Designing the PR100 Study

Puerto Rico Grid Resilience and Transition to 100% Renewable Energy

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IEEE Seminar to Puerto Rico & Caribbean Section Chapter, PE31

Photo from iStock

Overview of the Storms

- Irma hit the island on Sept. 6, knocking out power to almost a million customers.
- Two weeks later Maria hit, crossing almost the entire island from southeast to northwest.
- 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

Hurricane Path
Transmission Lines
Mountains

Photo from iStock

Impact of Storms on Grid Assets

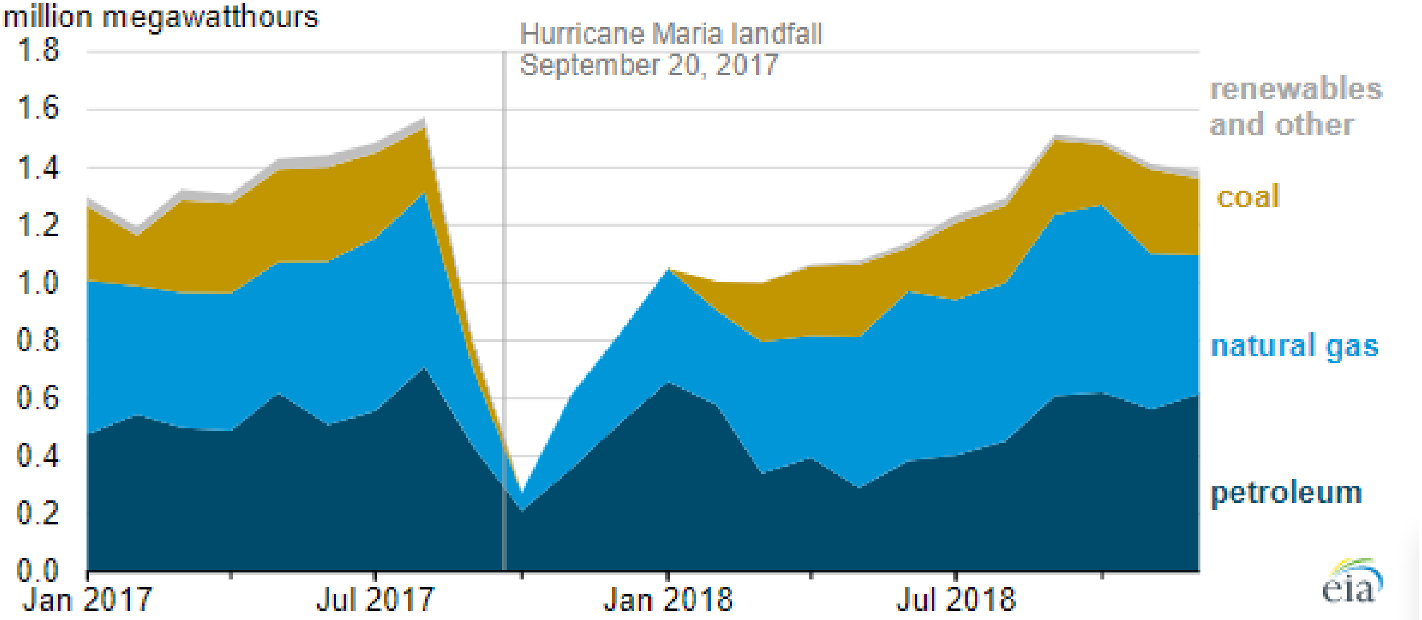
- The two hurricanes that hit Puerto Rico two weeks apart in 2017 resulted in a systemwide collapse and a U.S.- and global-record-setting blackout.
- Damage occurred to all elements (generation, distribution, and transmission) of Puerto Rico's already fragile energy system.
- FEMA allocated $3.2 billion 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

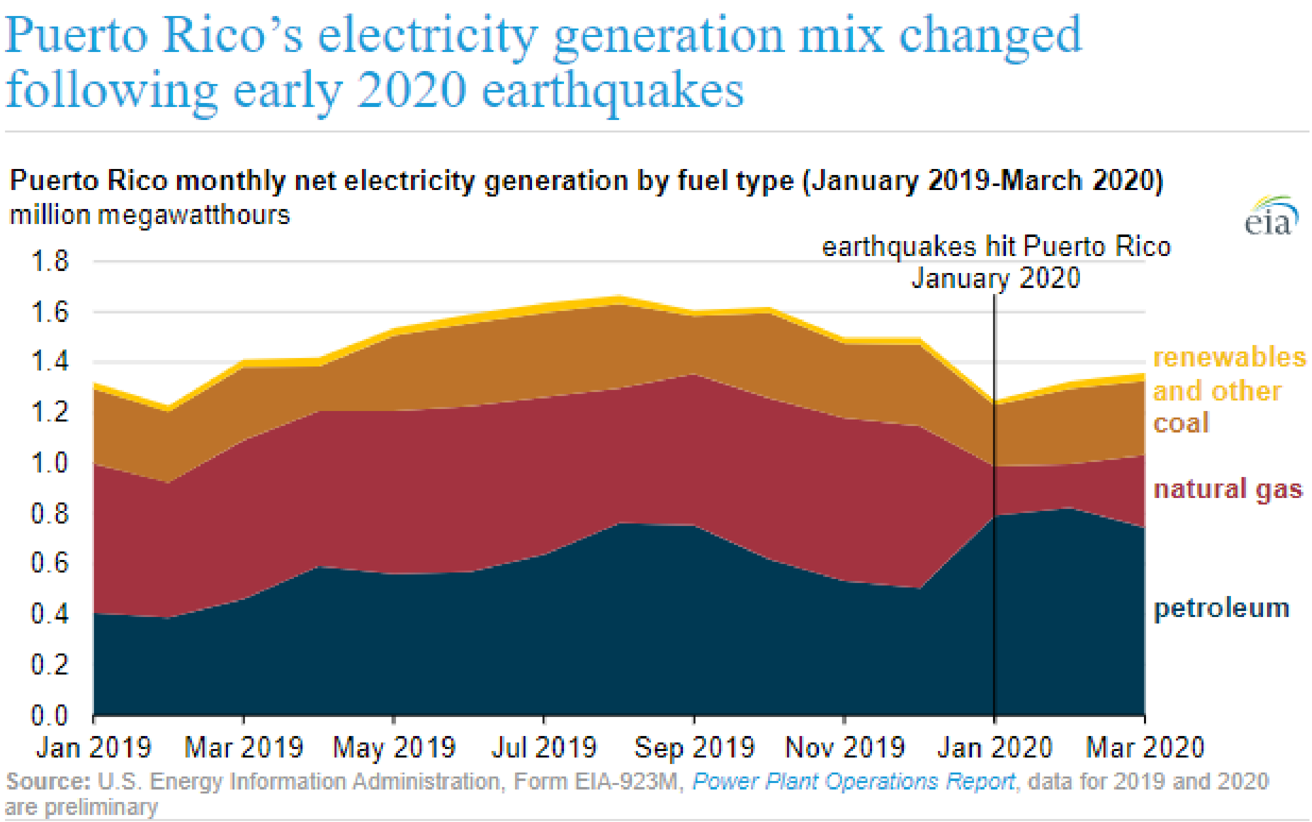
Monthly Puerto Rico net generation by fuel type (Jan 2017-Dec 2018)



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.



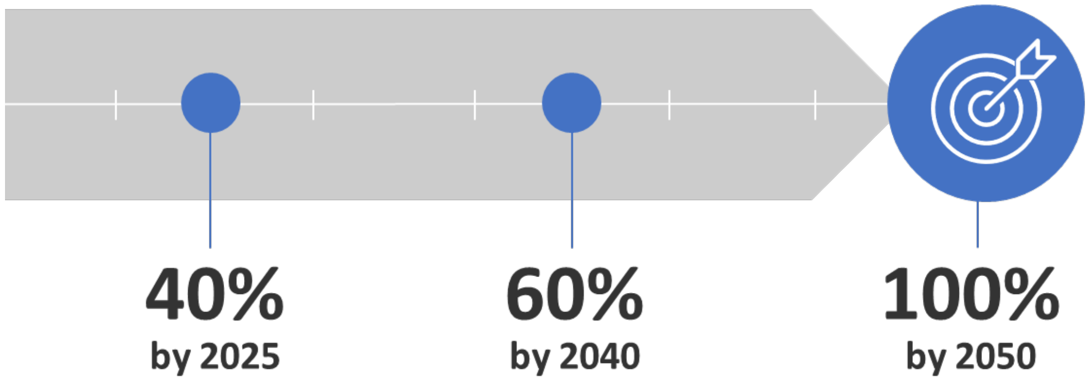
Energy Sector Recovery: Funding Sources

FEMA Hazard Mitigation Grant Program	FEMA Public Assistance	HUD CDBG–Disaster Recovery: Electric Grid	Other HUD CDBG-DR and CDBG-MIT disaster assistance programs
Amount: **$832.5M** Purpose: **Improve the resilience of disaster-damaged or undamaged facilities.** Recipient: **Central Office for Recovery, Reconstruction and Resiliency (COR3)** Subrecipient: **PREPA (and LUMA as an agent)**	Amount: **$9.5B** Purpose: **Restoration and hazard mitigation for disaster-damaged public utilities.** Recipient: **Central Office for Recovery, Reconstruction and Resiliency (COR3)** Subrecipient: **PREPA (and LUMA as an agent)**	Amount: **$1.9B** 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 PR DOH 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 ($300M):** Support resilient design and improvements that incorporate modern technology for life-sustaining purposes. R3 eligible. **Community Energy and Water Resilience Installations ($500M):** Same as above, but from CDBG-MIT with broader eligibility **City Revitalization Program ($1.29B):** 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**

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

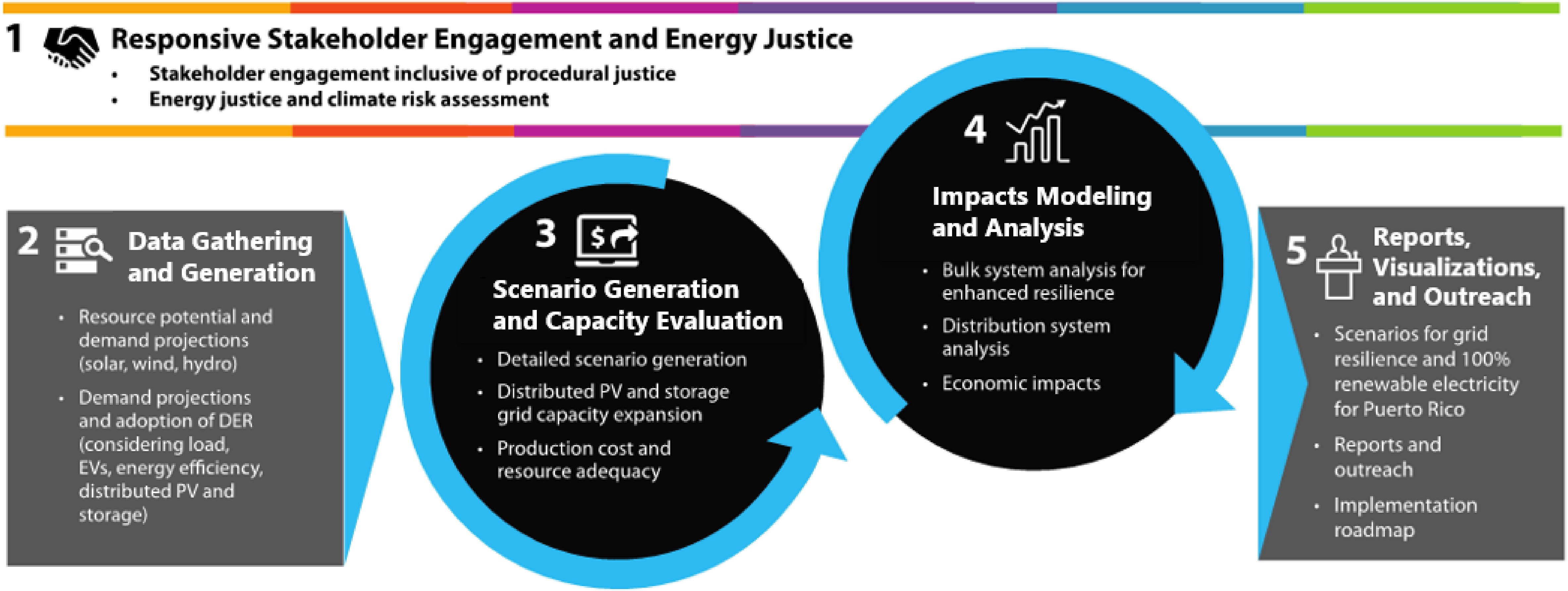
Puerto Rico sets 7th electric rate increase in just a year

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.

Puerto Rico 100% Renewable Energy Study



Graphic by NREL


Photo from iStock

PR100 Seeks To Answer These Complex Questions

- What are the pathways to achieving Puerto Rico’s 100% renewable energy target by 2050?
- Does reaching 100% mean big changes locally—like building new transmission lines?
- If Puerto Ricans adopt energy technologies like electric vehicles (EVs) and expand air-conditioning, how might that change total demand for electricity?
- How can Puerto Rico assure that the new system is reliable during extreme weather events?
- What are the impacts on jobs and the local economy?
- What needs to be done to support an equitable energy transition for all Puerto Ricans?
- What might this all cost?
- And what investments and actions are needed in the near term to enable Puerto Rico’s long-term objectives?

