Sandia National Laboratories

LONG-TERM CAPACITY EXPANSION PLANNING FOR ENERGY STORAGE TO SUPPORT LARGE LOADS & RELIABILITY

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PROJECT PROFILE

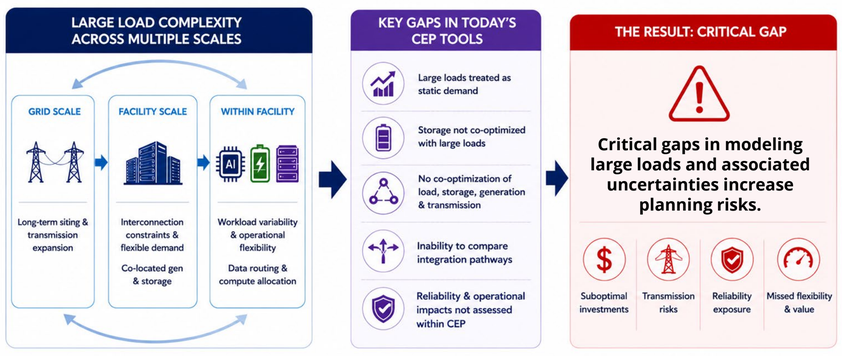
Topic: Analytics & Tools| Vertical: Analytics

Strategic Pathway: Optimize

Project start and finish: FY26-FY27

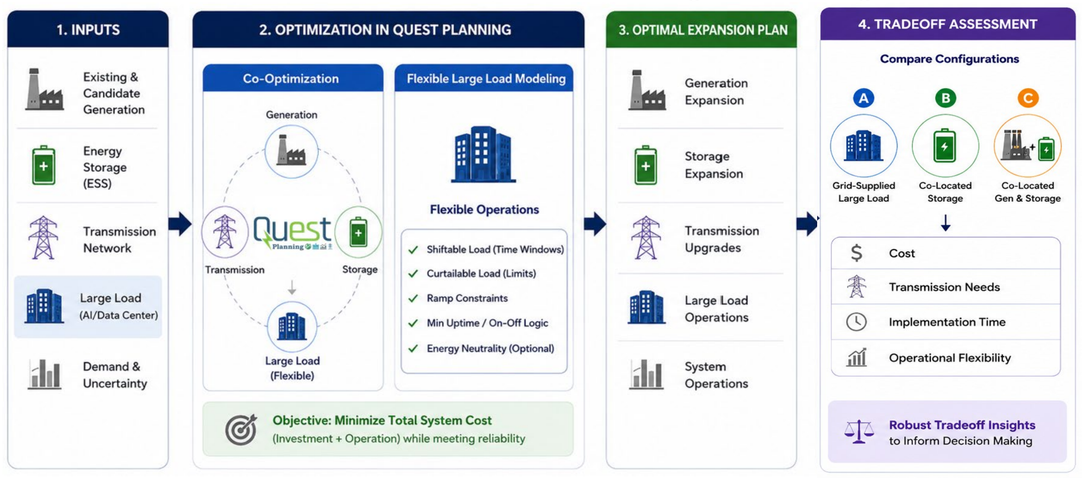
Problem

- **Problem:** Rapid load growth from AI data centers pose significant **economic** and **reliability** risks to the U.S. power system.
- **Motivation:** Failure to improve grid planning tools will result in sub-optimal grid investments and pose risks to the U.S. power system. Improvements to ESS models, co-optimization, and large load models are required.
- **Current practice:** Traditional capacity expansion planning (CEP) tools treat large loads as static demand and are not co-optimized with ESS, generation, and transmission assets across various configurations. Additionally, reliability is often evaluated at a basic level undermining future reliability risks



Large Load Modeling Approach

- Develop and maintain **QuESt Planning,** an open-source CEP model that enables ESS evaluation and modeling flexibility to optimize the evolving U.S. power system
- Integrate large load modeling into traditional CEP frameworks by enabling large load flexibility constraints and co-optimization of ESS, generation, transmission, and large load
- Enable robust tradeoff assessment capabilities of large load configurations



Co-optimization & large load flexibility incorporated into QuESt Planning

1. **WORKLOAD SHIFTING** (Energy Neutrality) $\sum_{t \in T} S_t = 0$ $\forall t$
2. **RAMP RATE LIMITS** (Flexible Load) $-R^{down} \le L_t - L_{t-1} \le R^{up}$ $\forall t$
3. **MINIMUM UPTIME** (Critical Workloads) $U_t \ge U^{min}$ $\forall t$
4. **CURTAILMENT / INTERRUPTIBILITY** $0 \le Curt_t \le \alpha^{max} L_t$ $\forall t$
5. **FLEXIBLE LOAD BALANCE** (Net Load Composition) $L_t = L_t^{crit} + L_t^{flex} - Curt_t - S_t$ $\forall t$

