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ENHANCING GRID RELIABILITY USING ENERGY STORAGE SYSTEMS

Identifying Challenges & Developing ESS Models for Grid Planning Studies

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PROJECT OVERVIEW

- **Project Goal:** Develop models and frameworks for accurately representing energy storage systems in grid reliability and planning studies.
- **Current Practice:** Existing grid reliability evaluation frameworks and tools do not accurately capture ESS operational and failure characteristics. They are not well coordinated with expansion planning and production cost modeling tools.
- **Why SNL:** Cross-cutting research at Sandia—expertise in power systems, ESS safety and reliability, demonstrations project.
- **Innovation:** Developing and integrating state-of-the-art ESS models that reflect their real world operation and failure characteristics into reliability and planning studies.
- **Impact:** The grid reliability and planning frameworks and open-source tools developed benefit stakeholders including utilities, researchers, and regulators to accurately capture the contribution of ESS toward enhancing grid reliability.
- **Alignment:** Enhance grid reliability and making electricity more affordable through informed and efficient planning.

CURRENT STATE OF RELIABILITY OF THE US GRID

- Key challenges identified by recent reports[1,2] in maintaining acceptable levels of grid reliability:
  - Load growth due to **data centers** and large industrial loads
  - Retirements of **firm capacity**
  - **Energy drought** due to more reliance on non-dispatchable resources—expose the system to *supply shortages*
  - Transmission challenges — more transmission in **construction phase** needed; increase mostly seen in planning phases

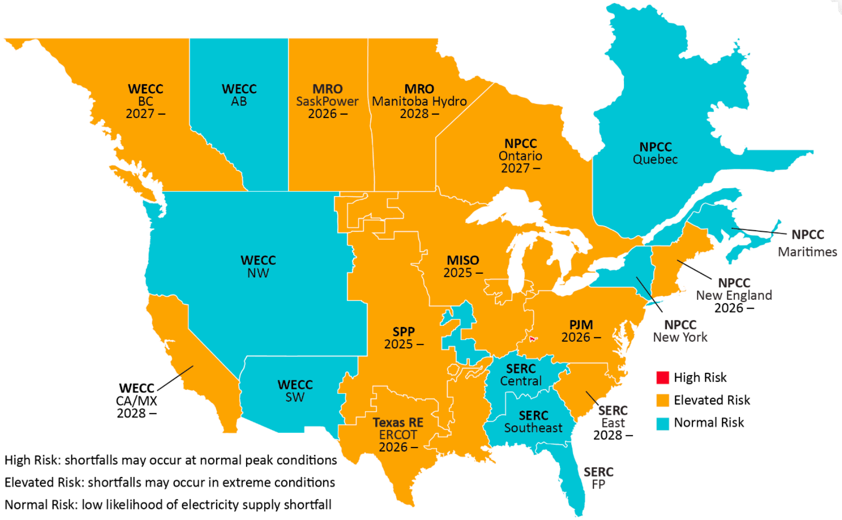


Figure 1: Risk Area Summary 2025–2029 for Regional Entities[1].

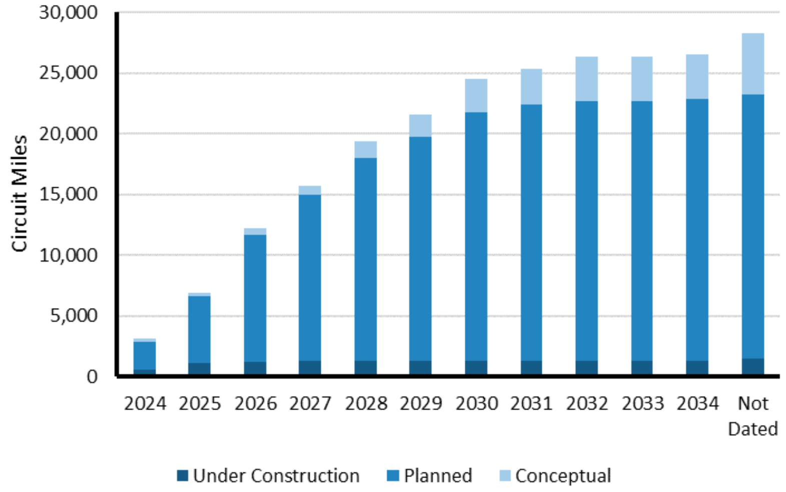


Figure 2: Future Transmission Circuit Miles >100 kV by Project Status[1].

1. 2024 Long-Term Reliability Assessment, NERC, July, 2025
2. Evaluating the Reliability and Security of the United States Electric Grid, US Department of Energy, July 2025

WHY ENERGY STORAGE?

- ESSs offer multiple reliability services to the grid
- Flexibility by time-shifting energy
- Mitigating uncertainties by addressing generation shortfalls during normal and abnormal operating conditions—provide energy when most necessary
- Interconnection queues are experiencing growing number of ESS capacity!

MISO	ERCOT	ISONE	NYISO
64,645	169,694	15,876	90,560

Table: ESS in interconnection queues of different ISOs (MW)

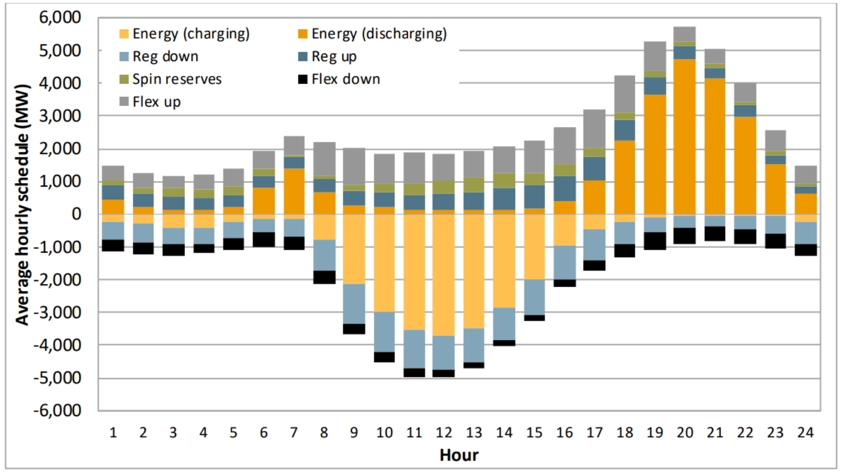


Figure 1: Average hourly ESS schedules by product in CAISO[1]