PR100 Scope

In scope

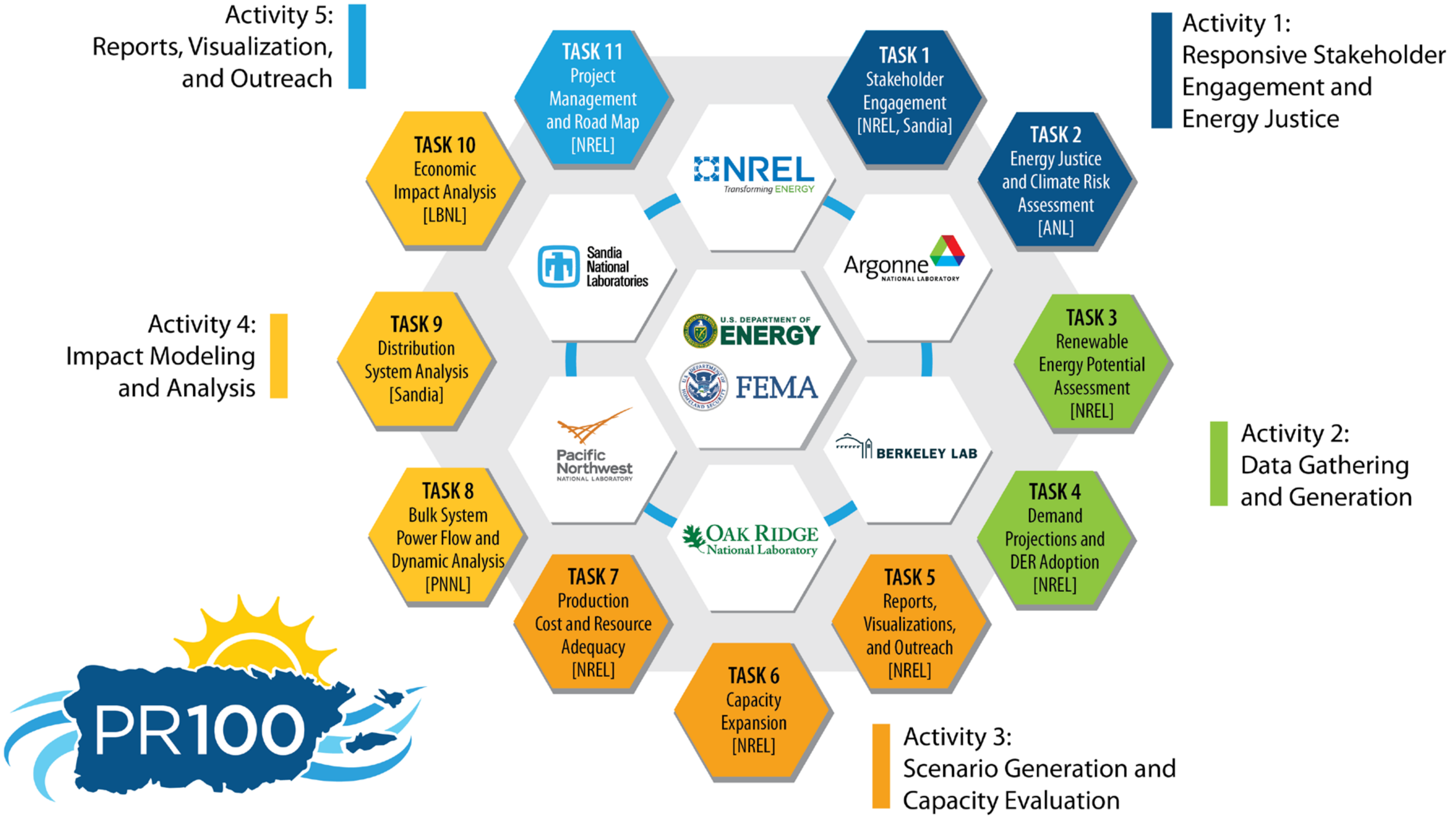
In this study, the project team will:

- 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 (IRP).

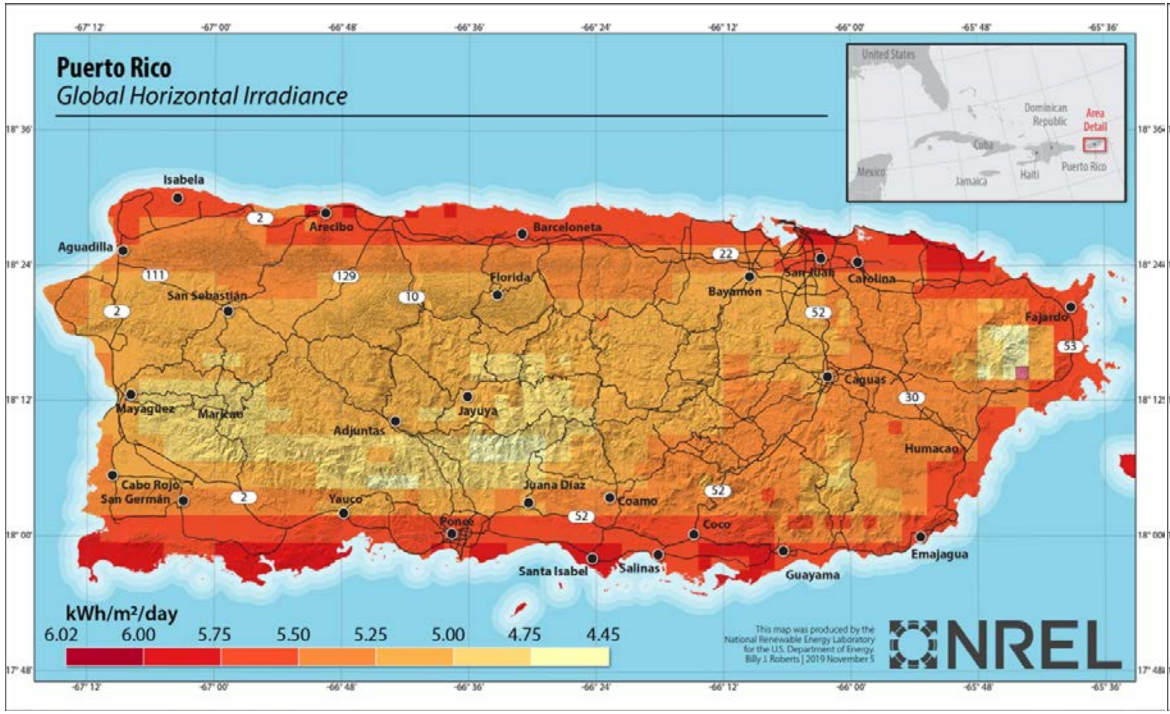

Activity 5: Reports, Visualization, and Outreach
Activity 1: Responsive Stakeholder Engagement and Energy Justice
Activity 4: Impact Modeling and Analysis
Activity 2: Data Gathering and Generation
Activity 3: Scenario Generation and Capacity Evaluation
TASK 11 Project Management and Road Map [NREL]
TASK 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
Argonne NATIONAL LABORATORY
BERKELEY LAB
Oak Ridge National Laboratory
Pacific Northwest NATIONAL LABORATORY
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY
FEMA
PR100

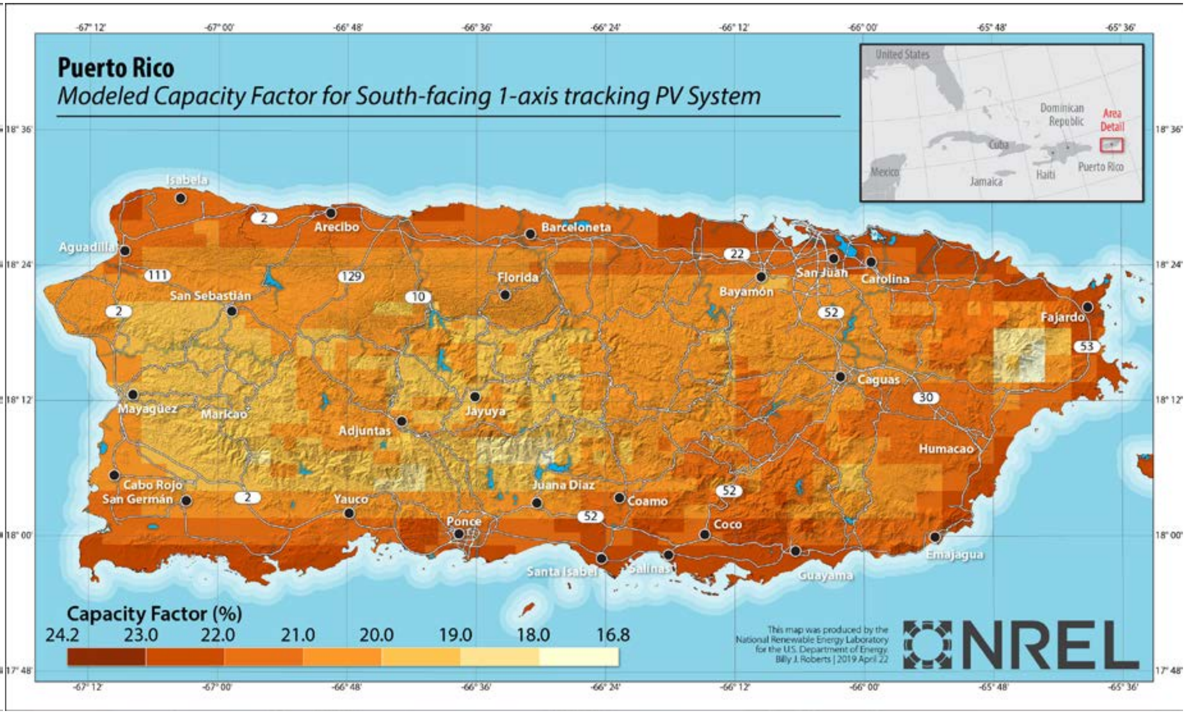
Stakeholder Engagement

- 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.
- Partnered with Hispanic Federation in Puerto Rico for facilitation and stakeholder engagement support.

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

Utility-Scale Solar PV Resource



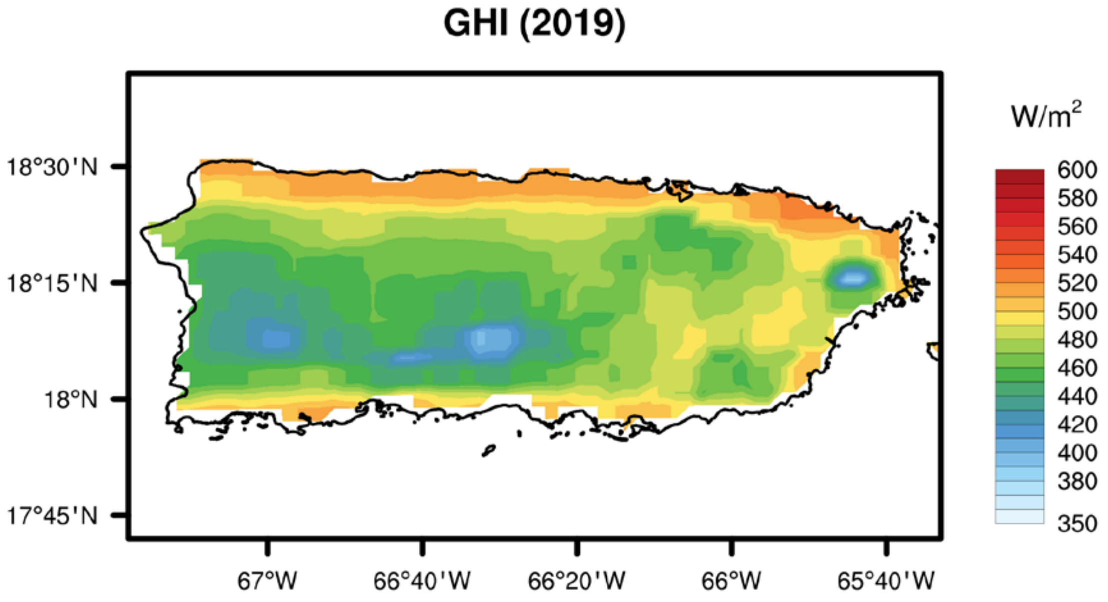


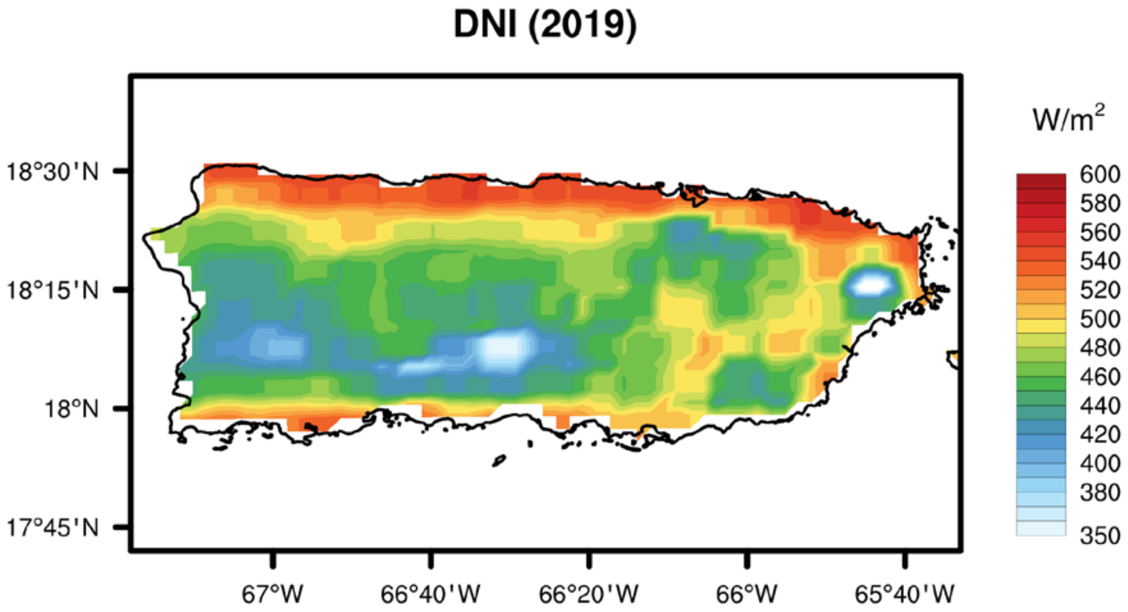
Average daily solar radiation over 20 years show that coastal areas around PR have the highest radiation and are favorable for solar development.

