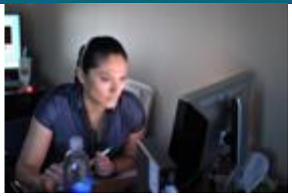
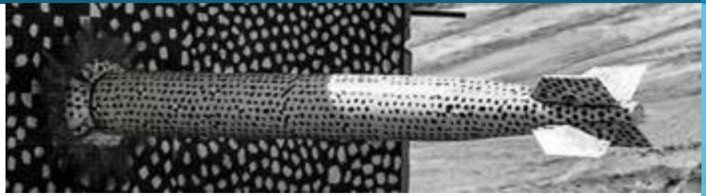
VALUATION OF ENERGY STORAGE: PROBLEMS, METHODOLOGIES, AND SOFTWARE TOOLS





PRESENTED BY

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Sandia National Laboratories

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SAND2024-03411PE

OUTLINE

- Energy storage applications
- Valuation analysis of energy storage
- Energy storage valuation problems:
  - Market problem
  - Generation problem
  - Transmission problem
  - Behind-the-meter problem
- QuESt Introduction

ENERGY STORAGE APPLICATIONS – POWER VS. ENERGY

- Power applications
  - Frequency regulation
  - Voltage support
  - Small signal stability
  - Renewable smoothing
- Energy applications
  - Energy arbitrage
  - Renewable energy time shift
  - Customer demand charge reduction
  - Transmission and distribution upgrade deferral

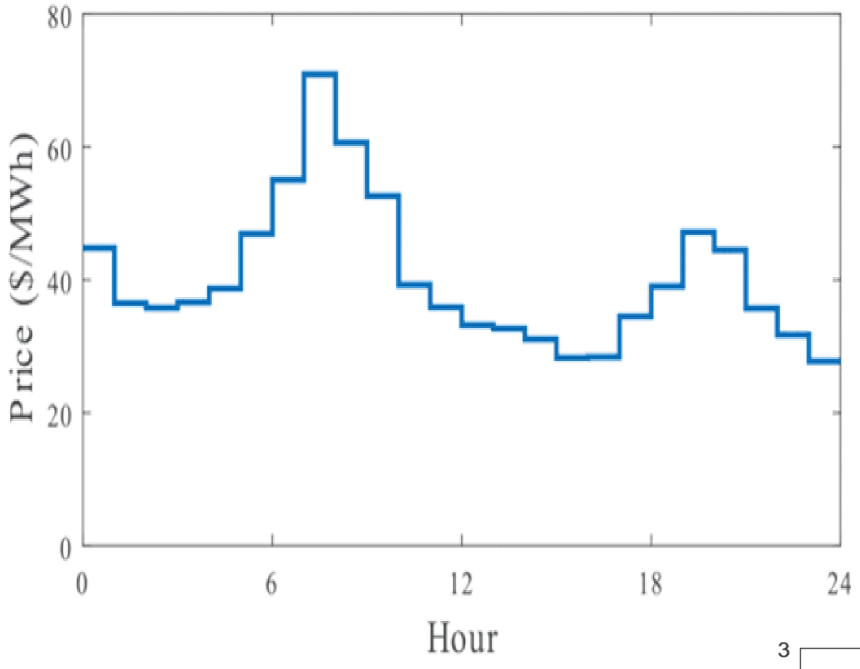
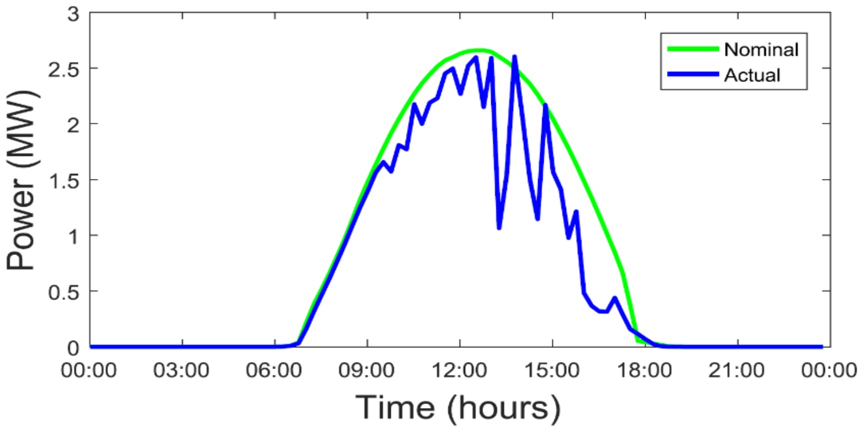


Image Credit - *Solar Power World*



ENERGY STORAGE APPLICATIONS – FTM VS. BTM

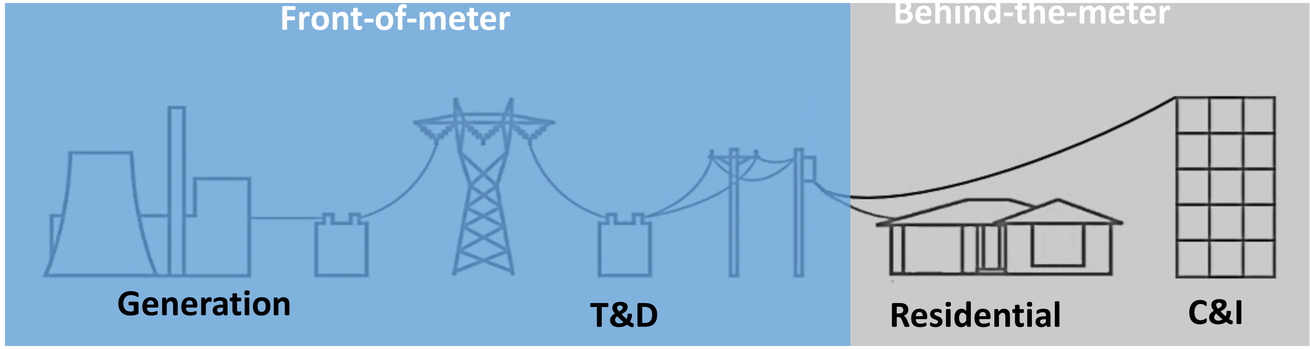


Image Credit: Navigant

- **Behind-the-meter** refers to the systems that are located at the customers' sites (homes, commercial and industrial facilities). BTM systems are usually owned by customers and intended for customers' use.

VALUATION ANALYSIS OF ENERGY STORAGE

- Identify revenue streams: what are the possible services that an ESS can provide?
- Select the right ES technology to provide those services.
- Evaluate the overall economic gain given the limits in performance of the selected storage technology.