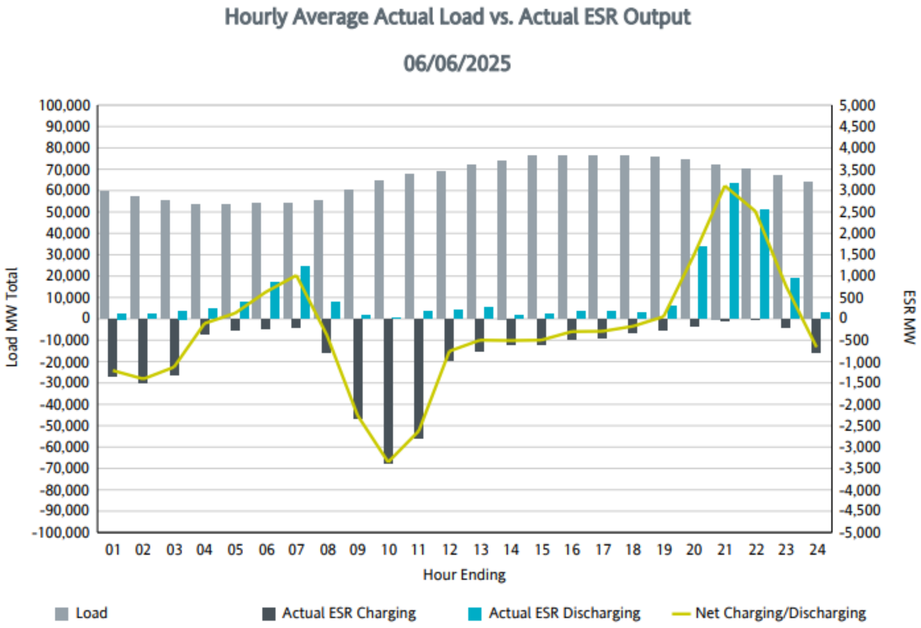


Figure 2: Hourly average actual load vs. actual ESS output in ERCOT[2]

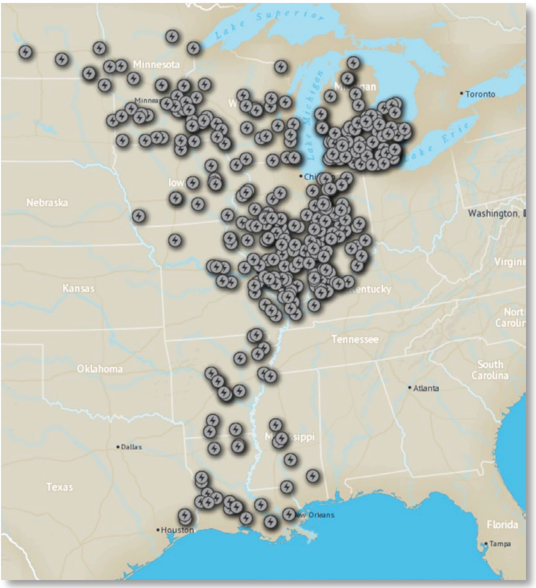


Figure 3: ESS in interconnection queue of MISO[3]

1. California ISO, *2024 Special Report on Battery Storage*, May 29, 2025.
2. ESR Integration Report, ERCOT
3. Generator Interconnection Queue—Active Projects Map, MISO

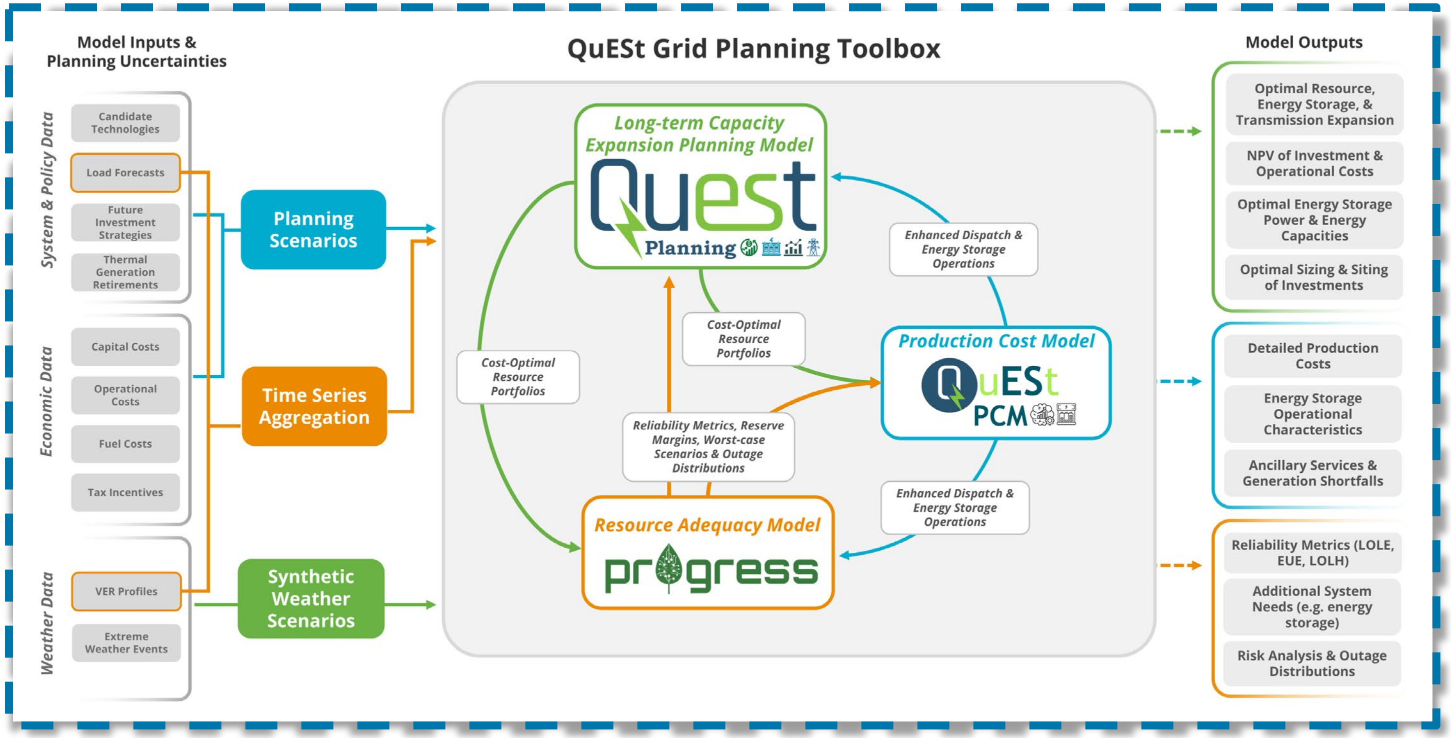
ESS MODELING CHALLENGES

Identify modeling challenges specific to ESS in the grid planning process and provide solutions

Modeling Challenges

- Energy limited nature
- Degradation, replacement costs, asset lifetimes
- Temporal resolution of planning framework
- Operation strategies
- Technology-specific model characteristics

Develop Grid Planning Toolbox



Improved grid planning tools enable well-informed investment and operational decisions

GRID RELIABILITY EVALUATION PROCESS

Definition

- Reliability of a power system pertains to its ability to satisfy load demand under specified operating conditions and policies

Quantification

- *Probability* and *frequency* of encountering failure states and the period of time system spends in failure states

Measure

- *Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE)* in days/year, *Loss of Load Frequency (LOLF)* in failures/year, *Expected Unserved Energy (EUE)* in MWh/year

Power Systems Reliability Analysis

Multi-Node Systems

Single-Node Systems

Composite System Reliability Analysis

- Conducts detailed examination of system.
- Focuses on evaluating overall capability of generation & transmission systems to provide adequate electrical energy to major load centers.
- AC/DC OPF models used.