High-capacity factors of 20% and above throughout PR demonstrate the favorability of solar development throughout the island.

Maps: *Grue at al. (2019), Solar Resource and Technical Potential Modeling (NREL Presentation); Grue et al. (2021), Quantifying the Solar Energy Resource for Puerto Rico (NREL Technical Report)*

Solar Resource for Recent Years



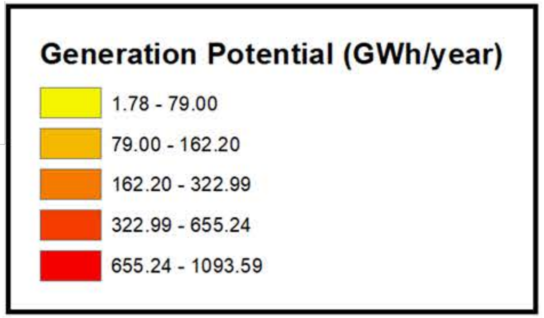


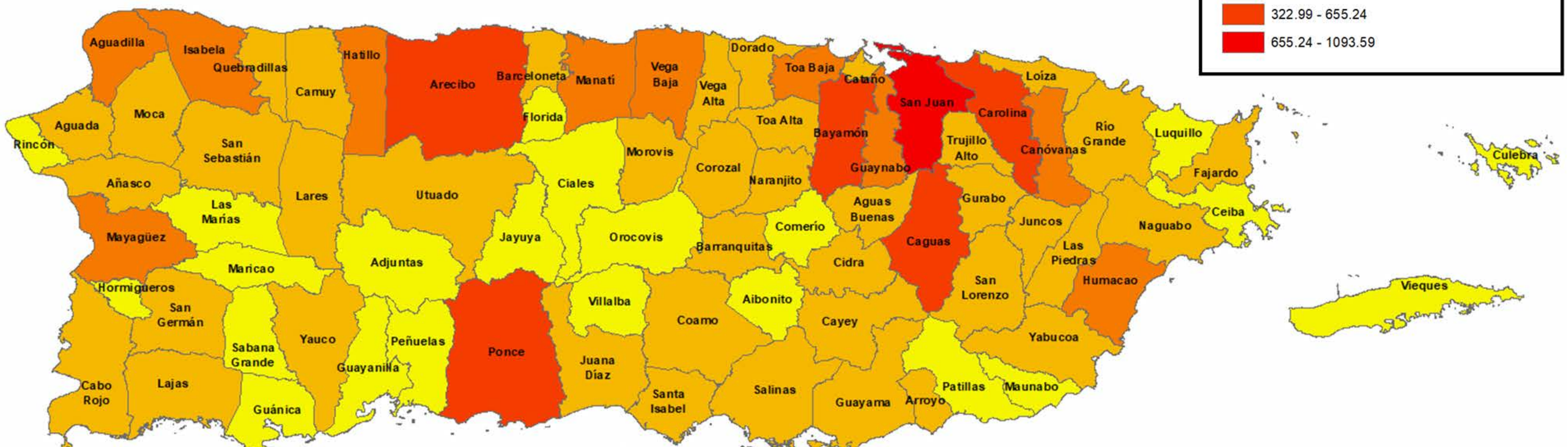
Solar datasets are being added for 2018-2020. Average Global and Direct Solar Radiation for 2019 shows that most of the island including the coastal regions have high solar resource.

Maps from NREL

Residential Rooftop Solar Potential by County

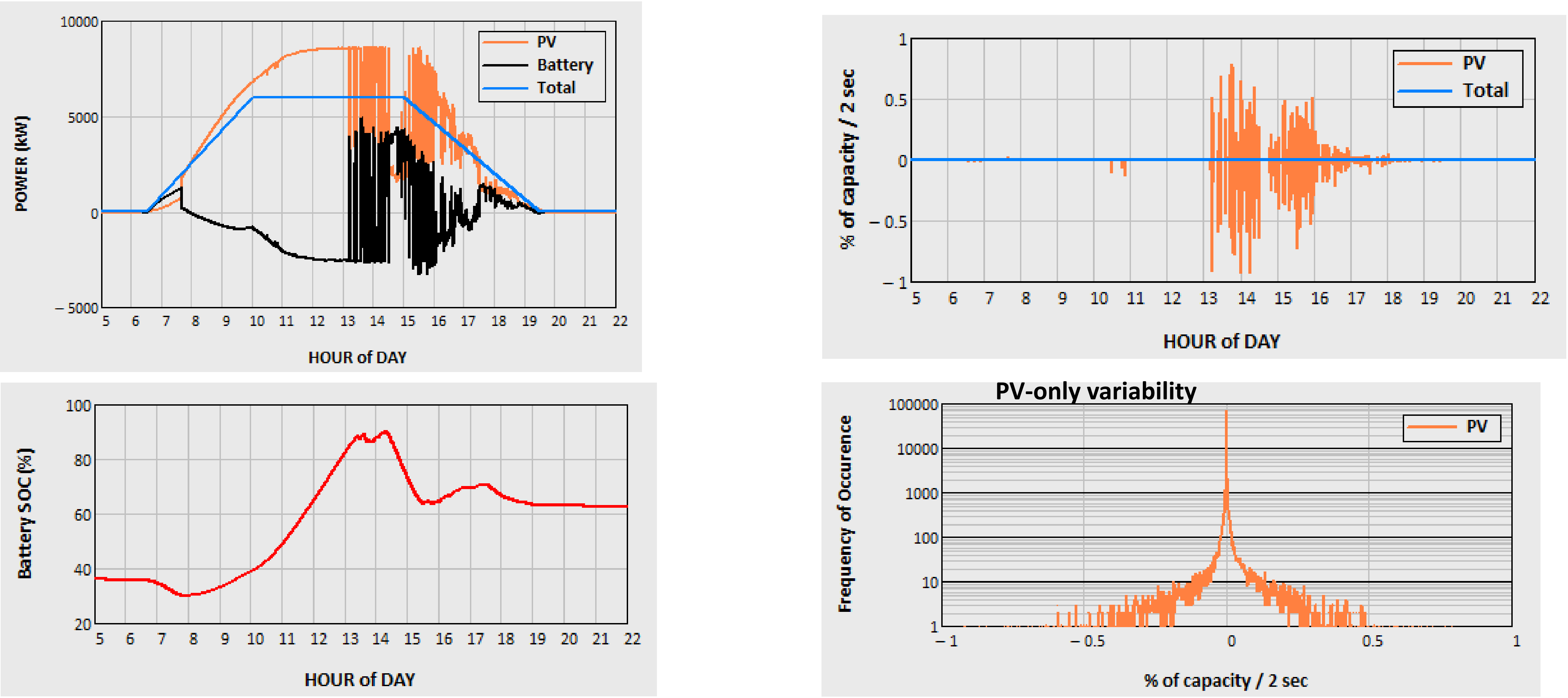
Distributed PV resource exceeds 20 GW of capacity potential —which also exceeds the current generation in Puerto Rico.



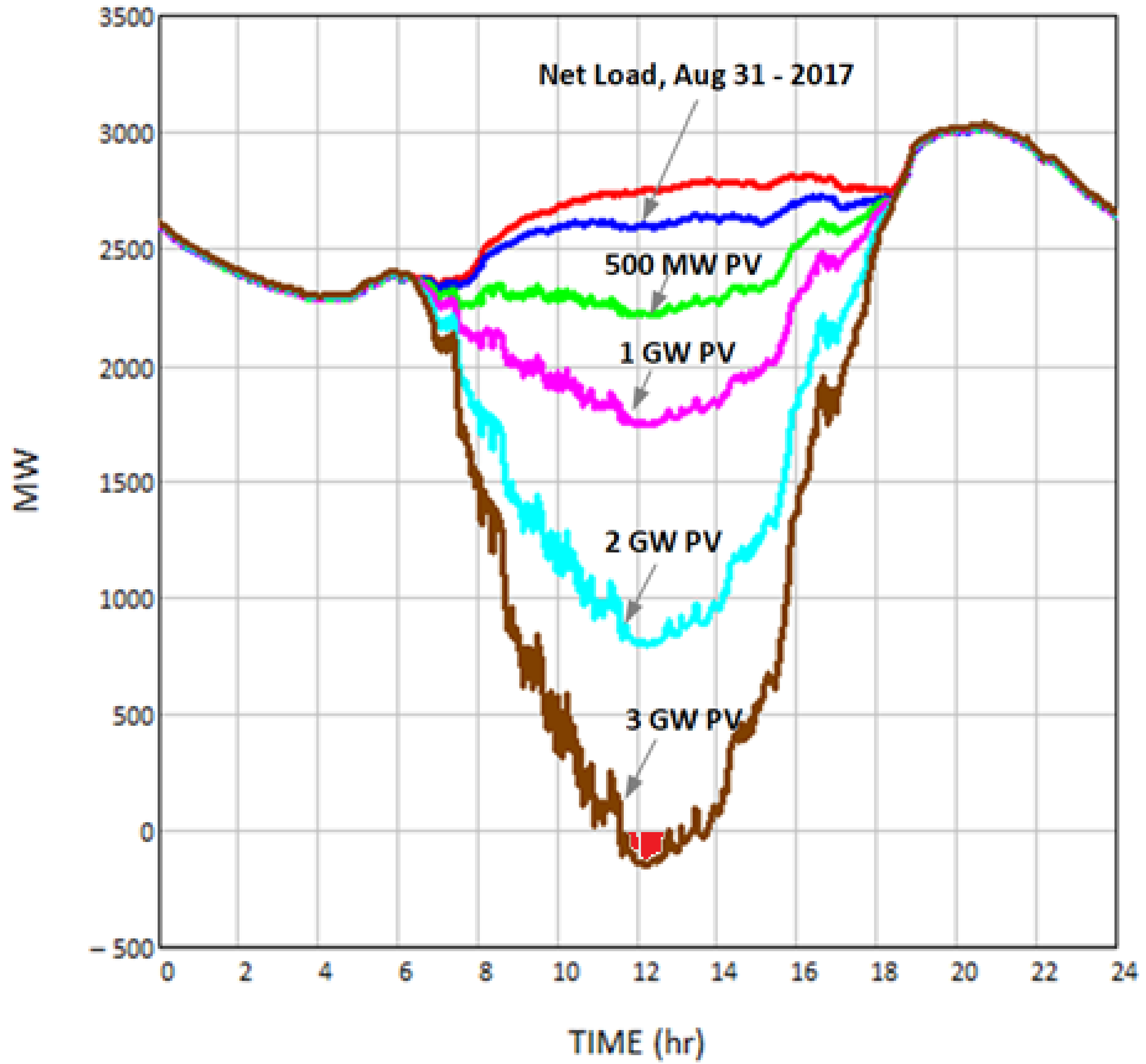


Data Sources: Visualization generated using NREL's Distributed Generation Market Demand (dGenTM) model; Residential rooftop solar PV potential for Puerto Rico from Mooney and Waechter (2020), Puerto Rico Low-to-Moderate Income Rooftop PV and Solar Savings Potential. https://www.nrel.gov/docs/fy21osti/78756.pdf.