ENERGY STORAGE VALUATION – MARKET PROBLEM

Given an energy storage device, an electricity market with a certain payment structure, and market data, how would the device maximize the revenue generated and provide value?

$$\max \sum_i \Big(\underbrace{\lambda_i (q_i^d - \eta_c q_i^r)}_{\text{arbitrage}} + \underbrace{q_i^{ru}(\lambda_i^{ru} + \delta_i^{ru}\lambda_i)}_{\text{regulation up}} + \underbrace{q_i^{rd}(\lambda_i^{rd} - \delta_i^{rd}\lambda_i)}_{\text{regulation down}} \Big) e^{-Ri}$$

subject to:

$s_{i+1} = \eta_s s_i + \eta_c q_i^r - q_i^d + \eta_c \delta_i^{rd} q_i^{rd} - \delta_i^{ru} q_i^{ru}$ state of charge definition

$0 \leq s_i \leq \bar{S}$ state of charge limits

$q_i^d + q_i^r + q_i^{ru} + q_i^{rd} \leq \bar{Q}$ power/energy charged limits

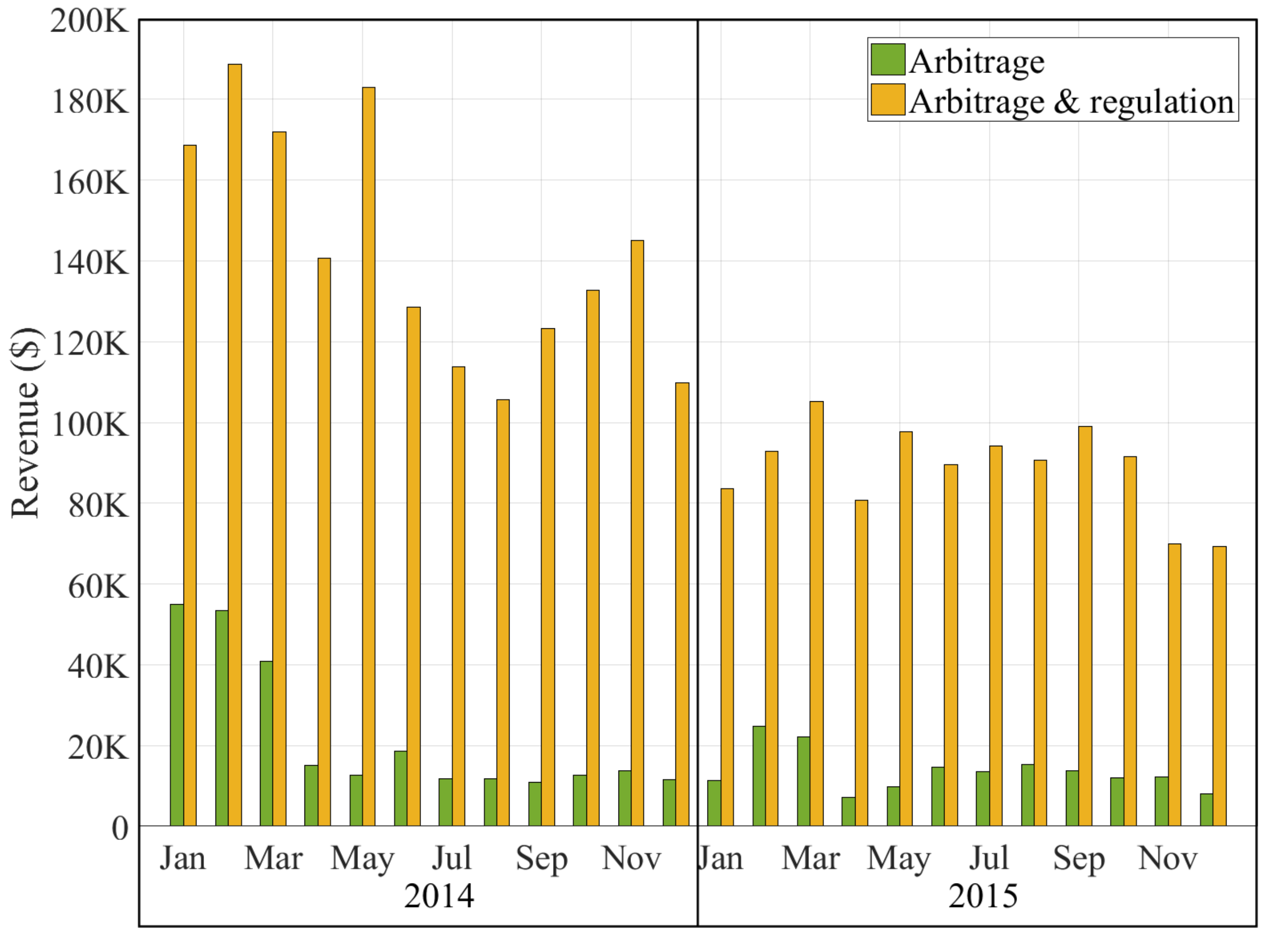
- Other constraints, such as requiring the final SoC to equal the initial SoC or reserving energy capacity for resiliency applications can be set.
- Varies based on market and available value streams

ENERGY STORAGE VALUATION – MARKET PROBLEM - EXAMPLE

The maximum revenue for arbitrage and frequency regulation of a 20MW/20MWh Li-ion BESS in MISO.

Table 1: Arbitrage and regulation optimization results 2014-2015

Month	$\%q^R$	$\%q^D$	$\%q^{REG}$	R^{arb}	R^{reg}	R^{tot}
01/14	26.61	6.59	100	$7.28K	$161.40K	$168.67K
02/14	28.13	7.89	100	$8.57K	$180.13K	$188.69K
03/14	23.66	3.76	100	-$1.77K	$173.68K	$171.90K
04/14	16.25	1.25	100	-$15.14K	$155.76K	$140.62K
05/14	15.73	0.81	100	-$15.58K	$198.48K	$182.90K
06/14	22.92	2.36	100	-$6.76K	$135.39K	$128.63K
07/14	19.49	1.08	100	-$11.50K	$125.20K	$113.70K
08/14	20.03	1.08	100	-$12.56K	$118.11K	$105.56K
09/14	16.94	0.83	100	-$12.07K	$135.40K	$123.32K
10/14	13.44	0.54	100	-$14.66K	$147.30K	$132.64K
11/14	14.03	0.14	100	-$16.79K	$161.91K	$145.12K
12/14	19.22	1.61	100	-$12.73K	$122.61K	$109.88K
			Total	**-$103.72K**	**$1,815.36K**	**$1,711.64K**
01/15	19.22	2.42	100	-$11.68K	$95.19K	$83.52K
02/15	27.83	5.51	100	-$1.68K	$94.47K	$92.79K
03/15	25.67	4.17	100	-$3.55K	$108.68K	$105.13K
04/15	15.28	1.25	100	-$12.42K	$93.09K	$80.67K
05/15	20.70	1.75	100	-$10.54K	$108.17K	$97.63K
06/15	29.31	2.78	100	-$5.37K	$94.90K	$89.53K
07/15	25.67	2.02	100	-$7.70K	$101.78K	$94.08K
08/15	31.05	3.36	100	-$4.95K	$95.64K	$90.69K
09/15	25.83	2.36	100	-$6.58K	$105.57K	$99.00K
10/15	18.55	1.88	100	-$9.98K	$101.60K	$91.62K
11/15	22.78	3.33	100	-$8.65K	$78.68K	$70.03K
12/15	16.53	0.94	100	-$10.27K	$79.49K	$69.21K
			Total	**-$93.35K**	**$1157.27K**	**$1063.92K**



ENERGY STORAGE VALUATION – GENERATION PROBLEM

Given an energy storage device, a utility generation fleet, how would the device minimize operating cost of this generation fleet while meeting its load?

