Efforts: 12-Month and Year-2 Deliverables

- **12-Month Deliverable: <u>Initial projections of retail rates</u>**
  - NREL scenarios plus legacy debt, pension obligations, post-bankruptcy and post-reorganization cost structures, financing impacts
- **12-Month Deliverable: <u>Initial JEDI model estimates</u>**
  - Develop Jobs and Economic Development Impacts (JEDI) model to integrate capacity & cost scenarios for all renewable generation technology types; local spending patterns
- **12-Month Deliverable: <u>Initial CGE model estimates</u>**
  - Computable general equilibrium (CGE) model and social accounting matrix
- **<u>Year 2 Deliverables</u>: Final results**
  - Retail rate projections
  - Economy, jobs, GDP, regional impacts

TASK 11.4: Implementation Roadmap

Presented by Matt Lave, SNL

Lead Lab: LBNL

Supporting: NREL

Implementation Roadmap

The PR100 team will:

- Advise stakeholders on the electric grid operation actions needed in both the near term and long term to follow a path to achieving the renewable energy goals in Act 17.
- Engage with the government of Puerto Rico and its stakeholders to understand current organization, technical capabilities, and operations.
- Support validation of expansion planning results based on national lab expertise and tools.
- Develop a transition plan and suggest paths for quick-impact actions (i.e., "near-term wins").

Thank You!

NREL/PR-5C00-84318