PV-storage hybrid operation (flexibility + dispatchability)



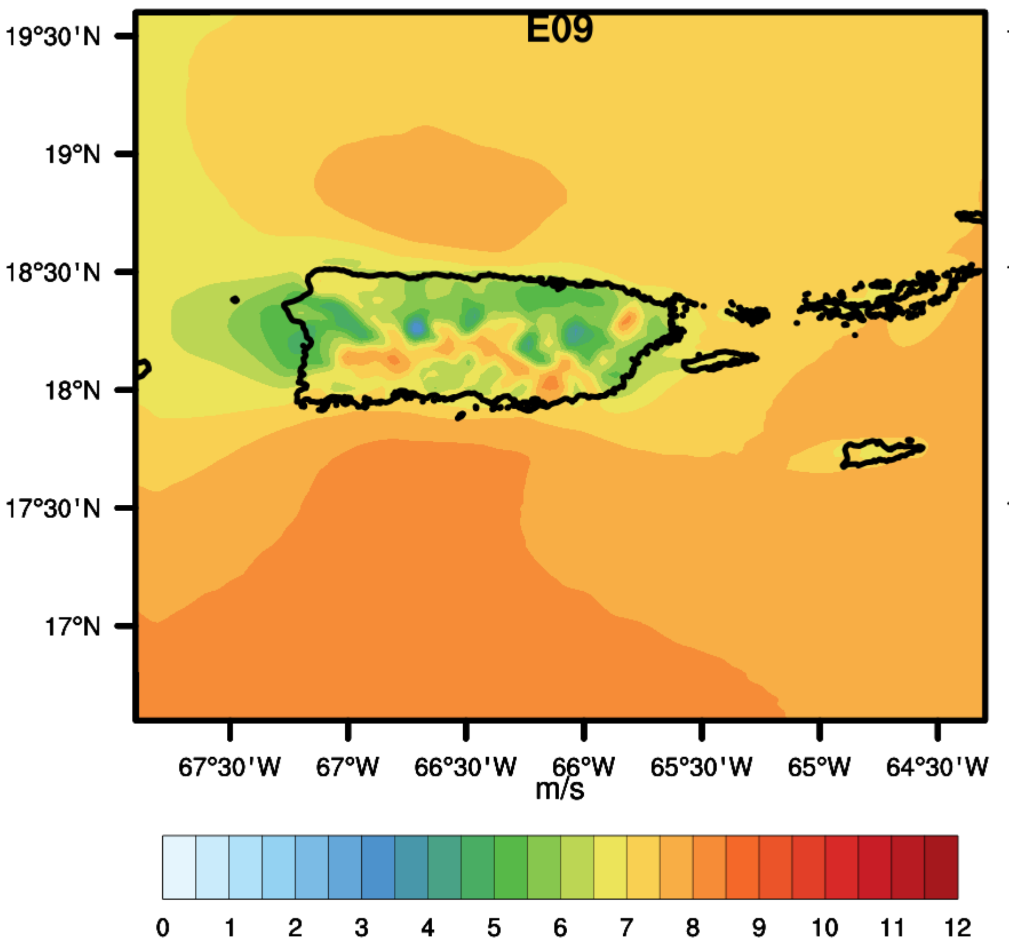
PV-storage plants



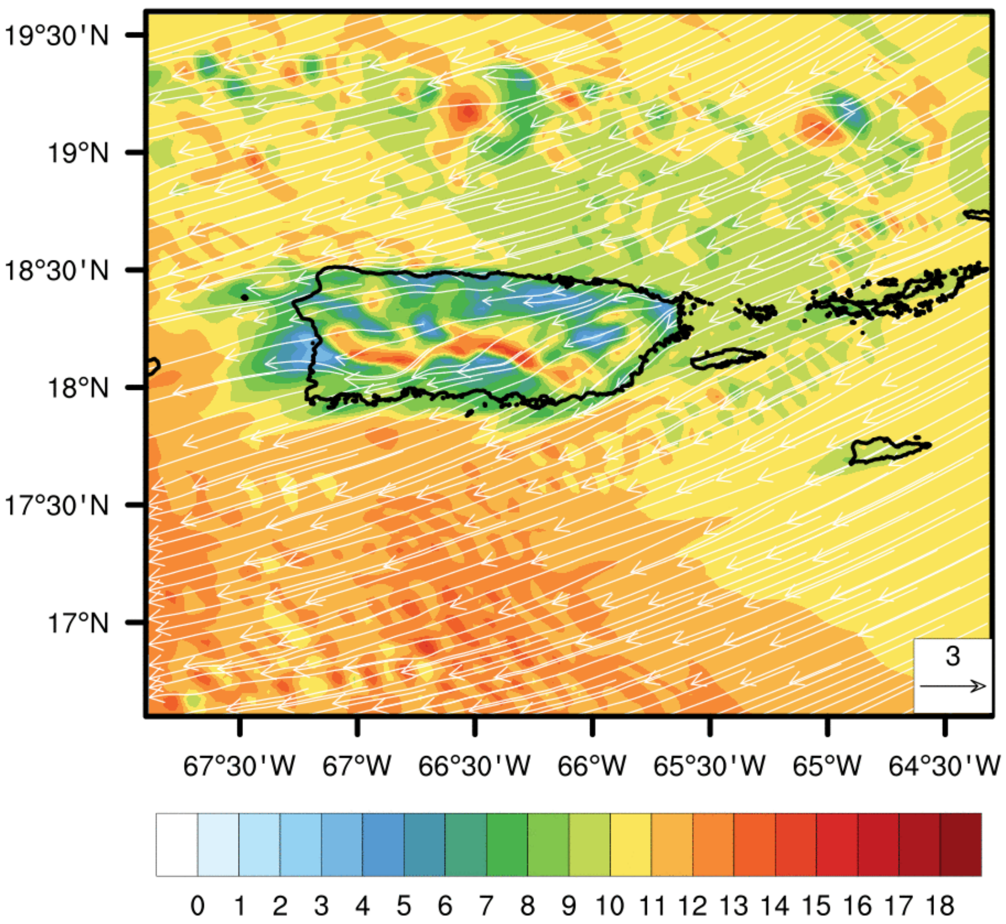
- Provide dispatchability for variable generation in Puerto Rico
- Aggregate ramp limiting, variability smoothing, cloud-impact mitigation on system levels
- Provision of spinning reserves
- AGC functionality
- Renewables forecast error correction services
- Primary frequency response (programmable droop control)
- Fast frequency response (FFR)
- Inertial response:
  - programmable synthetic inertia for a wide range of H constants emulated by BESS
- Reactive power/voltage/power factor control
- Advanced controls: ability of the plant to modulate its output for provision of power system oscillations damping, wide-area stability services
- Stacked services

Wind Resource Assessment

2019: 1-yr averaged wind speed@80m



Wind speed at 80m (m/s, 2019-01-01T00:00:00)

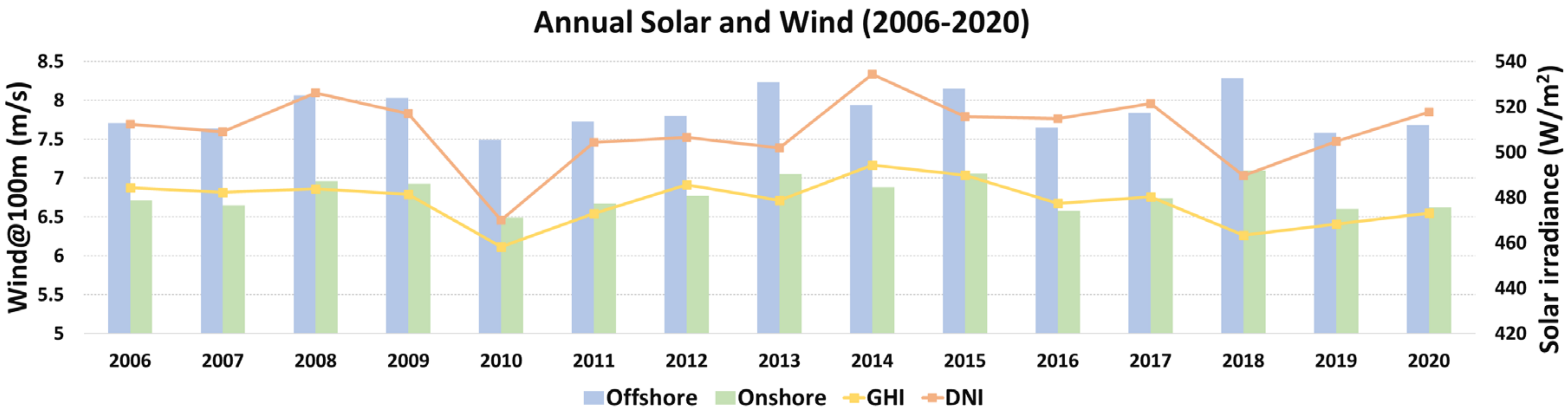


20 years of high-resolution offshore and onshore wind data was developed.

Map from NREL

Annual Wind and Solar Resource Comparison

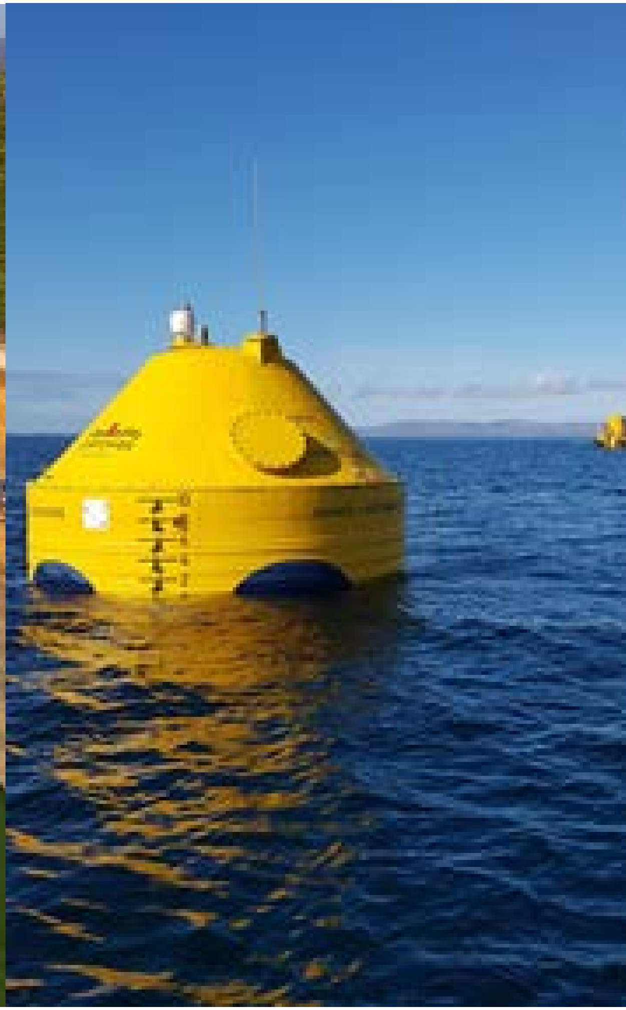
Averaged all grid points over PR domain



- Annual solar and wind resources and their variability were analyzed using NSRDB and NWP-based datasets for Puerto Rico (standard deviation for 15 of the 20 years- Offshore: 0.24m/s, Onshore: 0.19m/s, GHI: 9.41W/m^2, DNI: 14.92W/m^2).
- The year of 2018 shows the most abundant wind resource, and the sunniest year was 2014.
- The year of 2010 exhibits the lowest wind/solar resources compared to the other years.
- As expected, offshore includes more wind resources compared to onshore.

Graphic from NREL

Other Generation Options



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).

Demand Response Applications & Considerations

Motivation for Demand Response in Puerto Rico

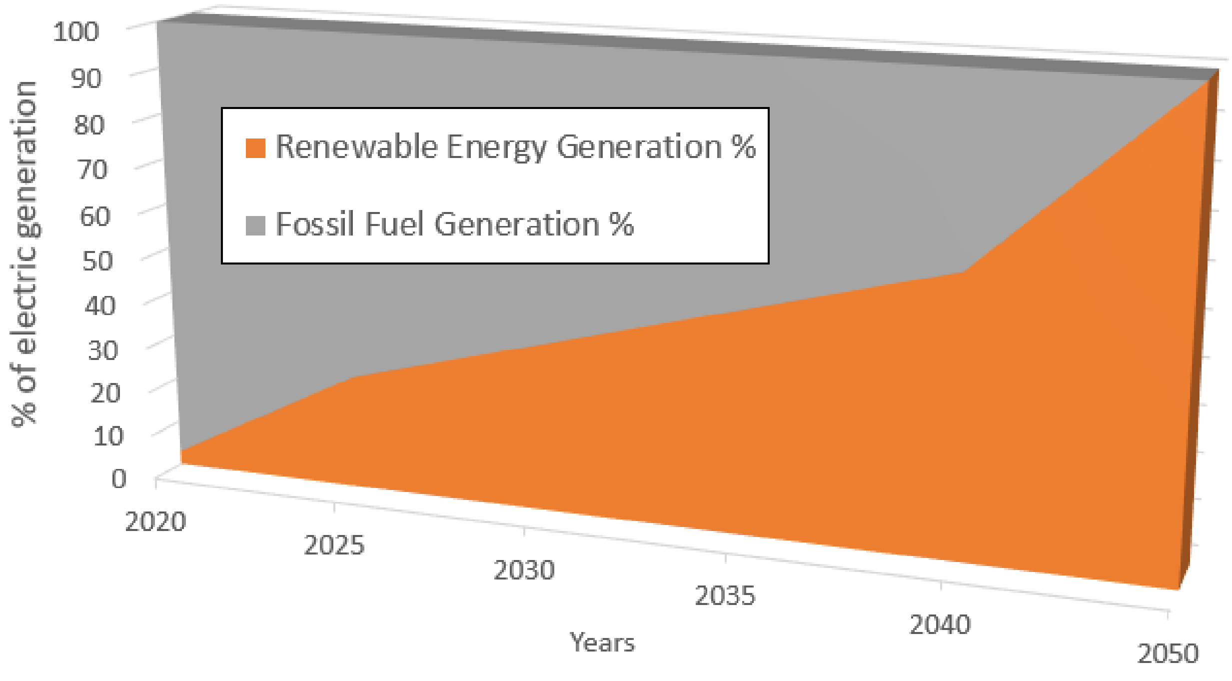
- DR reduces peak generation needs and can shift load to times of high VRE generation. This decreases Puerto Rico's reliance on fuel imports and accelerates the retirement of fossil-fuel peaker plants to meet PR goals.
- DR reduces customer electricity consumption and/or shifts consumption to times of lower rates, resulting in lower electricity costs. DR programs can also have financial incentives for participating ratepayers.
- DR increases load flexibility and helps grid operators more efficiently match the supply of VRE (e.g., solar PV and wind turbines) to demand at each hour of the day in order to achieve Puerto Rico's 100% RPS goal by 2050.
- DR contributes to system resilience and reliability by giving system operators more flexibility to match demand with supply on a regular basis and conduct more targeted load shedding on an emergency basis.