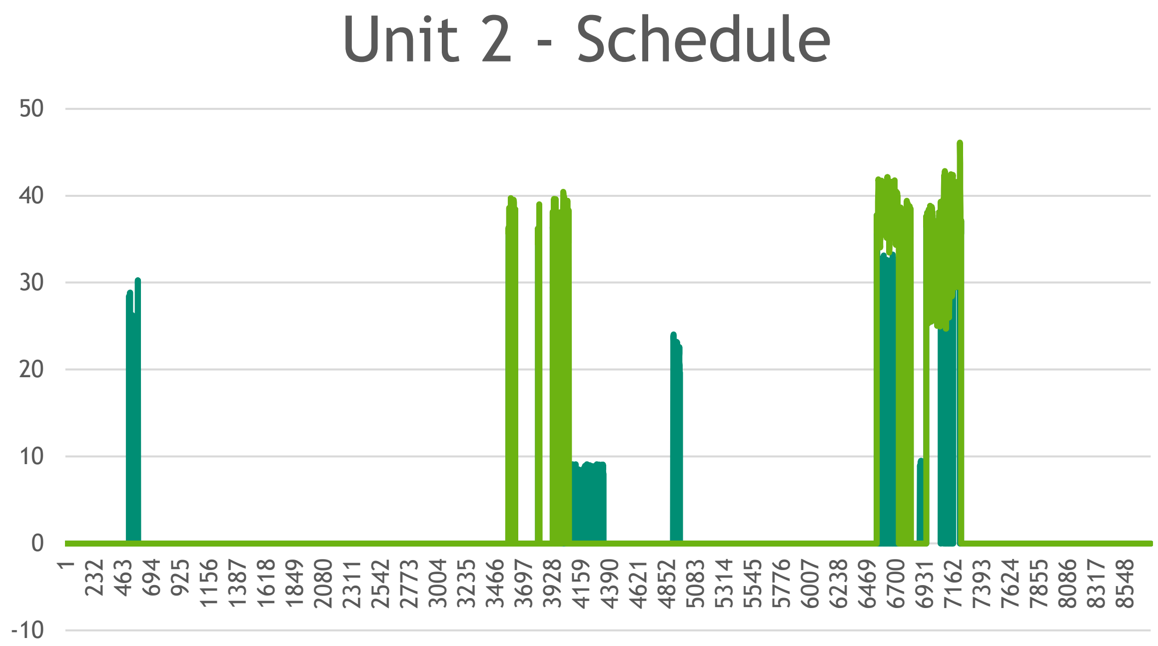
$$\min C = \sum_{i=1}^{24} \sum_{g=1}^{N} (f_g^i(P_g^i) cf_g + s_g^i cs_g + \alpha_g^i om_g)$$

- $f_g(P_g^i)$ is the fuel consumption of thermal unit g after time period i based on its power output P_g^i. cf_g is the fuel price for unit g
- s_g^i is a binary variable that indicates unit g starts at time i or not. cs_g is the start-up cost of unit g.
- α_g^i is a binary variable that indicates the status of unit g at time i. om_g is the variable O&M cost of unit g.

ENERGY STORAGE VALUATION – GENERATION PROBLEM - EXAMPLE

Case studies are conducted to evaluate the operating cost savings by using ESSs for a utility company in Alaska:

- 1 combined cycle, 4 gas units
- Minimum spinning reserve: 10MW if not islanded, 40MW if islanded.
- Natural gas price: 7.92/Mcf.
- Variable O&M cost and start-up cost for each unit are given in the following table.



	Fuel Cost ($)	O&M Cost ($)	Start-up Cost ($)	Annual Total ($)	Annual Saving ($)
Case 1 - No ESS	31,015,209	1,238,940	154,150	32,408,299	
Case 2 - 40MW/10MWh	30,700,007	1,218,237	59,810	31,978,055	430,244
Case 3 - 40MW/20MWh	30,681,801	1,227,761	24,845	31,934,407	473,891
Case 4 - 40MW/40MWh	30,723,217	1,178,834	15,445	31,917,496	490,802