Multi-Area Reliability Analysis

- Typically involves large network of interconnected utilities or control areas.
- DC OPF/transportation models used for network representation.

Generation Adequacy Analysis

- Evaluate ability of generation resources to meet total system load.
- Assumes transmission system to be capable of transporting generation to load centers without fail
- Transmission network is not modeled.

Contingency ranking

Stochastic/probabilistic load flow

State space decomposition

Monte Carlo Simulation

Hybrid methods

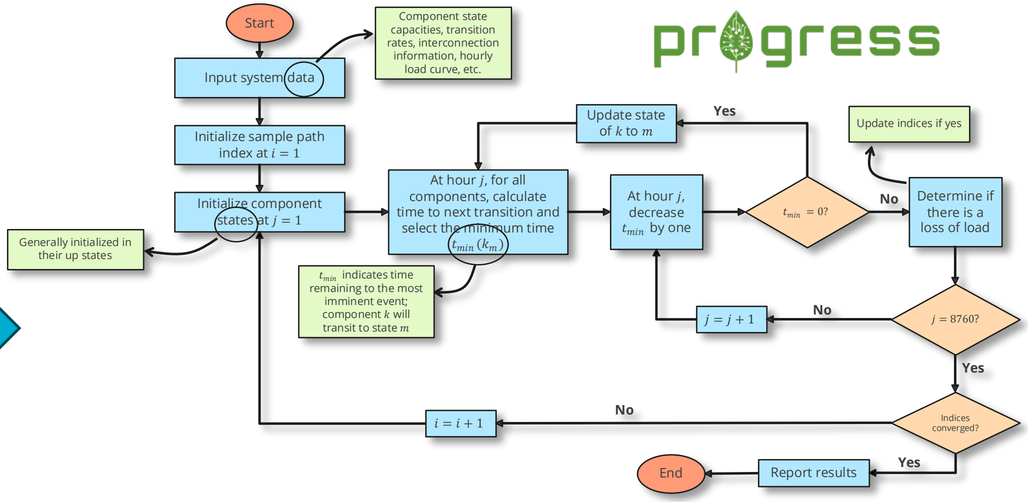
PROGRESS TOOL OVERVIEW

Sequential time-series model allows smooth integration of ESS

Input Data

- System topology
- Energy storage
- Thermal generators
- Weather
- Load profiles

Stochastic Monte Carlo Simulation Engine



progress

Generate samples (each 8760 hours long) with diverse weather conditions and component failures

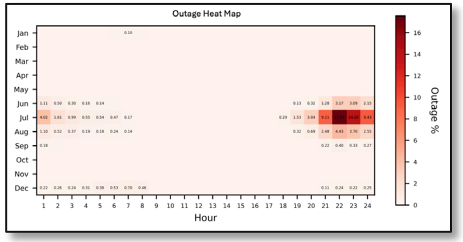
Optimize grid operation with energy storage every hour

Calculate reliability indices characterizing the frequency, duration, and magnitude of outages

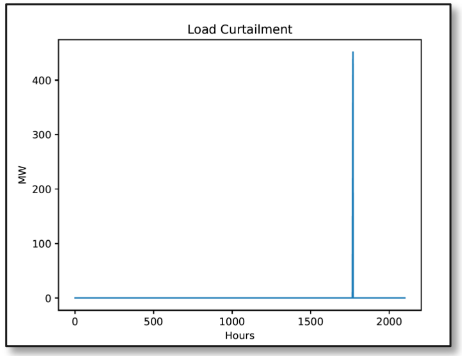
Key Outputs

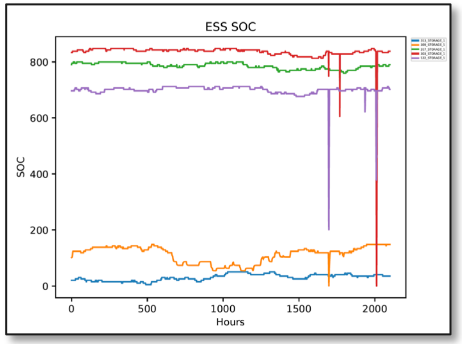
Quantify System Reliability

Index	Description
LOLP	Loss of Load Probability
LOLE	Loss of Load Expectation
MDT	Mean Down Time
nEUE	normalized Expected Unserved Energy
EPNS	Expected Power Not Served
LOLF	Loss of Load Frequency