Demand Impacts

- ↔ The electric usage on the island from estimates in the 2019 IRP.
- ↓ 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.

Scenario Modeling: What Is a Scenario?

A scenario is a possible pathway toward a clean energy future driven by a set of inputs.



Variable Scenario Inputs (examples):

Energy Demand

How will demand for electricity change over time?

- Economic inputs
- Expected energy efficiency and EV adoption
- Value of backup power

Energy Supply

How will demand be met with 100% renewable energy?

- Distributed solar and storage
- Large scale solar, wind, etc.
- Public Policy (like Act 17)
- Resiliency requirements
- Transmission cost

Initial Scenarios Definition in PR100

- The project team worked closely with the Advisory Group during the first six months of the study to define four initial scenario frameworks to model.
- The primary distinction between the four scenarios is varying levels of distributed PV and storage.
- Variations of load and land use, described in the following slides, will also be applied to select scenarios.

“Bookend” Scenario Concept

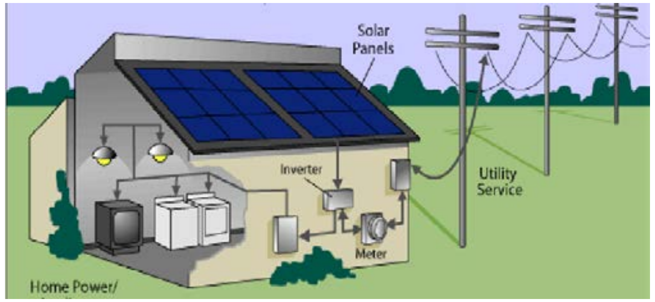
Scenario 1 is based on economic deployment only of distributed solar and storage

Scenario 4 is the most decentralized scenario.

Scenarios / Inputs	Scenario 1: Highest level of utility-scale generation	Scenario 2: Critical services are resilient	Scenario 3: Incentives for self-reliance for remote/LMI communities	Scenario 4: Maximum rooftop scenario
Distributed PV+storage deployment	Cost-effective deployment only for residential, commerical and industrial customers	Scenario 1 level PLUS mandated systems for all key community services facilities (hospital, police, utilities, community center, grocery, streetlights)	Scenario 1 + 2 PLUS mandated for buildings in LMI (low moderate income) and remote communities	Scenario 1,2 and 3 PLUS Mandate deployment on all viable buildings
	Anticipated Impacts			
Land use (Note: Exclusion areas included in all scenarios)	Most land use (utility PV and wind)	Middle Ground: Land usage for utility-scale plants would be between Scenario 1 and 4	Middle Ground: Land usage for utility-scale plants would be between Scenario 1 and 4	Minimal land use with maximum rooftop deployment
Total Electric System Costs (NOT retail rates)	LOWEST Cost (with only economic optimum deployment)	Middle Ground: Less costly than Scenario 4 and more than Scenario 1	Middle Ground: Less costly than Scenario 4 and more than Scenario 1	Likely HIGHEST cost (rooftop PV and batteries typically 3x cost of utility PV and batteries)
Resilience to normal grid operations	Adequate contingency, capacity and reserves to handle normal operations	Same as Scenario 1	Same as Scenario 1	Same as Scenario 1
Resilience to extreme events	LOWEST local resilience (but more than current grid)	Service faclities resilient but not individual houses.	Remote and LMI communities (like to be restored last) will be resilient.	Most resilient to extreme events at the building level.
Jobs	FEWEST jobs during construction and operations.	Middle Ground: More than Scenario 1 and likely fewer than Scenario 4	Middle Ground: More than Scenario 1 and likely fewer than Scenario 4	Likely more jobs with thousands of rooftop systems.

Setting the Bookends

Key Lever: Amount of Rooftop PV + storage



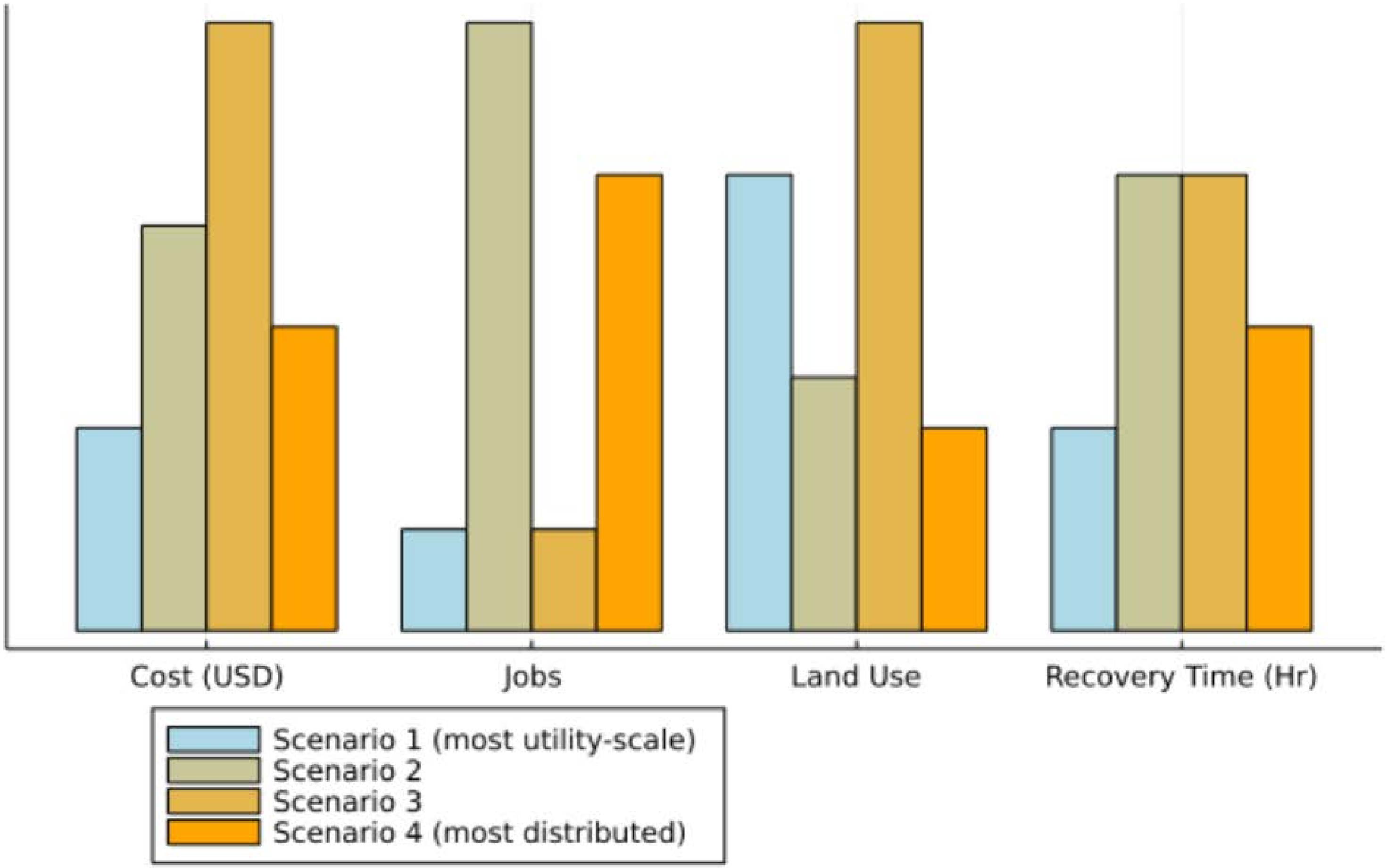
Middle Ground: Assume key rooftops used (remote, LMI, critical, and/or other)

Reference adoption (which could be significant)

<u>Assume</u> all available rooftops

Hypothetical Implications: Output Examples

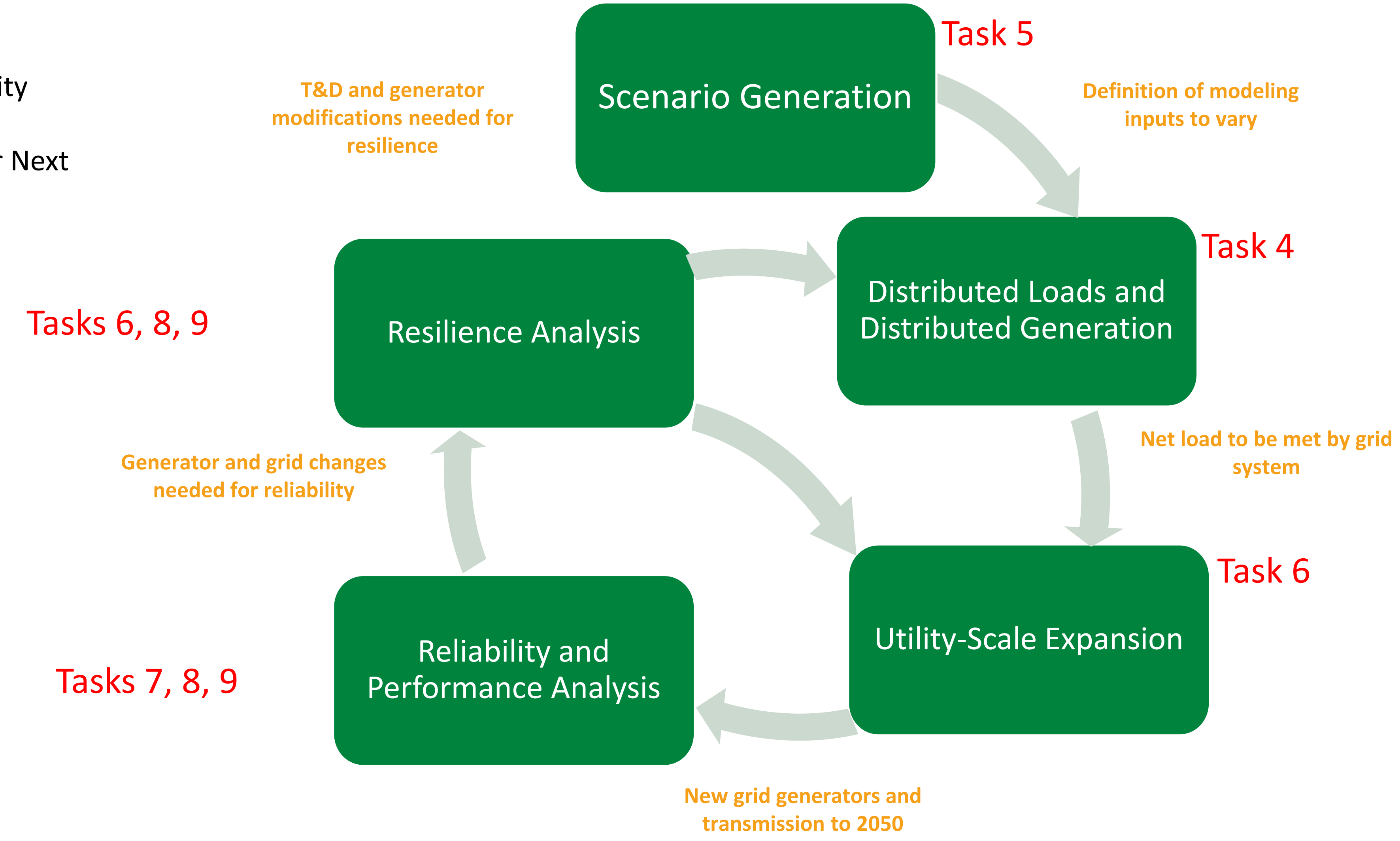
Note: For illustrative purposes only. Chart not based on real data or analysis