ENERGY STORAGE VALUATION – TRANSMISSON PROBLEM

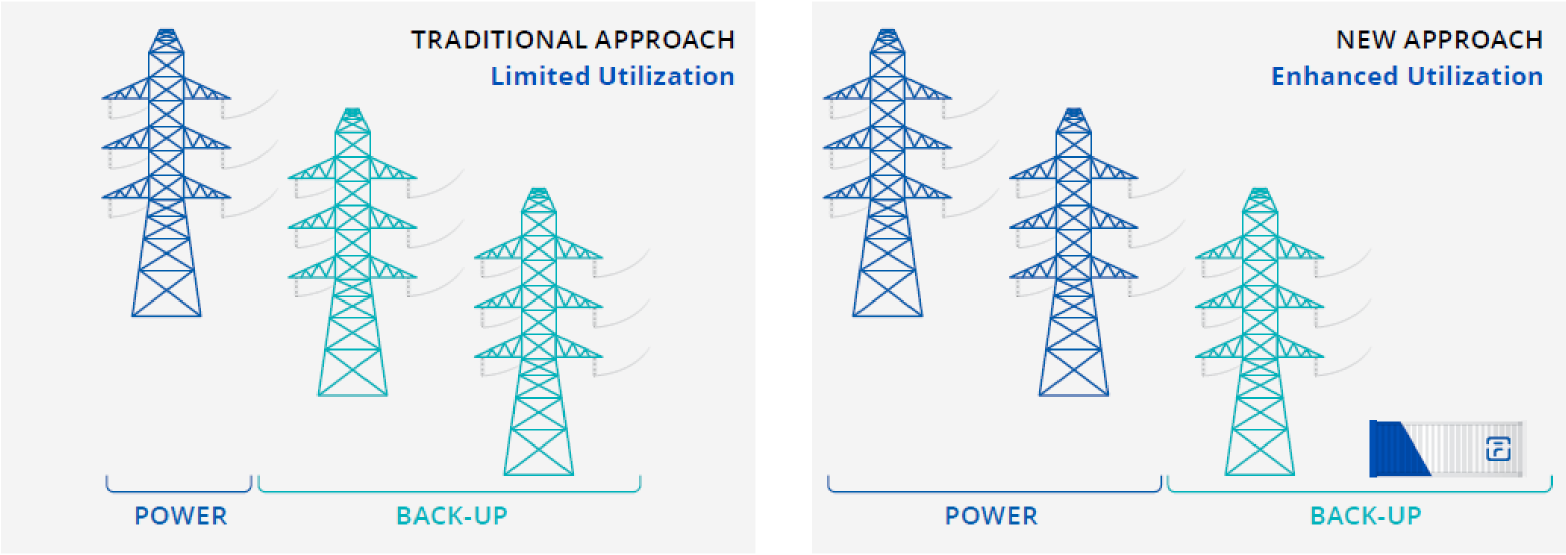
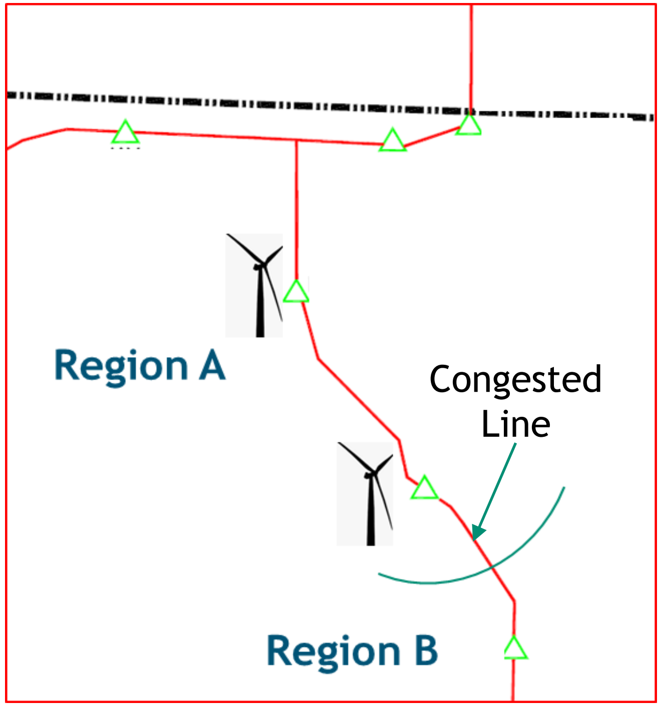
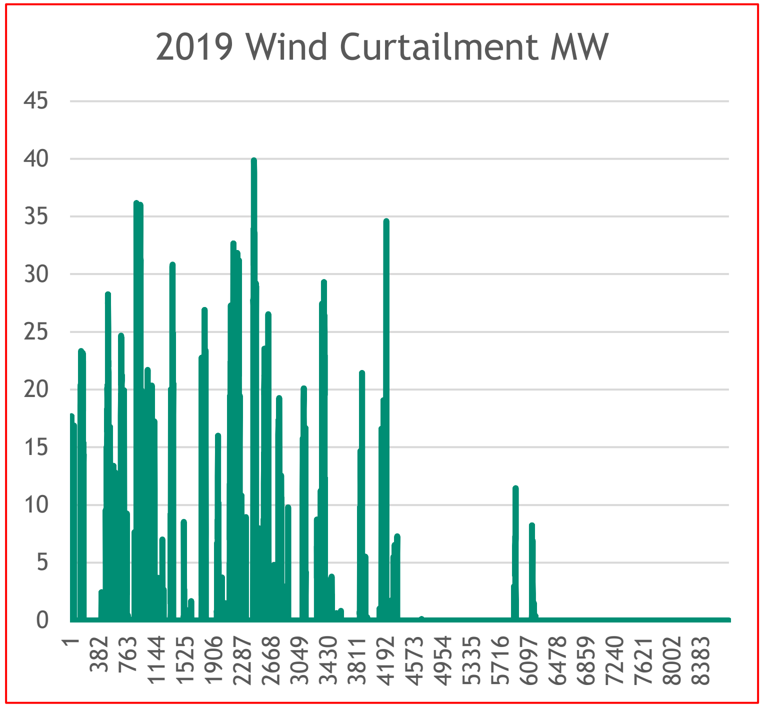


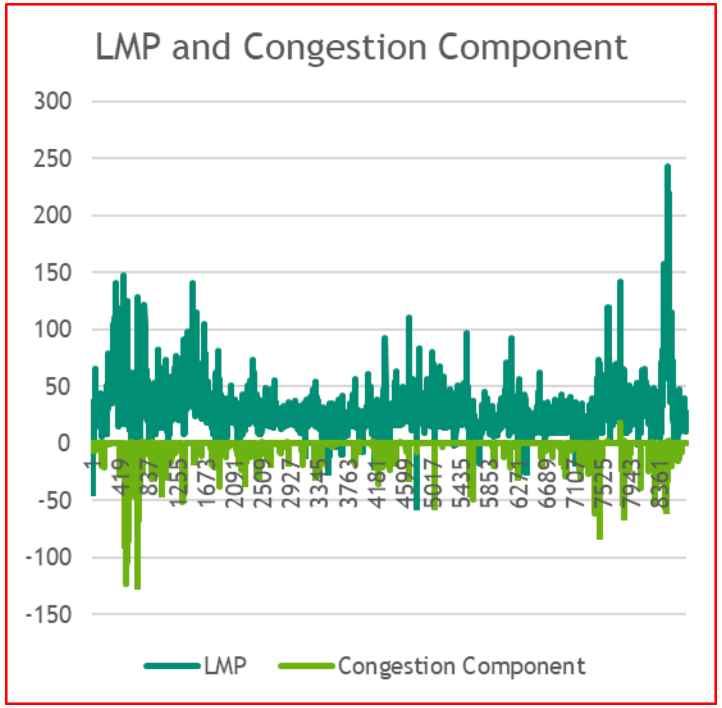
Image Credit: FLUENCE- Storage as Transmission White Paper

- Maximize the benefits from cost-base services together with market-based services:
  - Congestions relief: maximize opportunity for upstream generators to sell more energy at higher prices; minimize overall congestion cost
  - Market activities: energy arbitrage, ancillary services
- Evaluate the impact of virtual transmission in transmission planning: reduce the amount of transmission to meet N-1 security requirement.