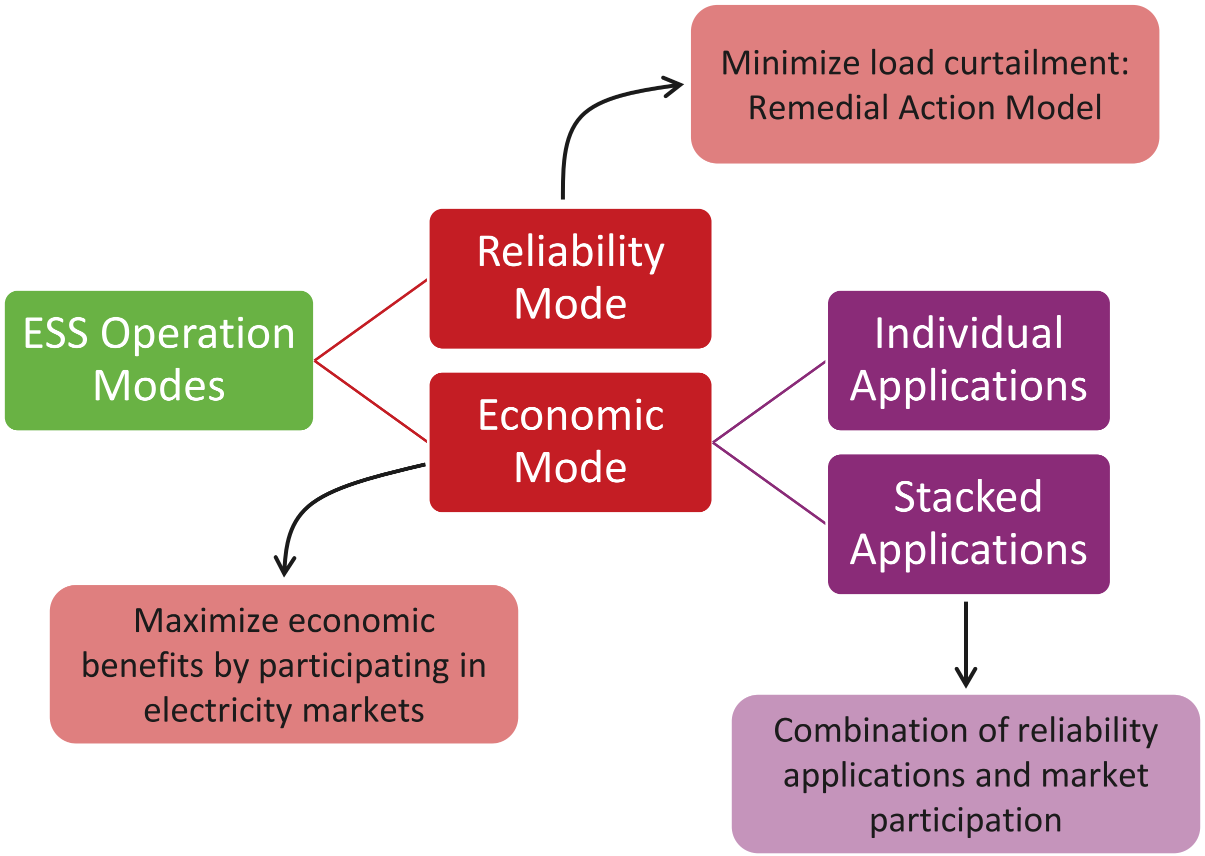
In-depth Outage Analysis





ESS OPERATION MODES

Objective

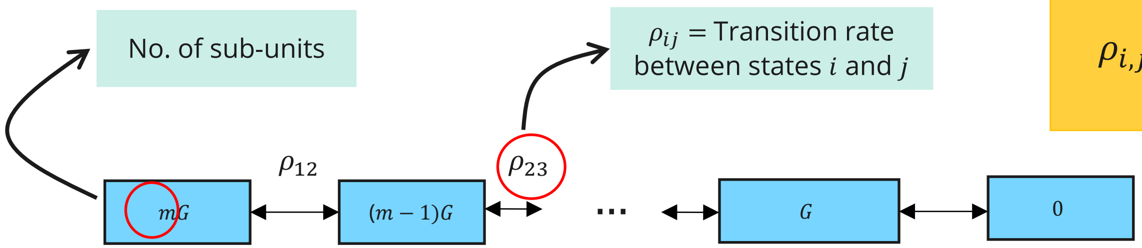


Constraints

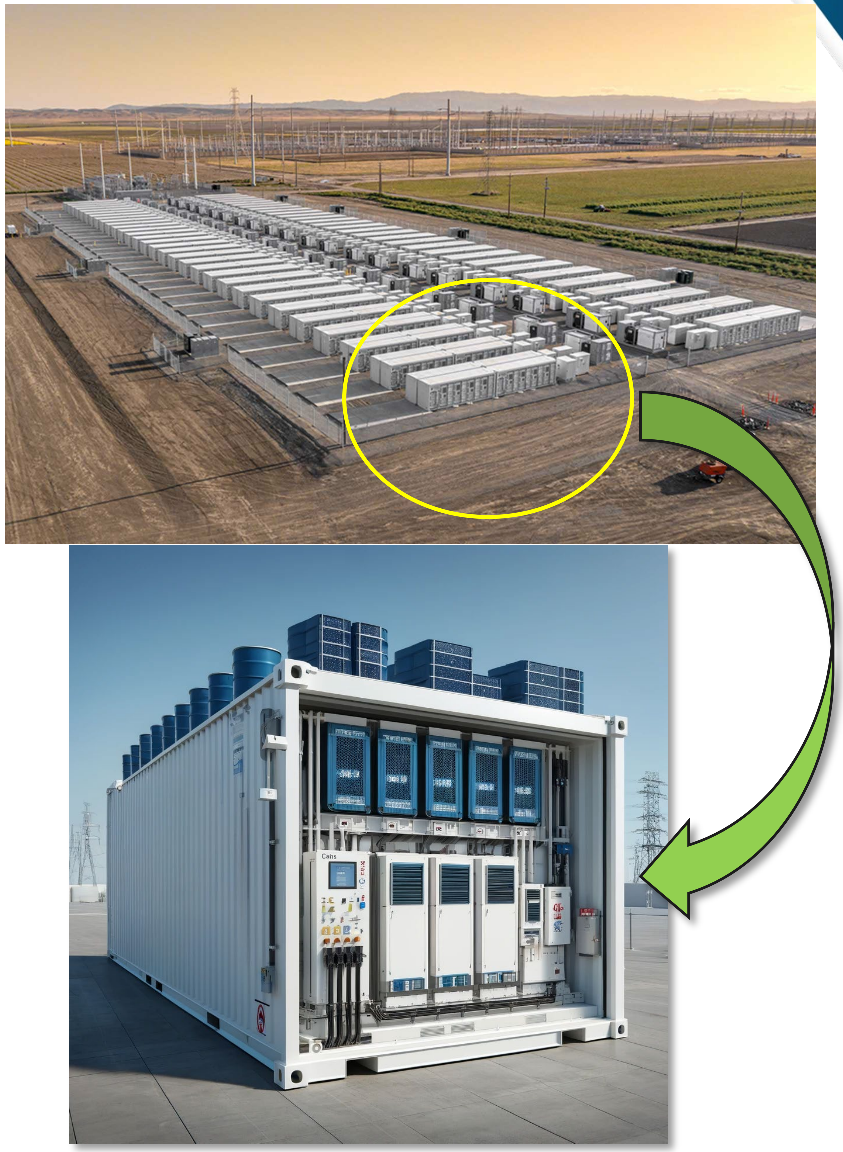
- Power Balance
- Generator Capacity Limits
- Transmission Limits
- ESS state-of-charge update
- ESS charge-discharge limits