Reliability and Resilience Modeling

Legend

- **Green Box** = Modeling Activity
- **Red Text** = Associated Tasks
- **Yellow Text** = Key Output for Next Modeling Activity



Engage Capacity Expansion Modeling

Existing System Representation
The baseline system (system as it exists today and as planned in the near term)

Future System Technology Options
Technologies the model can build to meet projected demand

Technologies
Generators: thermal generators, renewable energy, fuel production
Transmission: electric lines, fuel pipelines & transport, water lines and flows
Storage: fuel storage, batteries, pumped storage, water storage

Technology Attributes
Existing and maximum and minimum production and storage capacities, efficiencies, renewable resource potential, fuel mix requirements, externalities, costs

Additional Constraints
- Spatial/land-use constraints
- Renewable portfolio requirements
- Other emissions/externalities constraints
- Resilience requirements

engage
Generation and Transmission Capacity Planning via Constrained Economic Optimization

Demand and End-use Projections / Value Streams
- Electricity demand & value
- Heating demand & value
- Cooling demand & value
- Fuel demand & value
- Water demand/uses & value
- Other demands & values

Least-cost system that meets the load respecting all constraints

Optimized assets
Generation, transmission, and storage capacities

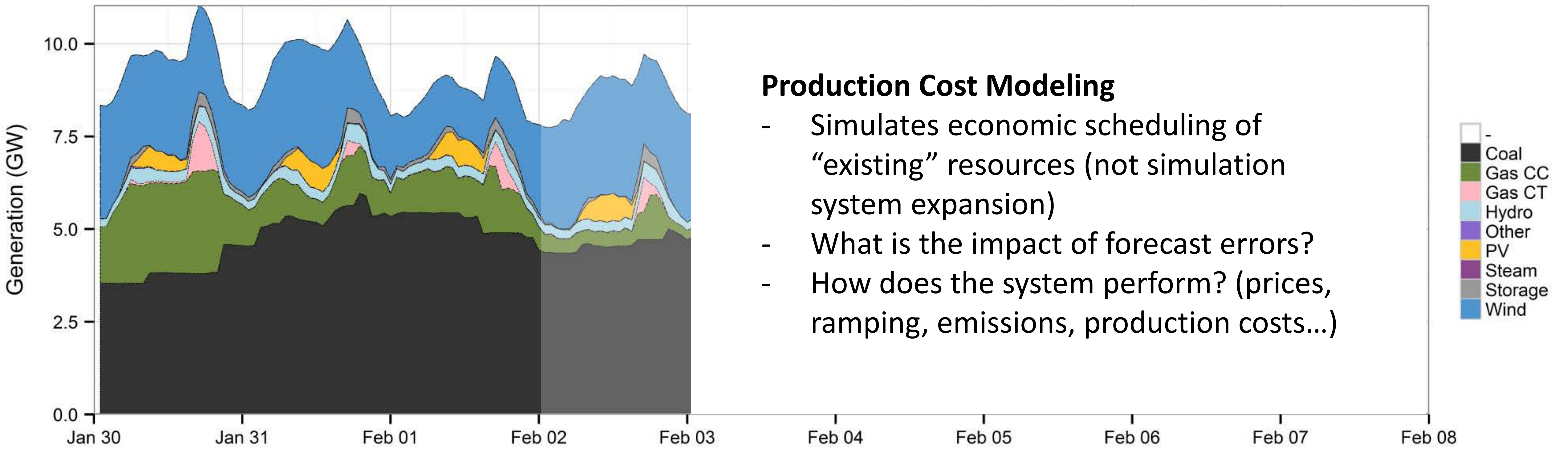
Resulting costs
- Investment (capital) costs
- Fixed and variable operating costs
- Levelized cost of energy (LCOE) for each carrier in the system

Other
- LCOE for each carrier
- Production, consumption, and export profiles
- Surface area (land, maritime) use
- Externalities: resources used, emissions, etc.

Production Cost and Resource Adequacy Modeling

Resource Adequacy

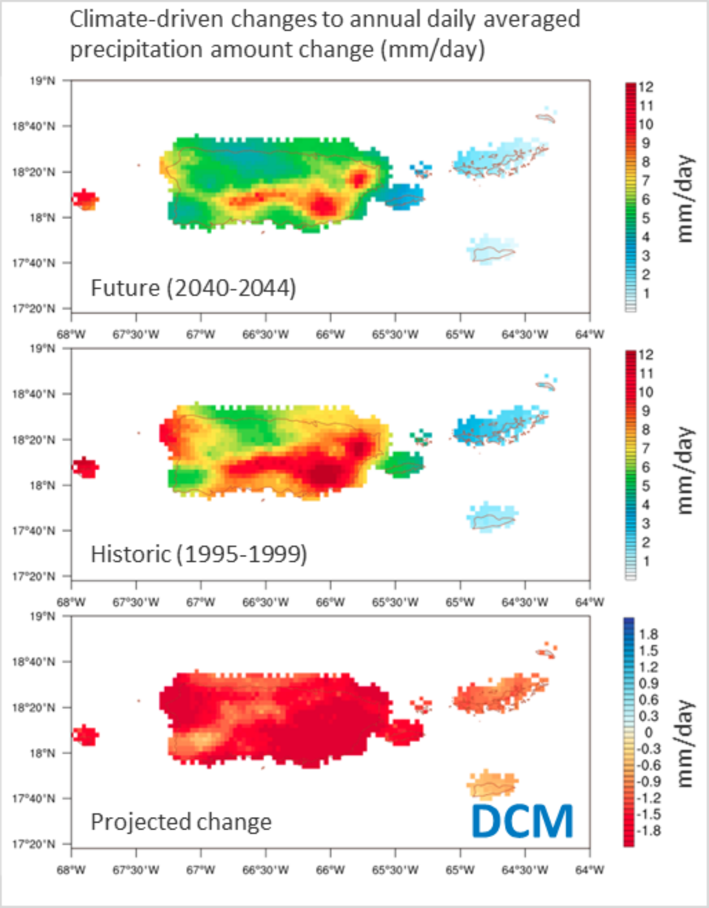
- Calculates the likelihood that a given system will be sufficient to meet demand
- Considers component outage rates, and the coincidence of renewable generator availability and demand time series
- Simplified representation of transmission (by region) and generator commitment/dispatch



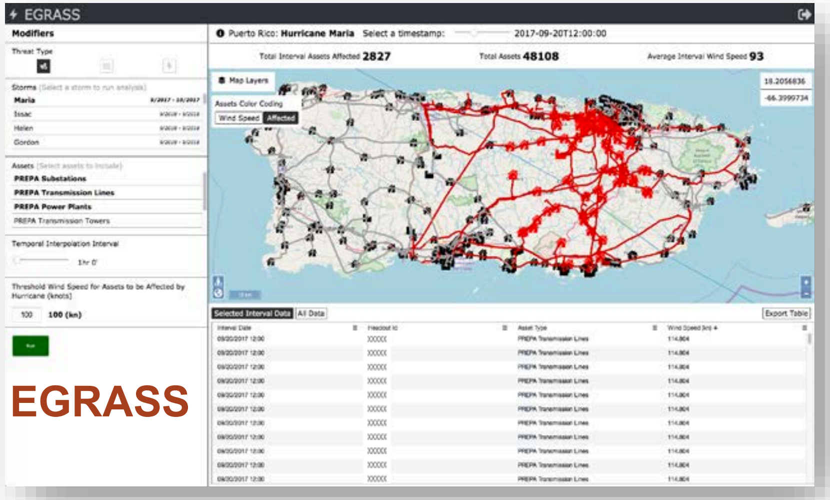
Production Cost Modeling

- Simulates economic scheduling of “existing” resources (not simulation system expansion)
- What is the impact of forecast errors?
- How does the system perform? (prices, ramping, emissions, production costs…)

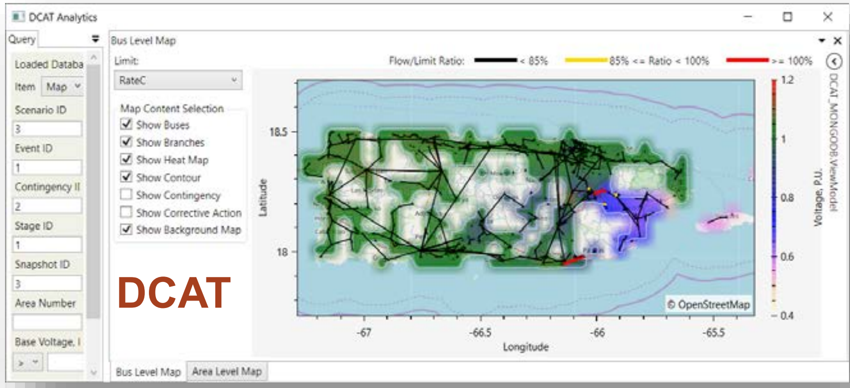
Impact Analysis: Weather to Grid Consequences Transmission & Distribution & Community Resilience Analysis



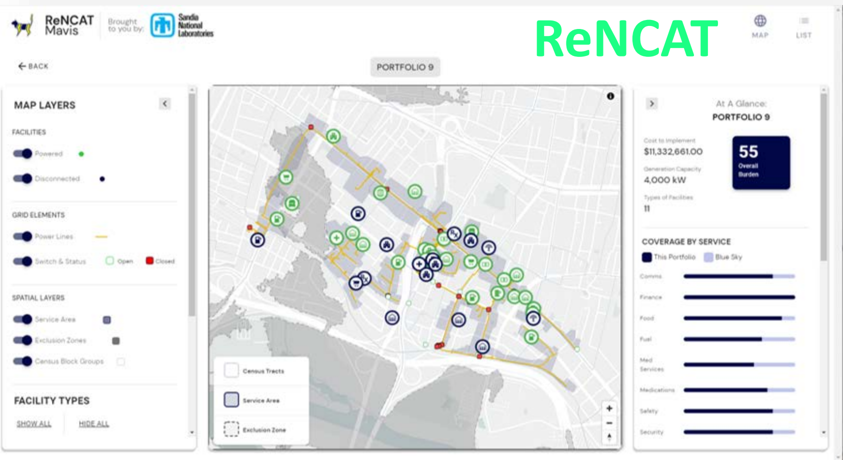
Downscaled climate model



Asset's failure models



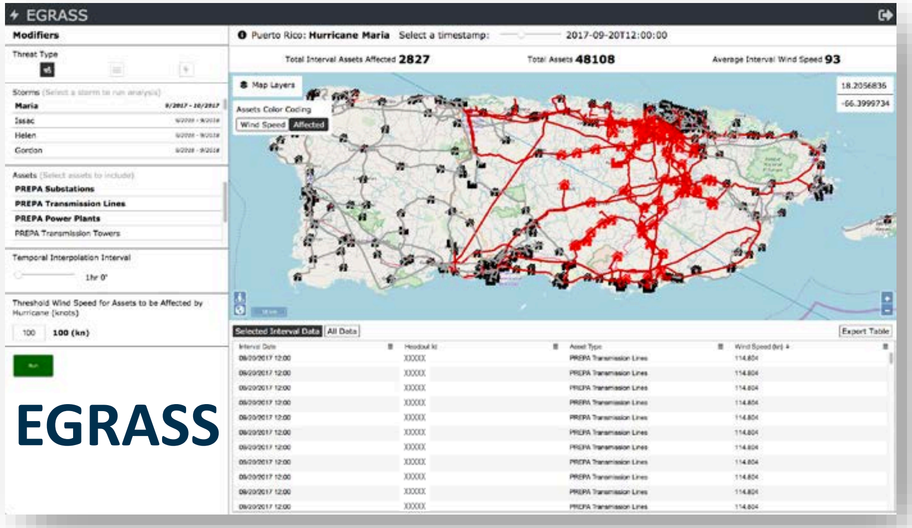
Transmission resilience



Distribution resilience

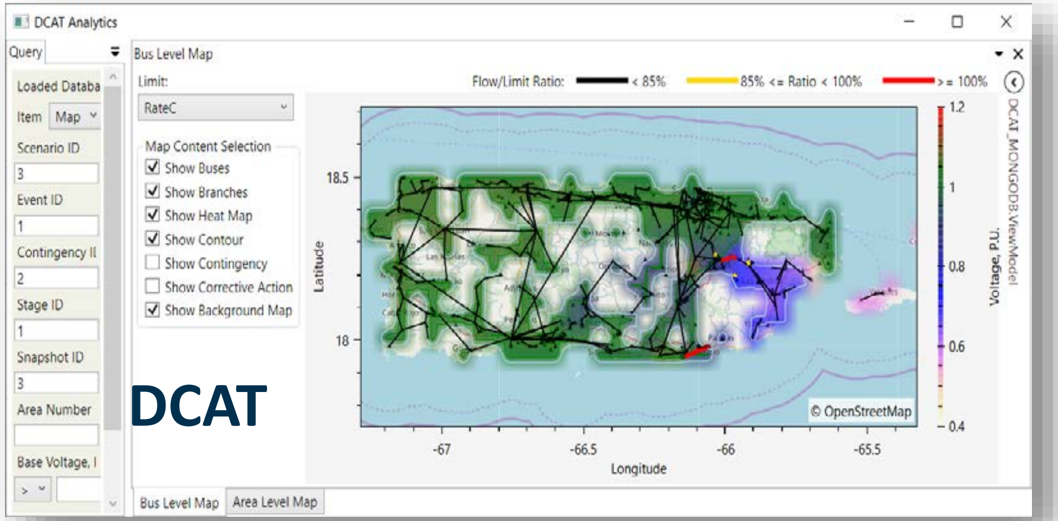
Transmission Resilience Analysis

National hurricane center data



Electrical Grid Resilience and Assessment System (EGRASS)