ENERGY STORAGE VALUATION – TRANSMISSON PROBLEM - EXAMPLE

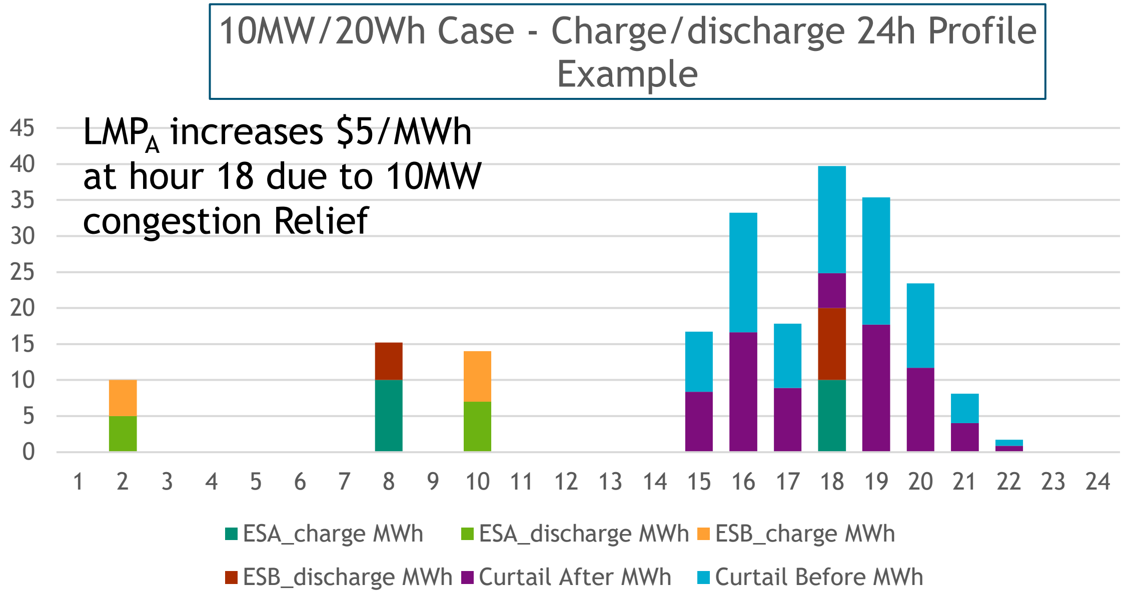


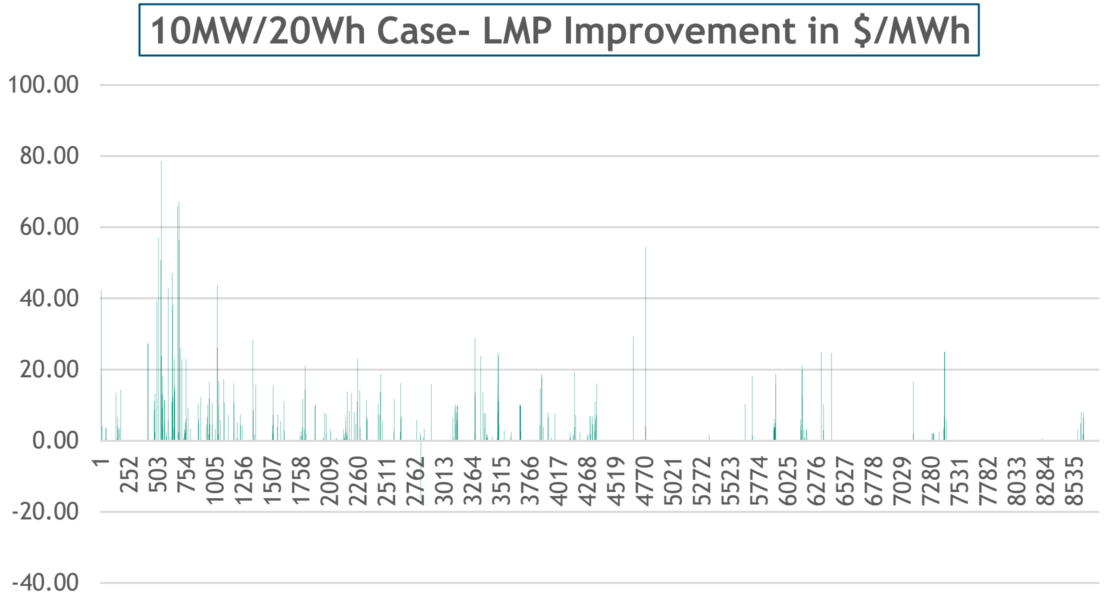


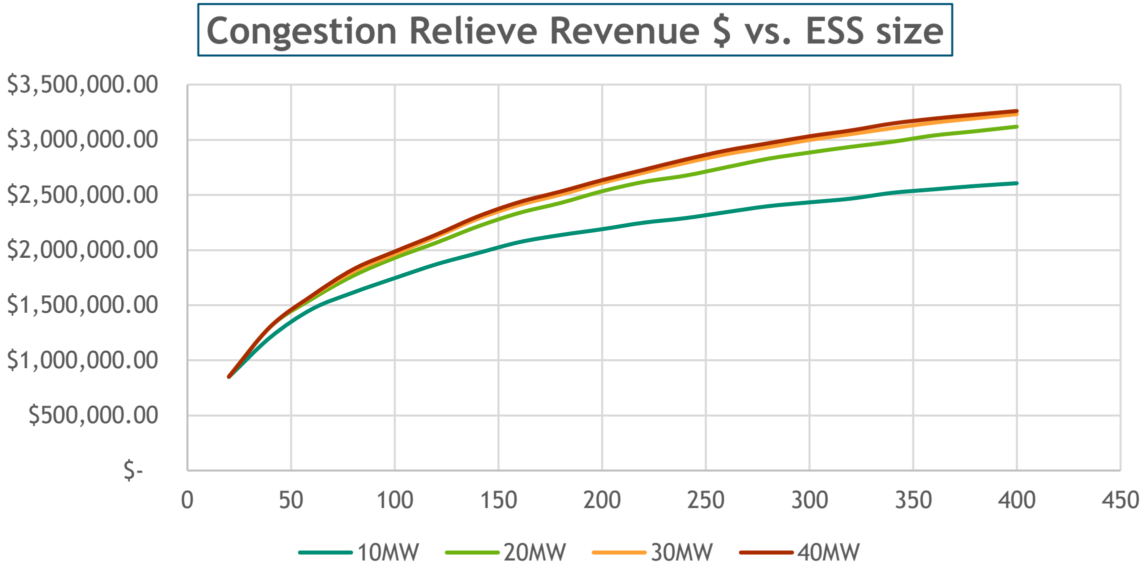


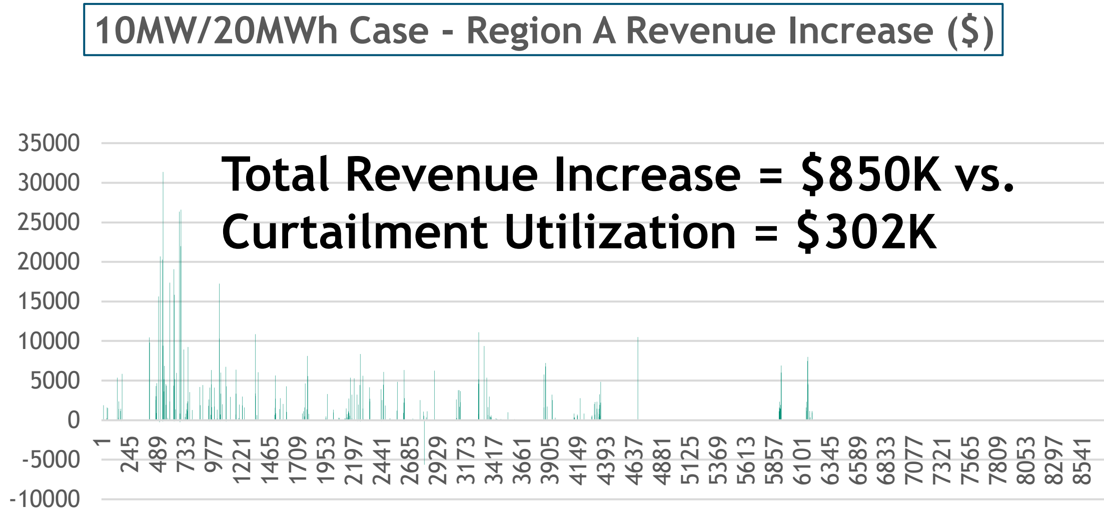
- Congestions make the marginal wind plant in region A curtail its output.
- Congestion component of LMP are negative indicating that if the congestions are relieved, more wind energy in region A can be sold to region B at higher LMPs
- In this case study:
  - Maximize the revenue for generators in region A by using storage as virtual transmission.
  - Compare with arbitrage benefit from wind curtailment.