ESS FAILURE MODEL

- Li-ion batteries considered
- Each ESS is made up of several sub-units
- Each sub-unit could be either a 20- or 40- feet long container housing a 2.5 MWh or 5 MWh sub-unit respectively[1, 2]
- It is assumed that a sub-unit is the smallest unit that can fail
- ESS operates at derated state when one/more sub-unit faces outage
- Multi-state model of ESS developed



$$\rho_{i,j} = \frac{N_{i,j}^{t}}{D_i}$$



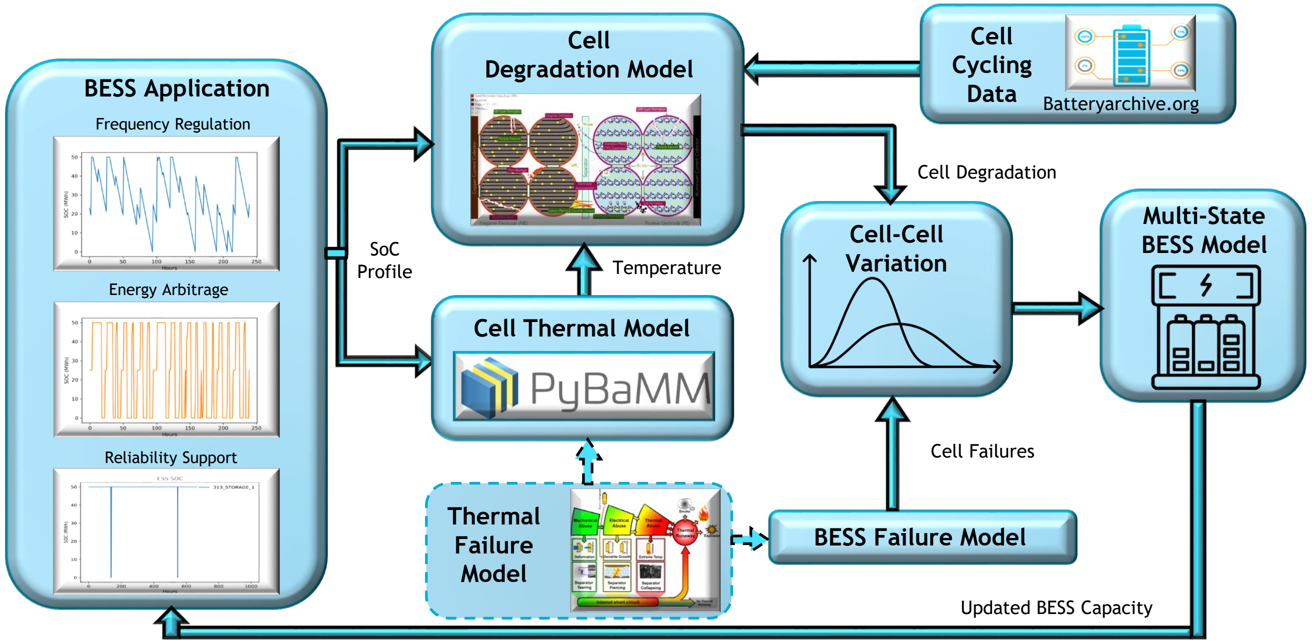
1. SAFT's 2.5 MWh ESS containers
2. 1 MW/2.5 MWh Energy Storage System

ESS FAILURE MODEL

Challenges

- Calculating failure rates for BESS complicated due to data scarcity
- Existing battery degradation models focused on cells rather than entire systems[1,2]
- Cell-to-cell variation and battery configuration/topology impact[3,4] capacity degradation of large systems

Probabilistic BESS Failure Modeling



Degradation figure: Edge, Jacqueline S., et al. "Lithium ion battery degradation: what you need to know." Physical Chemistry Chemical Physics 23.14 (2021): 8200-8221.
Thermal runaway figure: Feng, Xuning, et al. "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review." Energy storage materials 10 (2018): 246-267.
PyBaMM ref: Sulzer, V., Marquis, S. G., Timms, R., Robinson, M., & Chapman, S. J. (2021). "Python Battery Mathematical Modelling (PyBaMM)". Journal of Open Research Software,9 (1), 14.

$$f\,(\text{application, cell degradation model, thermal model, system topology, cell} - \text{cell variation})$$

↓

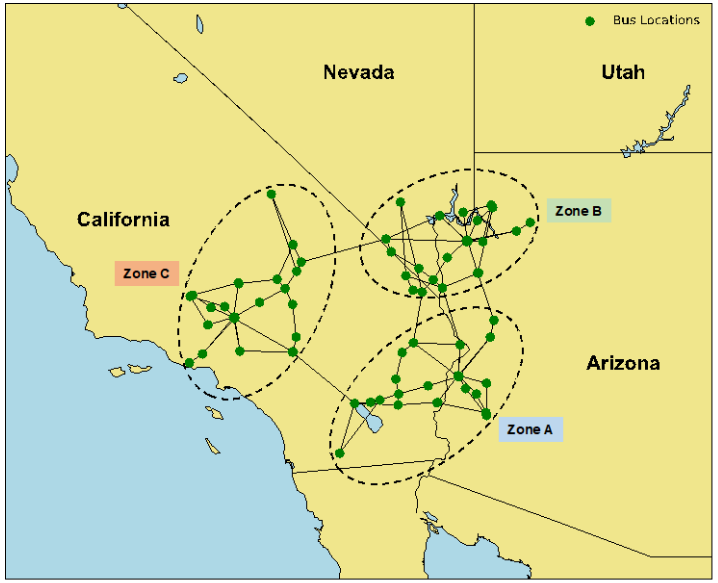
capacity fade, failure metrics ← Tune model with data collected by the demonstration team

[1] Koster, D., et al. "Degradation analysis of 18650 cylindrical cell battery pack with immersion liquid cooling system. Part 1: Aging assessment at pack level." Journal of Energy Storage 62 (2023): 106839.
[2] Wittman, Reed, et al. "Characterization of Cycle-Aged Commercial NMC and NCA Lithium-ion Cells: I. Temperature-Dependent Degradation." Journal of the Electrochemical Society 170.12 (2023): 120538.
[3] Kim, Kyunghyun, and Jung-Il Choi. "Effect of cell-to-cell variation and module configuration on the performance of lithium-ion battery systems." *Applied Energy* 352 (2023): 121888Kim, Kyunghyun, and Jung-Il Choi. "Effect of cell-to-cell variation and module configuration on the performance of lithium-ion battery systems." Applied Energy 352 (2023): 121888.
[4] Preger, Yuliya, et al. "Impact of Module Configuration on Lithium-Ion Battery Performance and Degradation: Part I. Energy Throughput, Voltage Spread, and Current Distribution." *Journal of The Electrochemical Society* (2025).