- Infrastructure probability of failure
- Monte Carlo generation of N-k sequences



Dynamic Contingency Analysis Tool (DCAT)

- Dynamic cascading failure analysis
- Vulnerability with multiple N-k sequences

- EGRASS-DCAT used for Puerto Rico
  - Resilience evaluation of new generation scenarios
  - Scenarios comparing underground versus overhead transmission resilience
- DCAT applied to Texas, Western and Eastern Interconnections

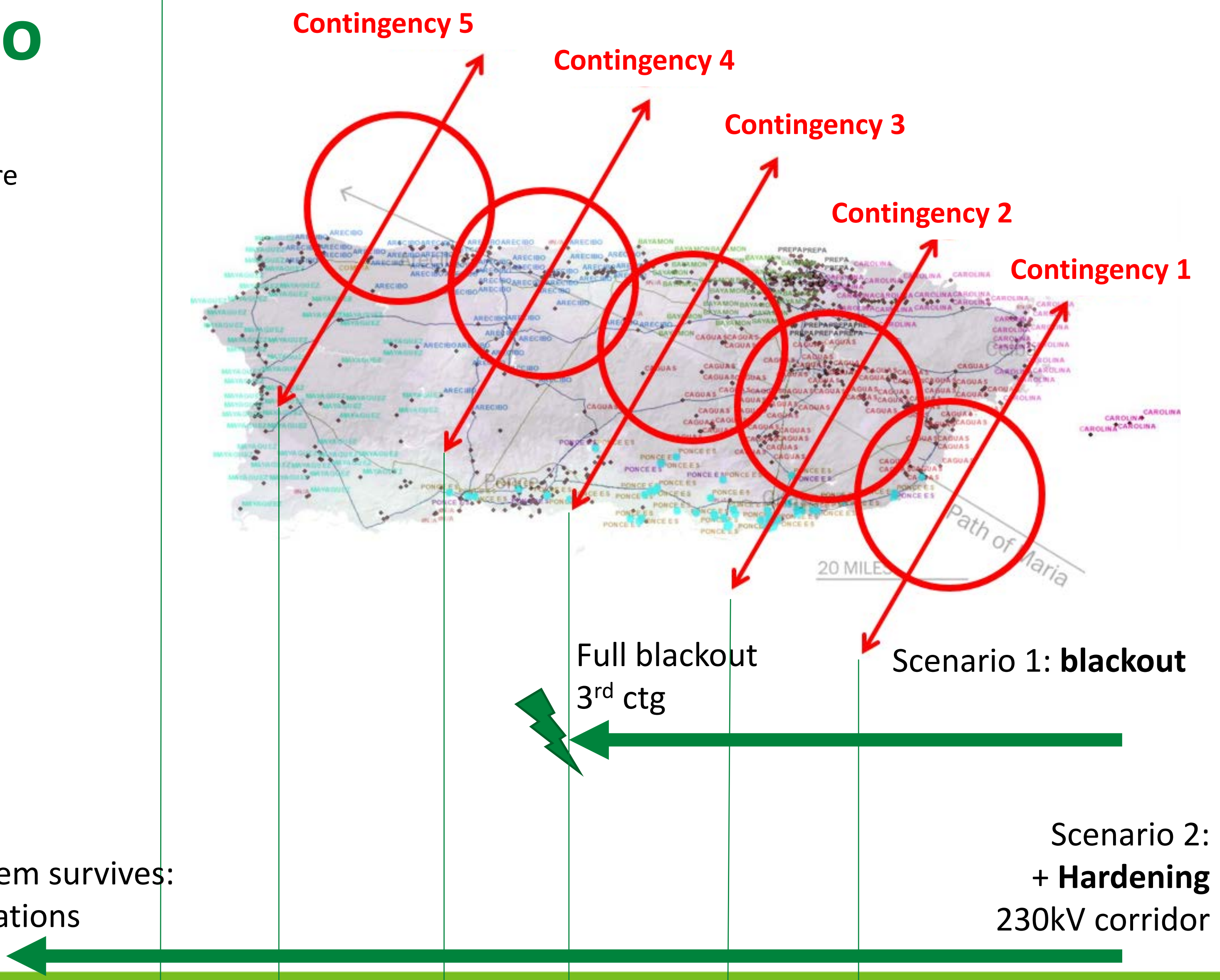
DCAT Application to Puerto Rico

- Large amount of results data
  - 78,000+ contingencies on component failure analysis
  - Hurricane scenarios – time sequence of contingencies
- Deriving recommendations
  - Priority transmission assets
  - Transmission hardening
  - Protection coordination
  - Voltage support
  - Preventive operational actions
  - High solar scenarios

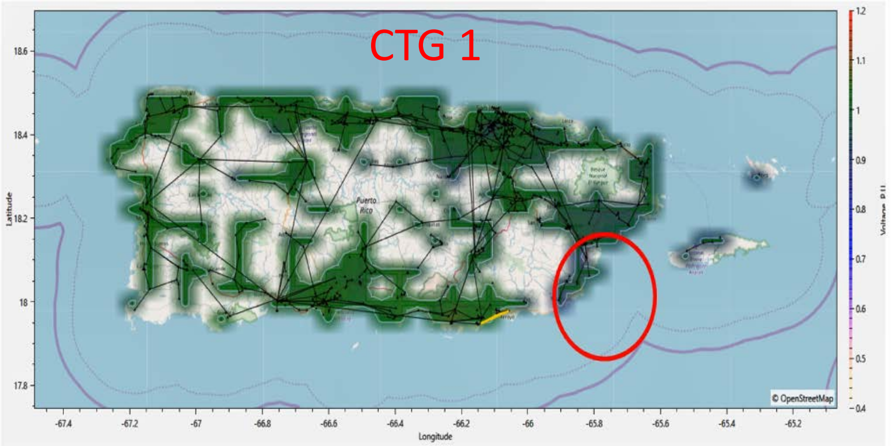
Developing DCAT capabilities for efficient planning and operation for upcoming hurricanes

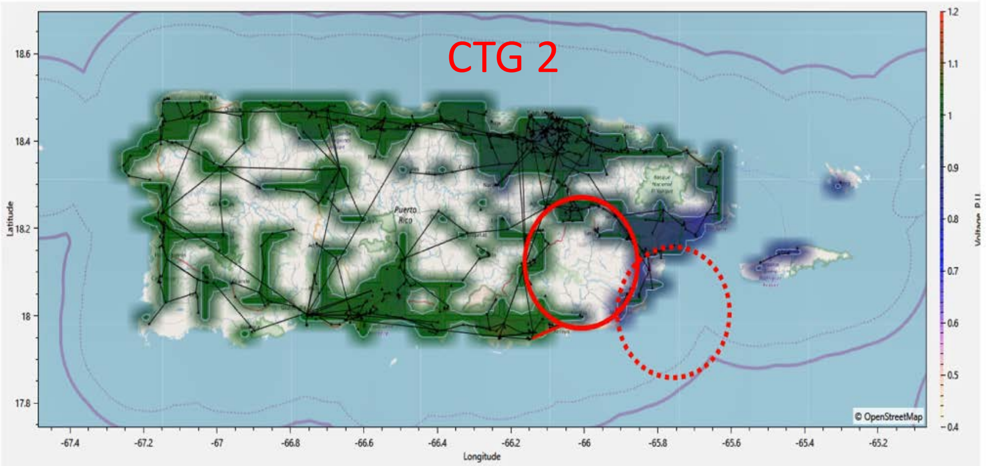
M Elizondo, X Fan, S Davis, B Vyakaranam, E Barrett, S Newman, P Royer, P Etingov, A Tbaileh, H Wang, U Agrawal, W Du, P Weidert, D Lewis, T Franklin, N Samaan, YV Makarov, J Dagle. *Risk-Based Dynamic Contingency Analysis Applied to Puerto Rico Electric Infrastructure*. PNNL-29985. Richland, WA, Pacific Northwest National Laboratory, May 2020 - https://www.osti.gov/biblio/1771798

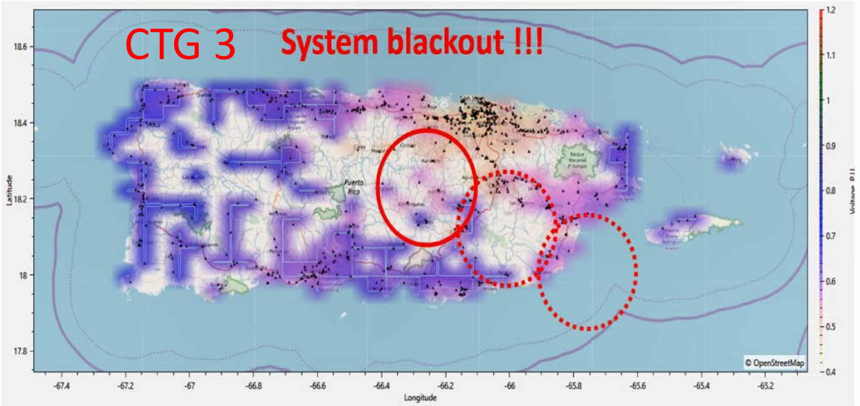
Illustrative Example
(Not actual Maria)



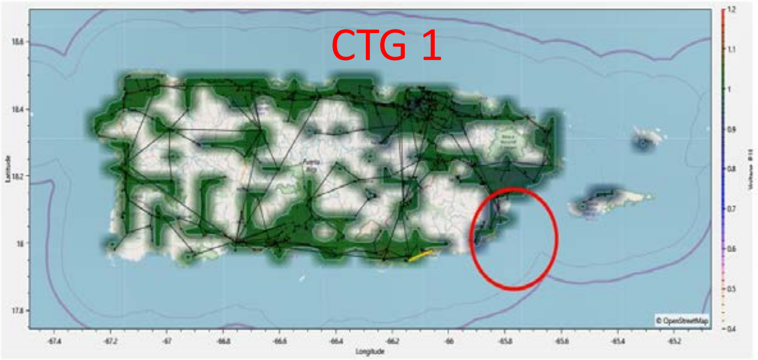
Puerto Rico Illustrative Example:
Scenario 1 – No Hardening nor Corrective Actions