Incorporating Large Load Flexibility

- Incorporate flexibility costs in the objective
- Co-optimize storage, generation, transmission, large load operations, and co-located generation/storage

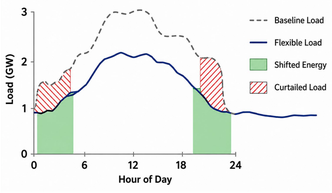
Enhanced Objective Function

Minimize total system cost

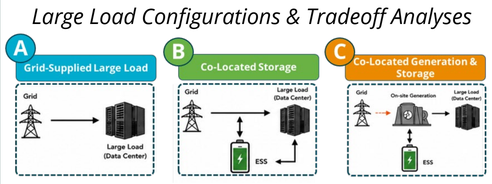
$$\min \sum_{y} \left(C_y^{gen} + C_y^{trans} + C_y^{ESS} + C_y^{ops} + C_y^{flex} \right)$$

Generation Investment Cost (C_y^{gen}) + Transmission Investment Cost (C_y^{trans}) + Energy Storage Investment & Replacement Cost (C_y^{ESS}) + Operations Cost (C_y^{ops}) + Flexible Load Penalties (C_y^{flex})

Synthetic Load Profile & Workload Shifting



Large Load Configurations & Tradeoff Analyses



Tradeoff Analyses

- ***Costs vs. Reliability (Load Curtailment)***
- **Transmission expansion vs. Operational flexibility**
- **Implementation configuration vs. Economic Benefit**

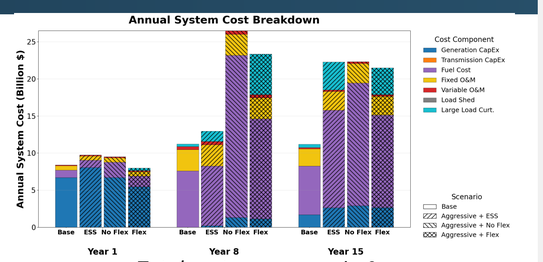
Role of Energy Storage

- When co-located, storage can provide flexibility needed to shift, shape, and meet large load demands
- Supports the bulk power system and enables transmission deferment
- Co-located generation and storage enhances energy independence and provides highest reliability for critical large loads

Large Load Case Study Results

Case Study - IEEE RTS-GMLC test system – 15 yr horizon

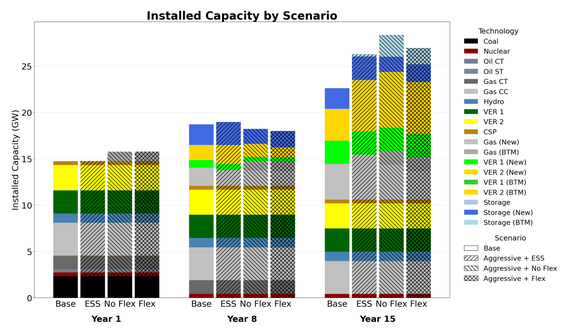
Scenario	Large Load Commissioning	Large Load Configurations	Large Load Flexibility
Baseline + Flex	Base (1.5 GW) (year 1 & 5)	A	✓
Aggressive Growth + ESS	Aggr. (3.5 GW) (year 1, 8, 15)	A, B	✓
Aggressive Growth + No Flex	Aggr. (3.5 GW) (year 1, 8, 15)	A, B, C	X
Aggressive Growth + Flex	Aggr. (3.5 GW) (year 1, 8, 15)	A, B, C	✓



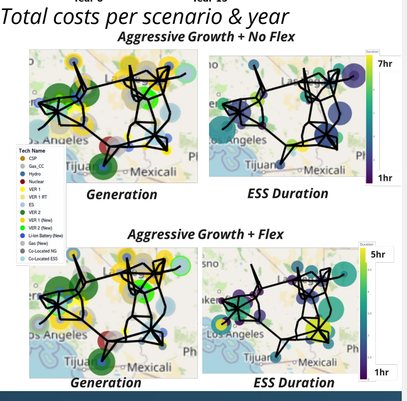
Total costs per scenario & year

Key takeaways:

- Siting and sizing of ESS are impacted when implementing different configurations and flexibility options
- Flexibility and large load configurations impact total system costs and optimal ESS duration

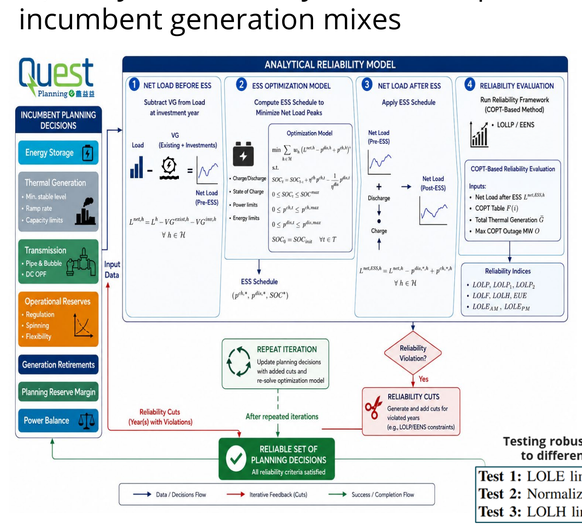


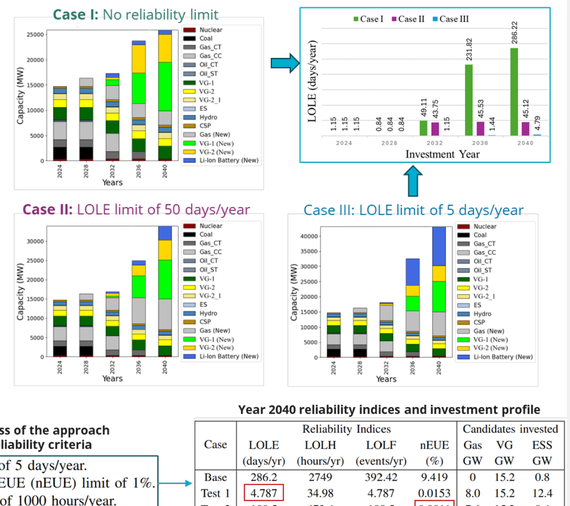
Total generation & ESS per scenario & year



Reliability-Based CEP

- **Goal:** Develop a reliability-constrained capacity expansion planning approach
- **Proposed method**: 1.) Quest Planning generates incumbent investment decisions 2.) Analytical reliability framework performs a quick adequacy assessment for all incumbent generation mixes





Testing robustness of the approach to different reliability criteria

Test 1: LOLE limit of 5 days/year.
Test 2: Normalized EUE (nEUE) limit of 1%.
Test 3: LOLH limit of 1000 hours/year.

Year 2040 reliability indices and investment profile

Case	Reliability Indices LOLE (days/yr)	LOLH (hours/yr)	LOLF (events/yr)	nEUE (%)	Candidates invested Gas GW	VG GW	ESS GW
Base	286.2	2749	392.42	9.419	0	15.2	0.8
Test 1	4.787	34.98	4.787	0.0153	8.0	15.2	12.4
Test 2	100.5	473.4	100.5	0.9011	7.6	15.2	0.4
Test 3	186.3	995.2	191.5	2.5643	5.6	16.8	0.4

CONCLUSIONS & IMPACT

- **QuESt Planning** enables utilities, ISOs, and researchers to perform long-term grid planning to ensure the U.S. power system is secure, reliable, and affordable.
- **New features of QuESt Planning released** (*target: 08/2026*): Large load integration features and robust co-optimization functionality
- **Downloaded 500+** times from GitHub
- Paper presented at ***IEEE EESAT 2026*** *and* ***2026 IEEE PES General Meeting (GM)*** and accepted to ***2026 PMAPS Conference***
- Moderated panel at ***2026 IEEE PES T&D***: "*The Role of Energy Storage Systems in Grid Planning & Operations to Support Large Electric Load Growth*"
- Presented at the ***2026 FERC Software Conference*** on the QuESt Grid Planning Toolbox
- Presented in panel at ***2026 IEEE PES GM*** on energy storage and large loads
- **Integration with other grid planning** tools, such as *ProGRESS* and *QuESt PCM,* using *QuESt Workspace* allows users comprehensive grid planning options

FUTURE DIRECTIONS

- Incorporate stochastic modeling of large loads to capture future planning uncertainties
- Partner with a utility to perform large-scale case study
- Further strengthen the coordination with ProGRESS and QuESt PCM in the QuESt Grid Planning Toolbox

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