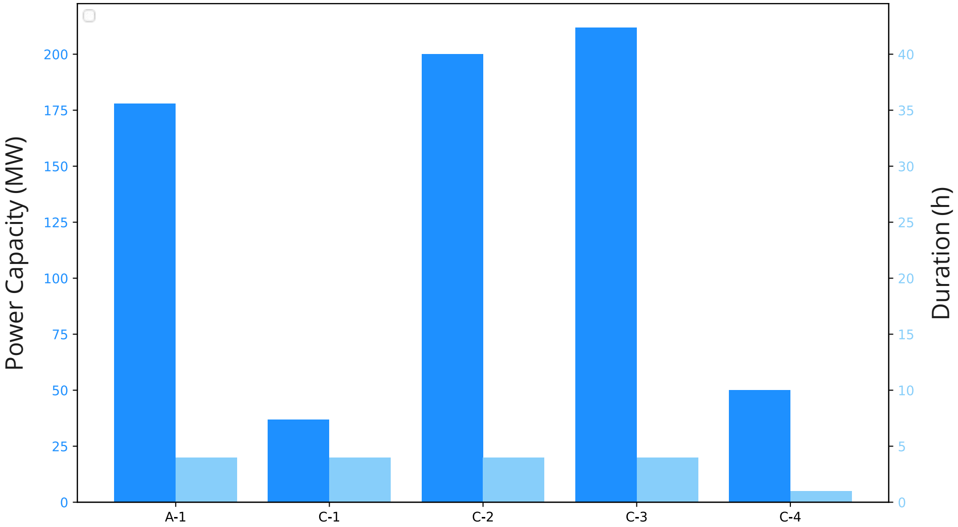
RTS CASE STUDY

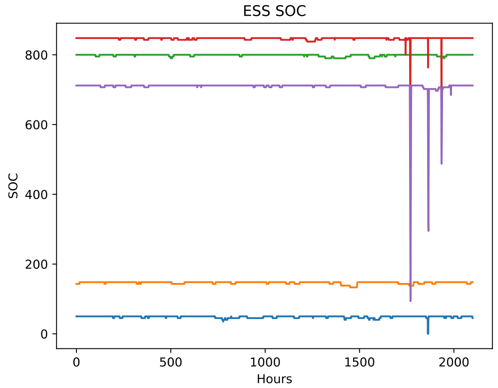
How can BESS failures affect grid reliability?

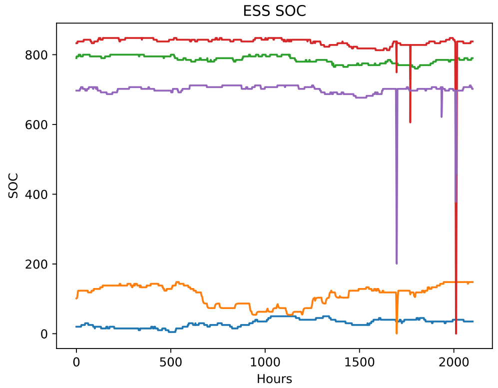
RTS GMLC

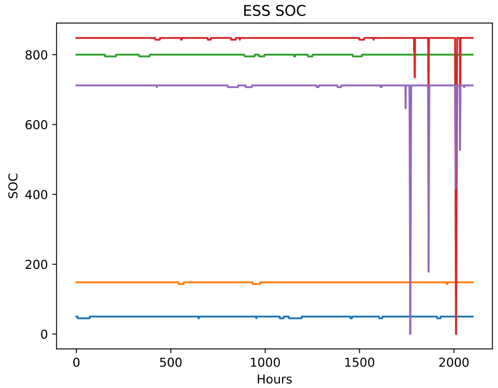


ESS DATA









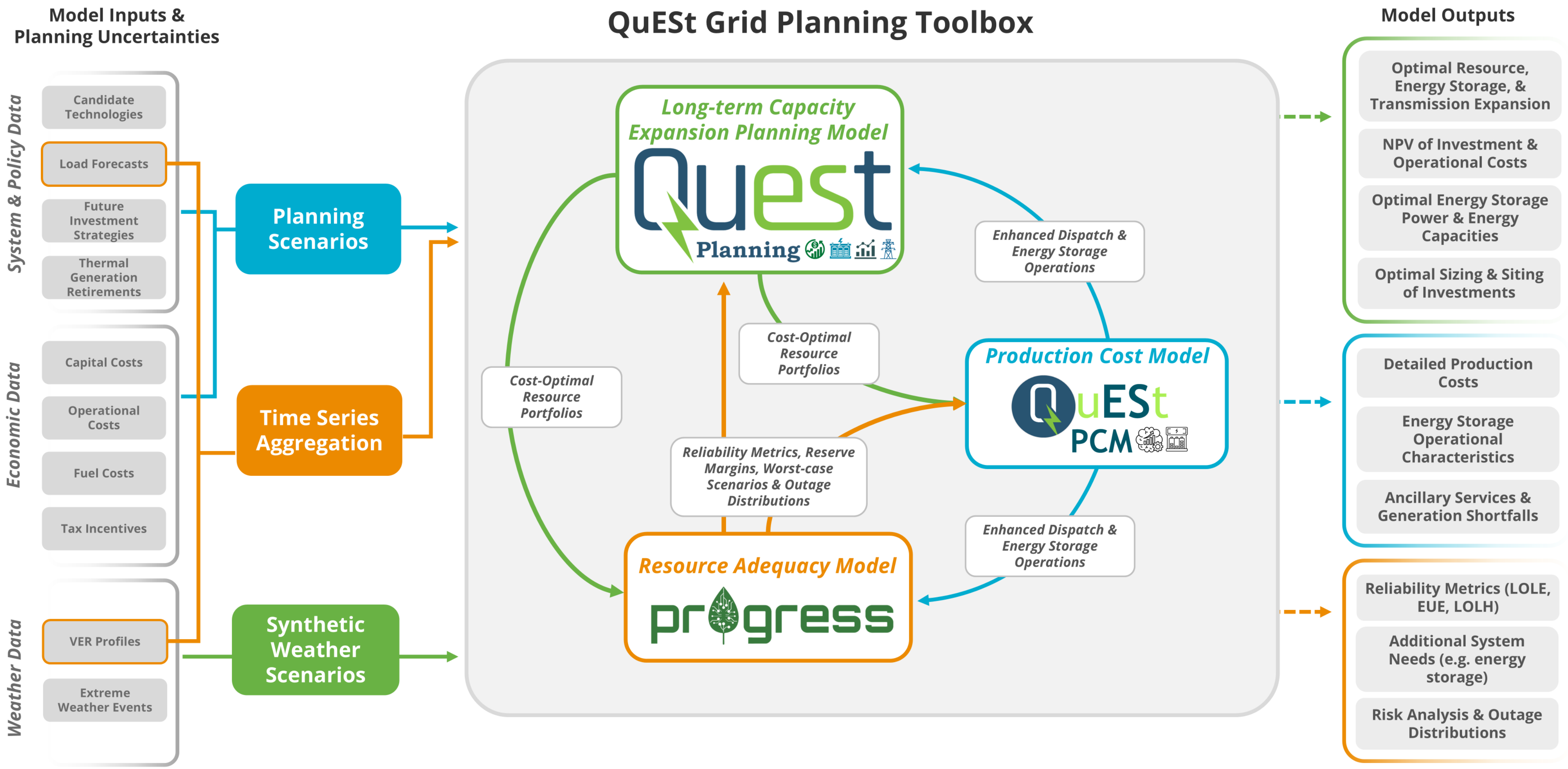
Legend

LOLP	Loss of Load Probability
LOLE	Loss of Load Expectation
MDT	Mean Down Time
nEUE	normalized Expected Unserved Energy