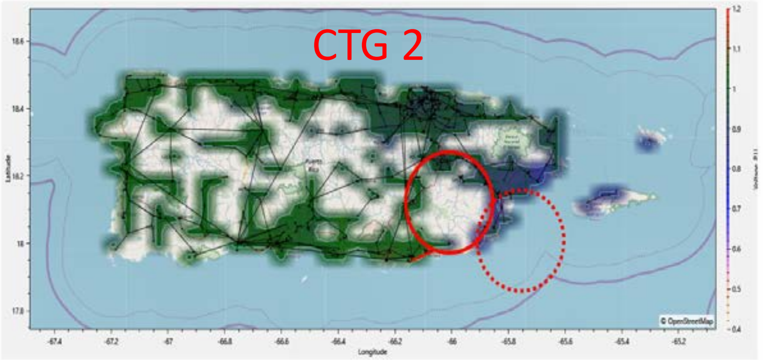


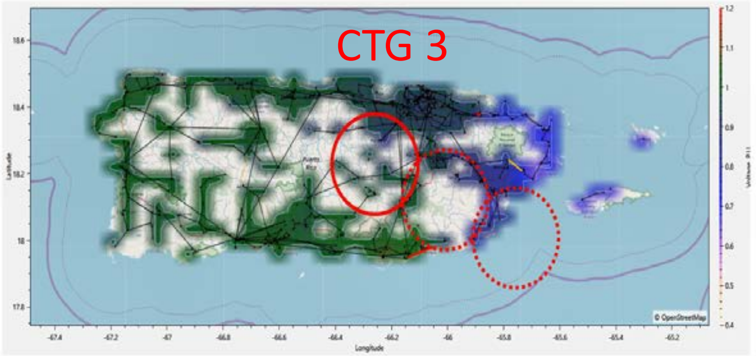


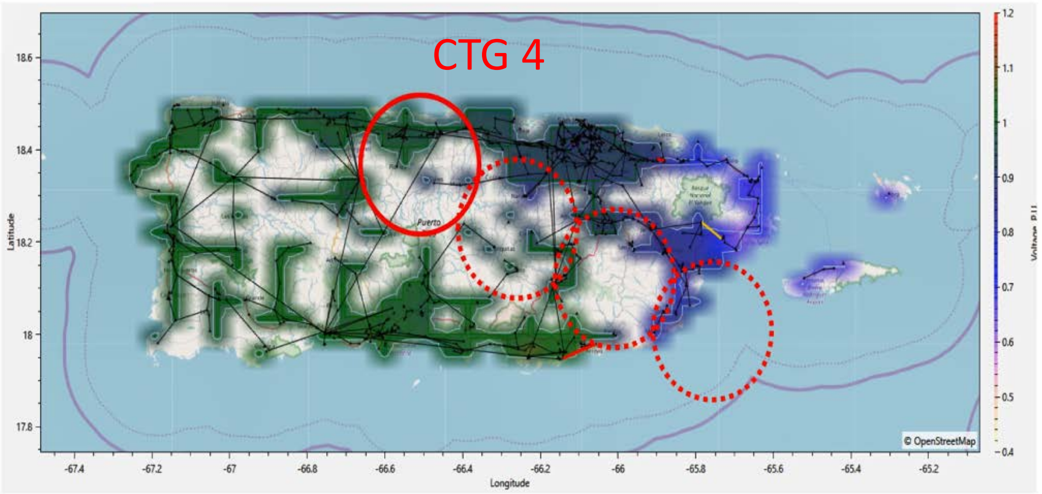


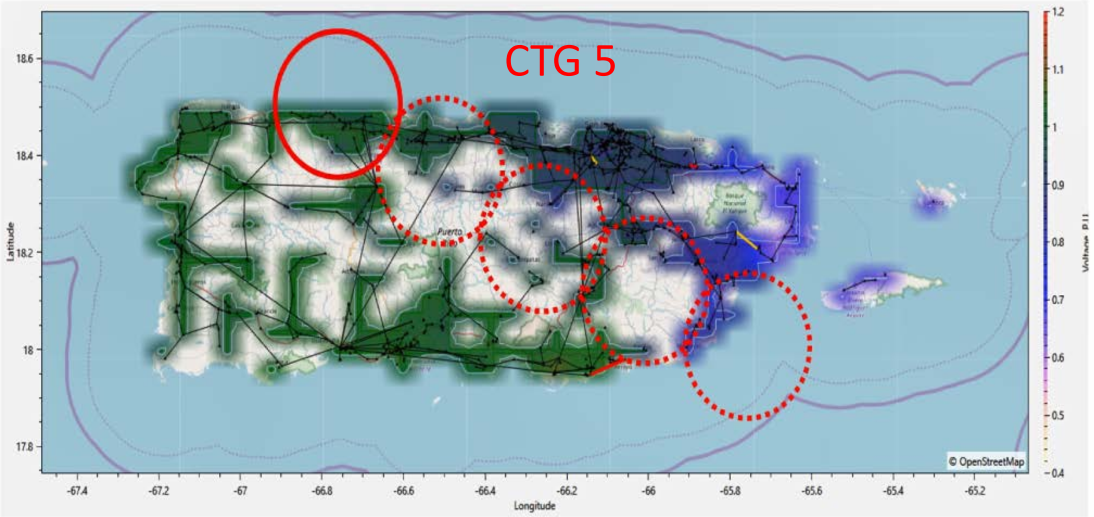
Puerto Rico Illustrative Example: Scenario 2 – Hardening Only





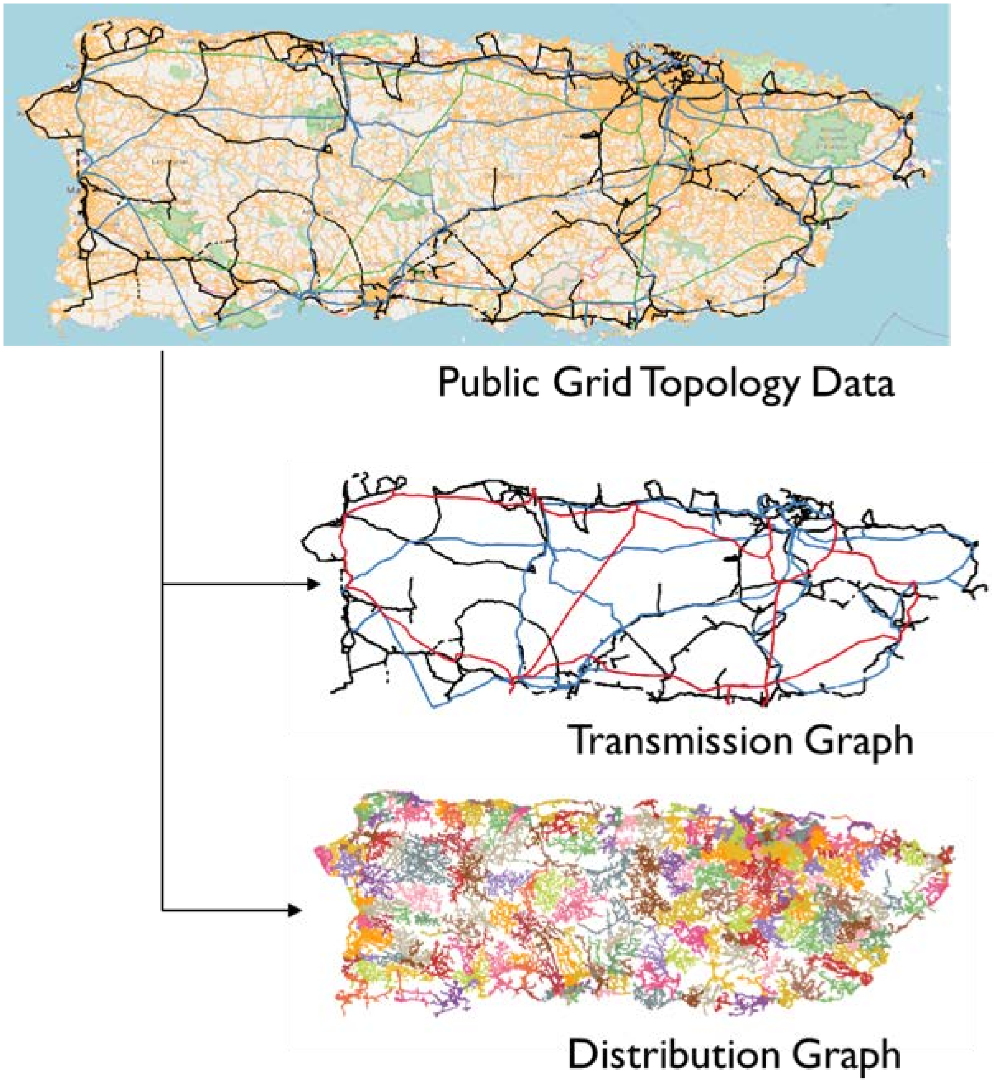




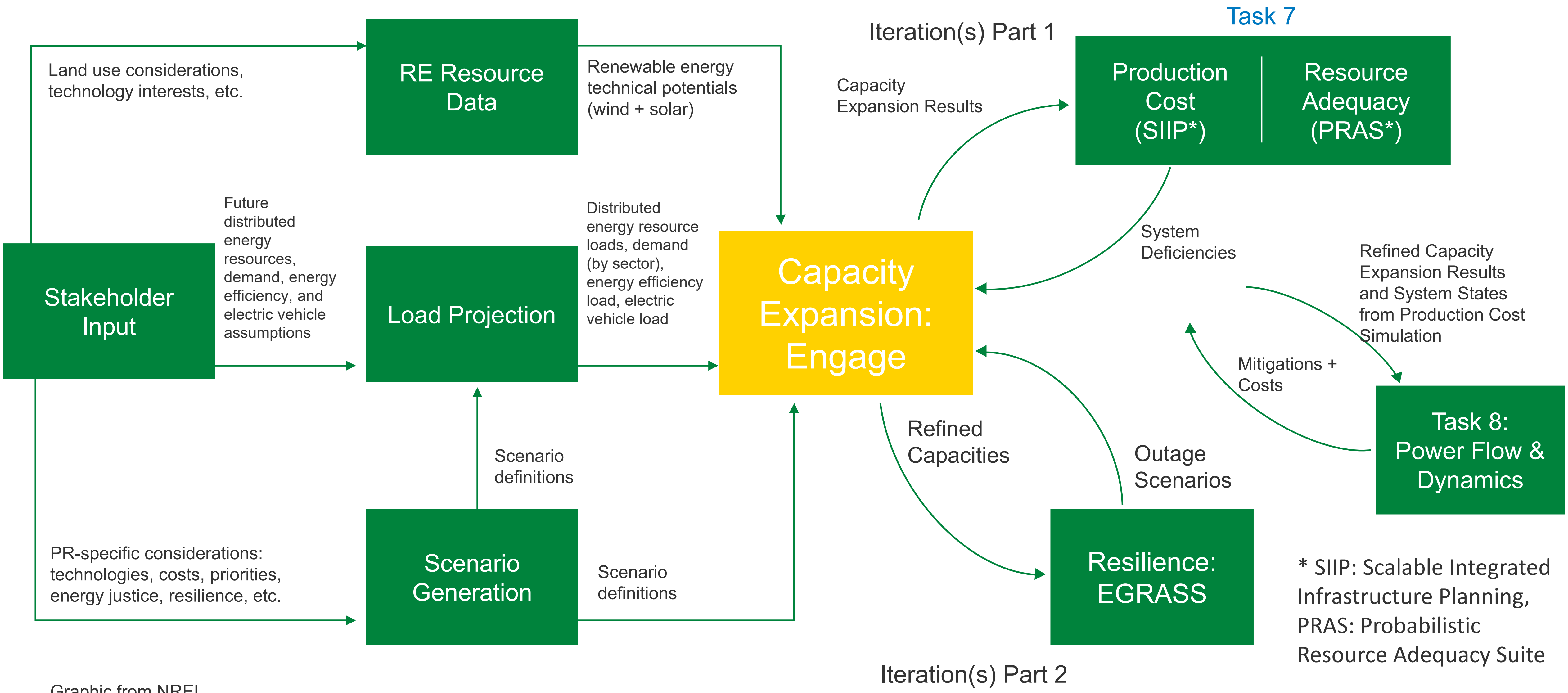


Distribution System Analysis

- Resilience benefits under the 100% renewables scenarios, including opportunities for microgrid formation
- Strategies for changes to operating strategies, controls, or infrastructure to enable higher renewable capacity
- Comparison of system resilience to more common faults and more rare natural disasters with traditional generation versus equivalent amounts of DERs with effective distribution-level control strategies



Scenario Modeling



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

Graphic from NREL

Economic Impact Analysis

Economic Impact Analysis

Retail Rate Analysis

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

Gross Macro-economic Analysis

How will the Puerto Rico economy be impacted by the renewable energy generation investments needed to meet the 100% goal?

How many jobs in Puerto Rico will be created by the renewable energy generation investments needed to meet the 100% goal?

Net Macro-economic Ana lysis

How will the Puerto Rico economy be directly and indirectly impacted by the transition to 100% renewable energy generation, including reliability investments?

How will changes in electricity rates affect consumers?

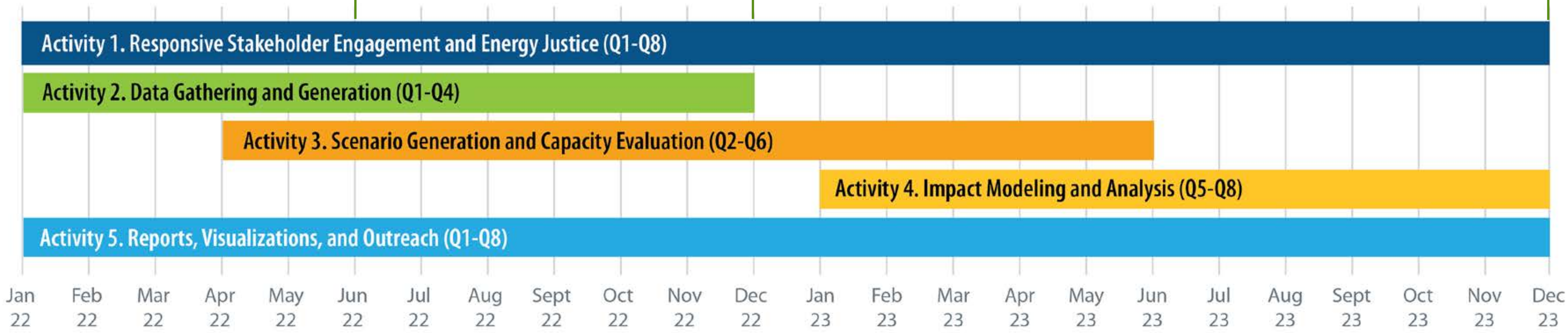
How will these economic impacts vary across different regions?

Project 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.



Puerto Rico Grid Resilience and Transition to 100% Renewable Energy Study

A Virtual Event

PR100 Six-Month Progress Update

July 21, 2022
11 a.m.-12:30 p.m.
Eastern Time

PR100

U.S. DEPARTMENT OF ENERGY

FEMA

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- This work is supported by FEMA through an interagency agreement with DOE.
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- Supported by voluntary participation of the more than 80 members of our Advisory Group whose input ensures the process and results will reflect their priorities and perspectives.

Questions?

Thank you

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