ENERGY STORAGE VALUATION – TRANSMISSON PROBLEM - EXAMPLE







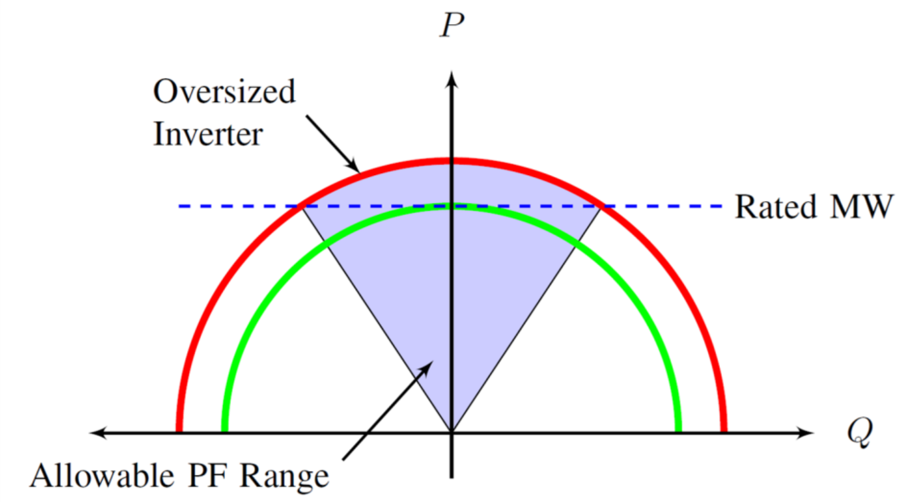


ENERGY STORAGE VALUATION – BTM PROBLEM

Given an energy storage device, a utility tariff structure, how would the device minimize the electricity bills for the customers?

$$\min\{C_E^m + C_N^m + C_D^m\}$$

s.t. energy storage and inverter constraints
C_E^m is the energy charge of period m
C_D^m is the demand charge of period m
C_N^m (≤ 0) is the net metering charge of period m.



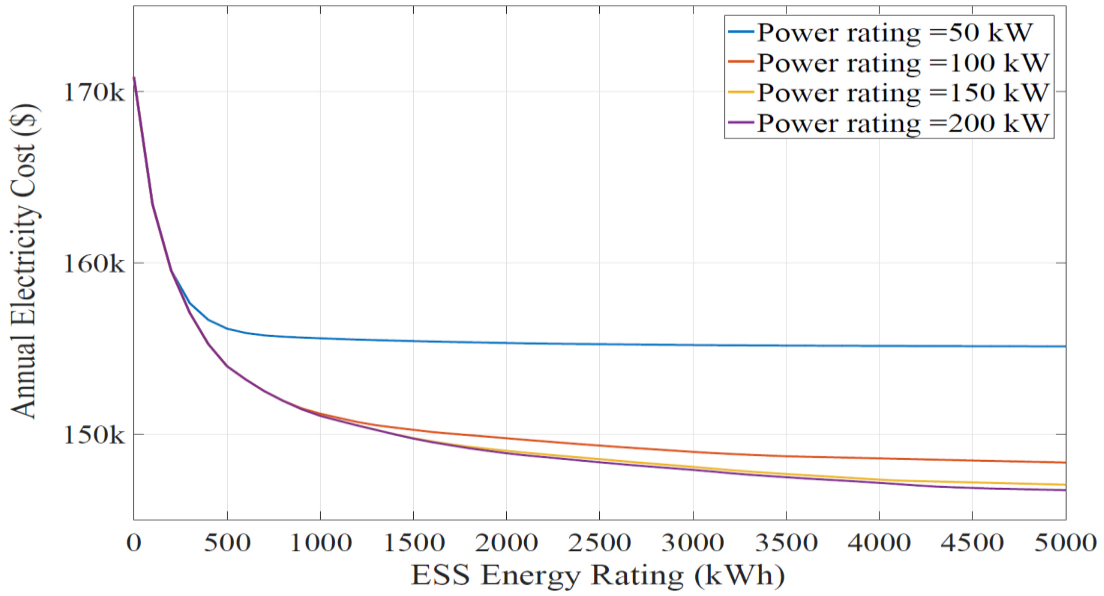
ENERGY STORAGE VALUATION – BTM PROBLEM - EXAMPLE

- An industrial customer in New Mexico is considered: a water treatment facility (300kW peak load) with 100kW PV.
- Fixed energy rate and TOU demand rate are applied.
- Penalty is applied for power factor lower than 0.9

Energy rate: $\text{pr} = 0.04537\ [\$/kWh]$
Peak-hour (6am-9pm) demand rate: $\text{d}_{\text{pk}} = 24.69\ [\$/kW]$
Off-peak (9pm-6am) demand rate: $\text{d}_{\text{opk}} = 6.12\ [\$/kW]$
Net-metering rate: $\text{pr}_{\text{s}} = 0.03[\$/kWh]$

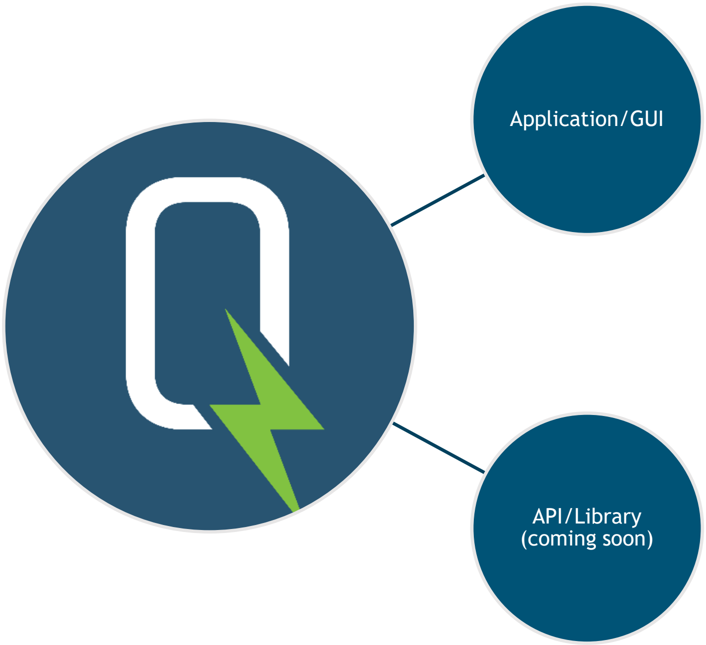
Case 1: TOU management without power factor correction