Reliability Indices

Case	MTTF (h)	MTTR (h)	LOLP	LOLE (days/year)	MDT (h)	nEUE (ppm)
Base	100	20	1.223e-4	0.349	0.712	7.0
Less Reliable	40	30	1.388e-4	0.391	0.805	8.0
More Reliable	250	20	1.195e-4	0.340	0.700	6.9

GRID PLANNING TOOLBOX



TOOL INTEGRATION

Coordination of grid planning tools required for adequate ESS modeling and decision-making

Expansion Planning

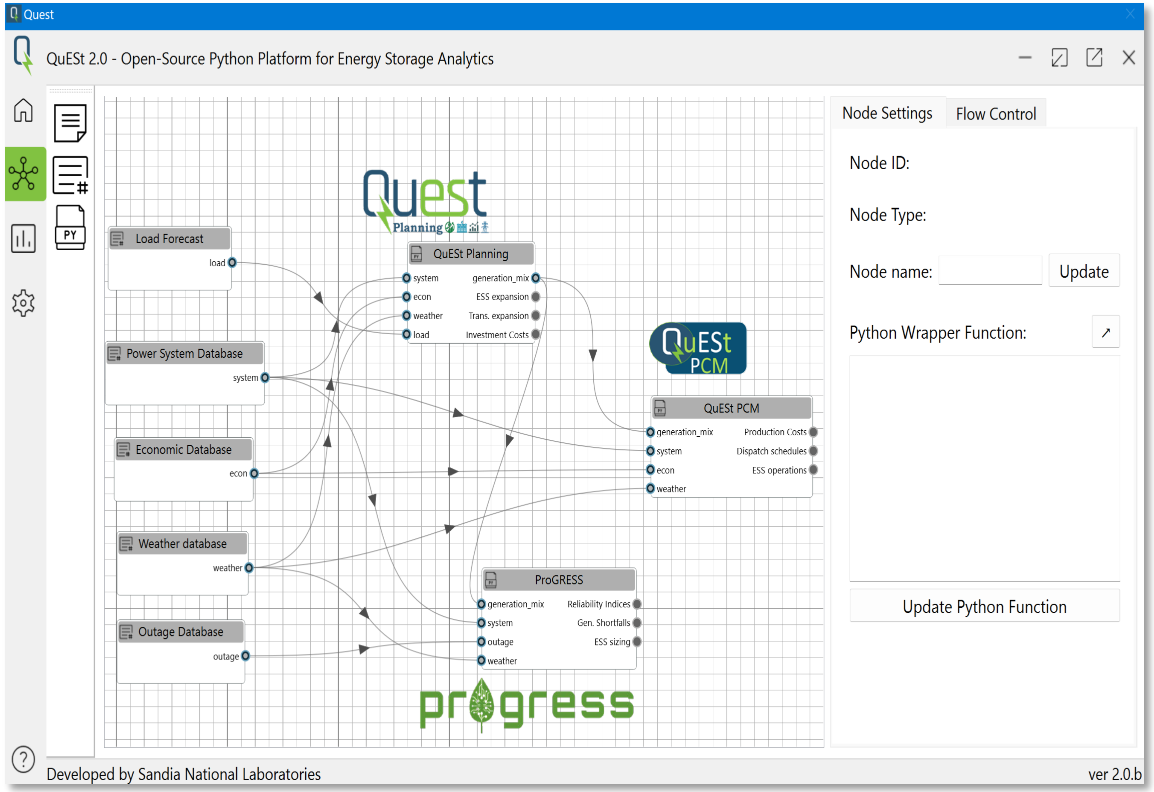
- Reduced order nodal or zonal models
- Down-sampled temporal scope
- Economic dispatch and DC power flow

Resource Adequacy

- Nodal, zonal, or copper sheet model
- 8760-hour long samples with economic dispatch or remedial action model each our
- Markov chain Monte Carlo based scenario analysis

Production Cost Model

- Detailed nodal models
- Hourly, sub-hourly unit commitment and economic dispatch
- Ancillary services scheduling

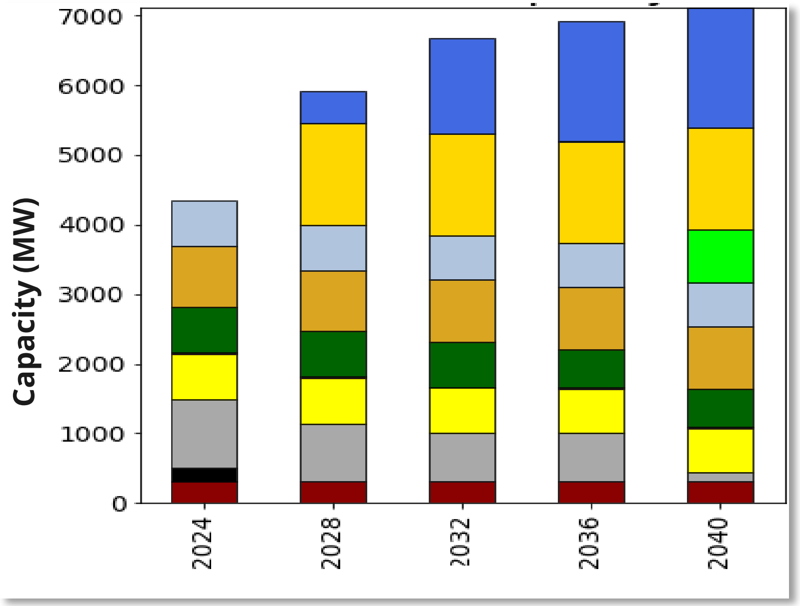


Deploy QuESt Workspace to develop custom Python scripts to demonstrate tool coordination

NEW MEXICO CASE STUDY

Coordinating planning tools to define role of ESS in enhancing grid reliability

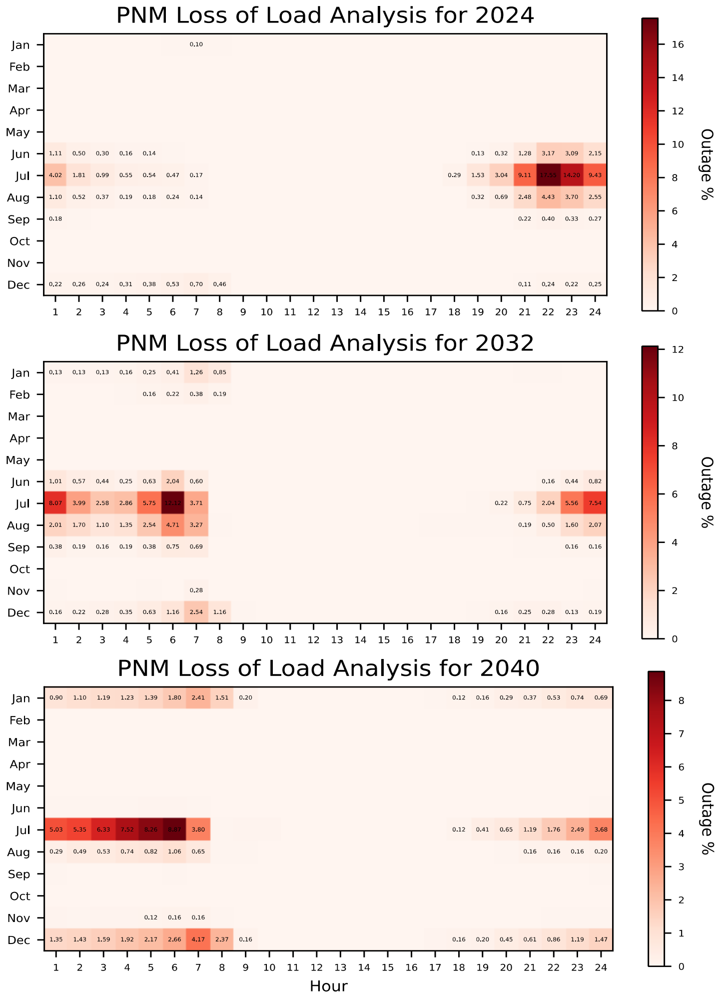
Quest Planning



2032: 320 MW, 10hr
2040: 1250 MW, 18hr

progress

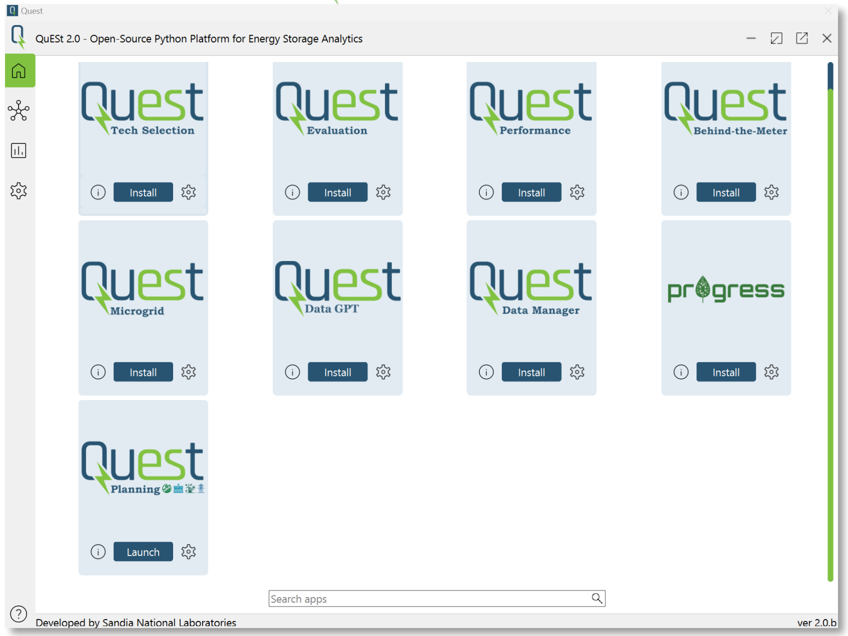
Case	LOLE (d/y)	LOLH (h/y)	EUE (MWh/y)
2024	0.67	1.80	241
2032	0.10	0.25	32.33
2040	0.10	0.36	84.28

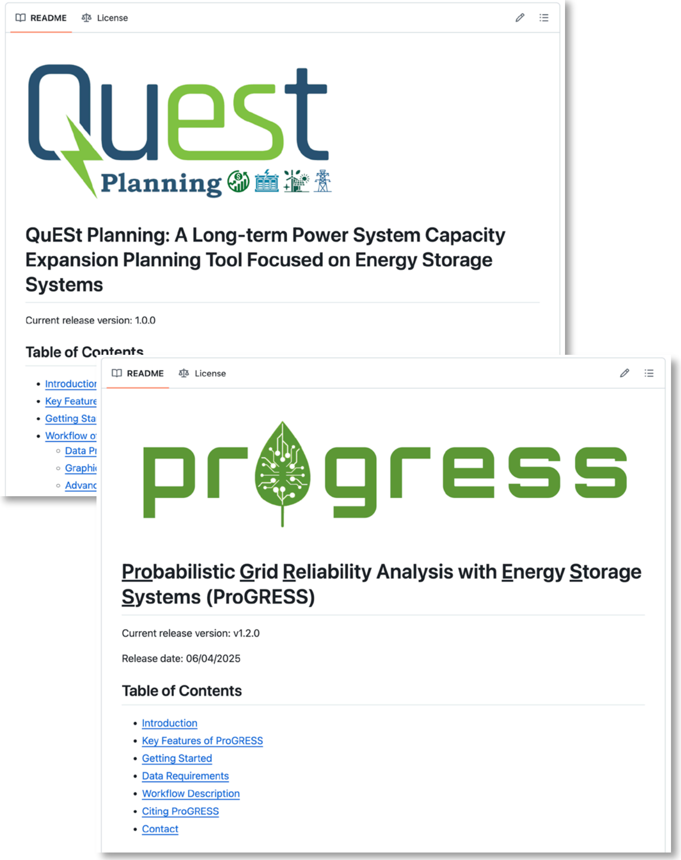


ESS added to portfolio generated by expansion planning tool to improve system reliability to desired levels

DISTRIBUTION

- Available on GitHub
  - PROGRESS
  - QuESt Planning
- Available via QuESt 2.0 platform
- Available on pypi, can be pip installed
- Executable version (.exe file) available for Windows users
- Documentation available on GitHub, in-app, and GitHub Pages





SUMMARY

- ESS will play key role in supporting **US grid reliability** by providing *flexibility* and *mitigating uncertainties*
- ESS characteristics should be *adequately modeled in planning studies* to capture contribution toward grid reliability
- Grid planning tools such as *resource adequacy, expansion planning, and production cost models* should be reformed to incorporate ESS models
- Proper *coordination between tools* is essential for integrated grid planning with ESS

ACKNOWLEDGEMENT

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