Case 2: TOU management with power factor correction



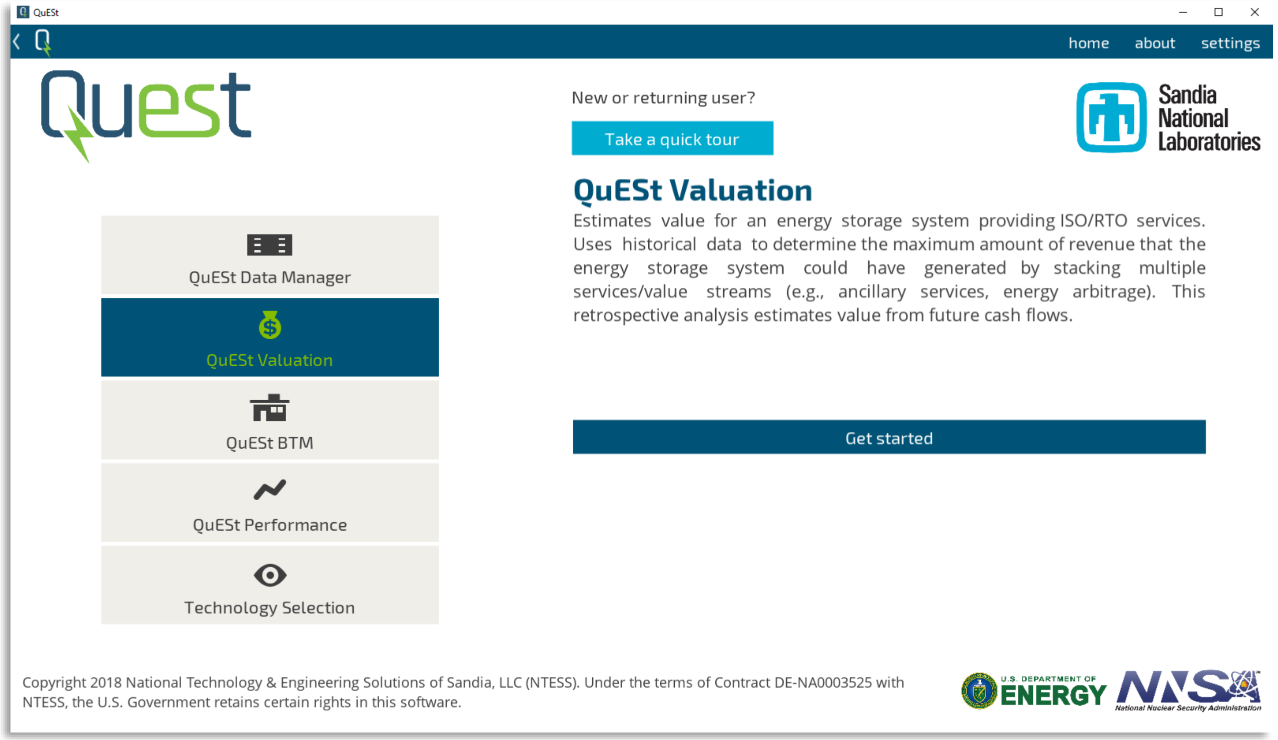
- Optimal size: 200kW/1MWh.
- Total saving: $30k (16.8%)
- Peak demands have been shifted to off peak hours.

QuESt Overview



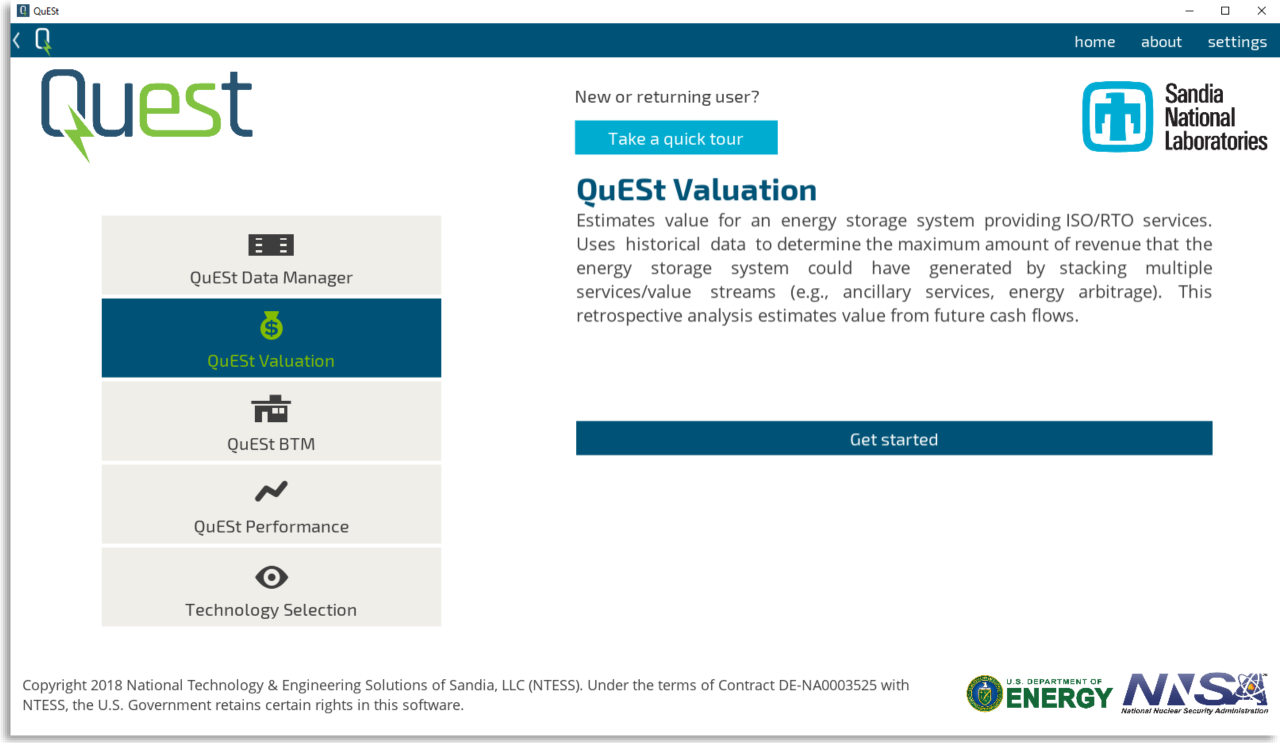
- Developed for user experience
- No hassle installation

- For power users
- Use for Python scripting
- More capabilities



- Energy storage analysis software application suite
- Version 1.0 publicly released in September 2018
- Version 1.6 available on GitHub
  - https://github.com/sandialabs/snl-quest

QuESt - Applications



Current:

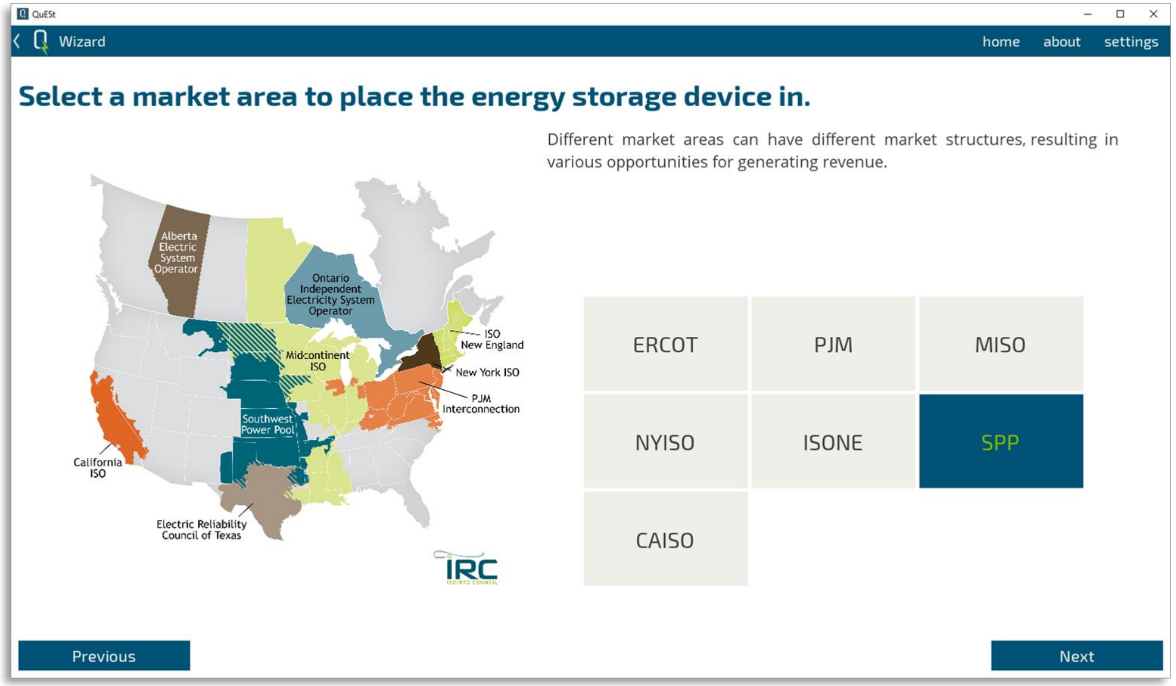
- **QuESt Data Manager** – Manages acquisition of data.
- **QuESt Valuation** – Estimate potential revenue generated by energy storage systems providing ancillary services in the electricity markets of ISOs/RTOs.
- **QuESt BTM** – Estimate the cost savings for time-of-use/net energy metering customers using behind-the-meter energy storage systems.
- **QuESt Technology Selection -** Support storage technology selection given applications and other requirements
- **QuESt Performance -** Evaluate energy storage system performance in different climates

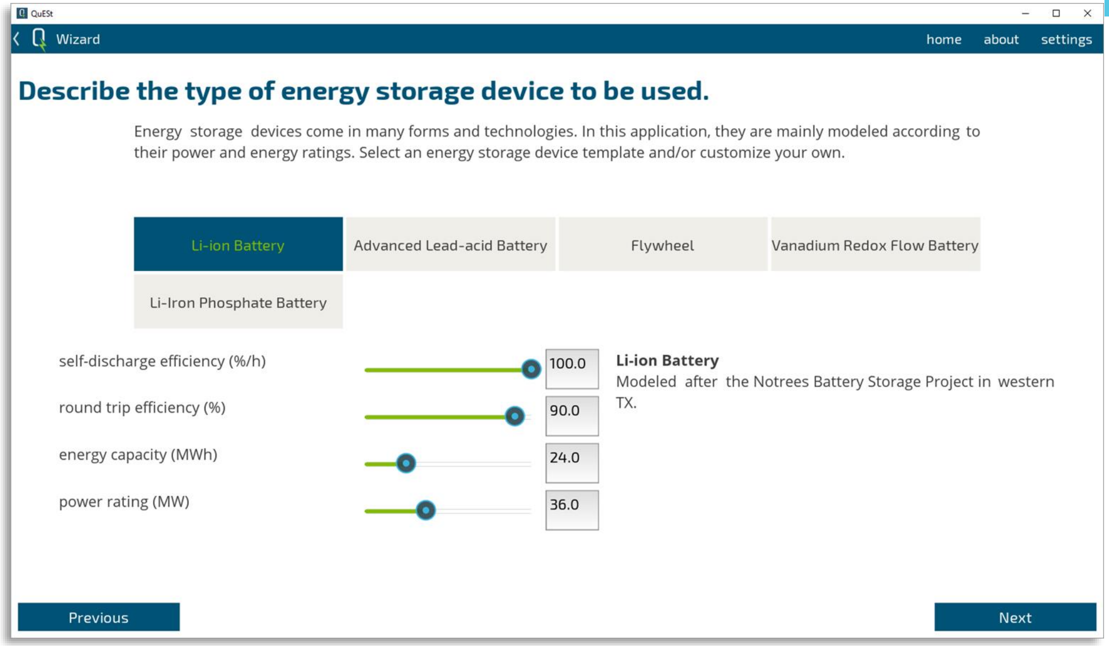
Next Release: QuESt Microgrid, QuESt Equity

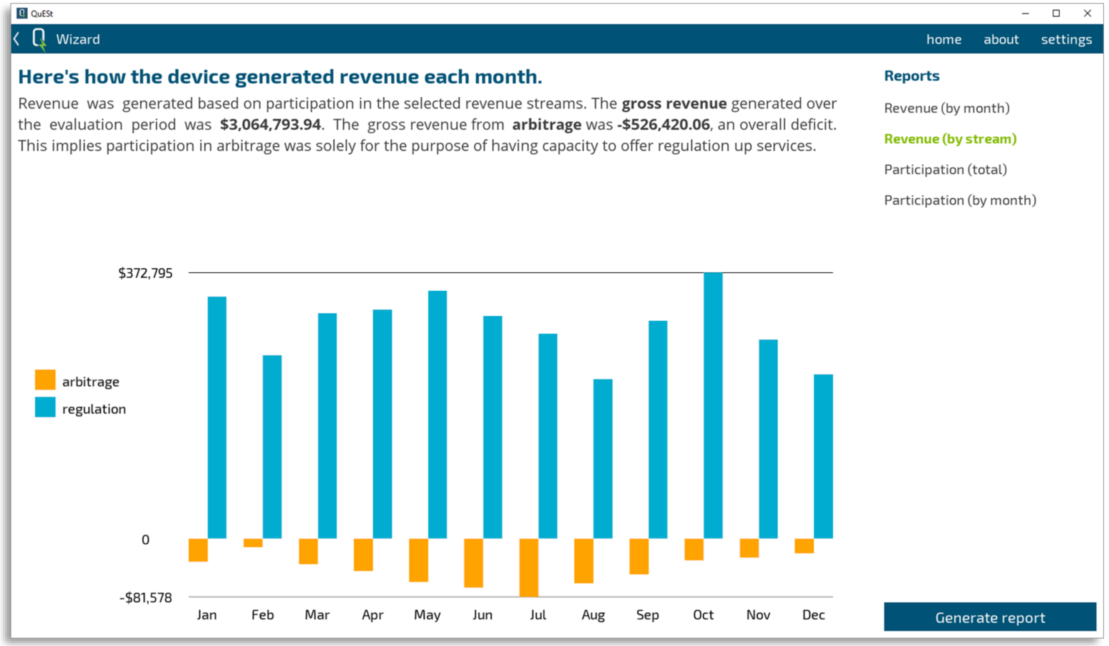
QuESt - Workflow

1. Decide what type of analysis to do.
   - ISO/RTO value stacking => QuESt Valuation
   - Behind-the-meter applications => QuESt BTM
2. Grab the appropriate data from QuESt Data Manager.
   - ISO/RTO market data
   - Utility rate structure
   - PV profile
   - Load profile
3. Select the appropriate application from the first step.
   - Set up the analysis and run it
   - View and process results

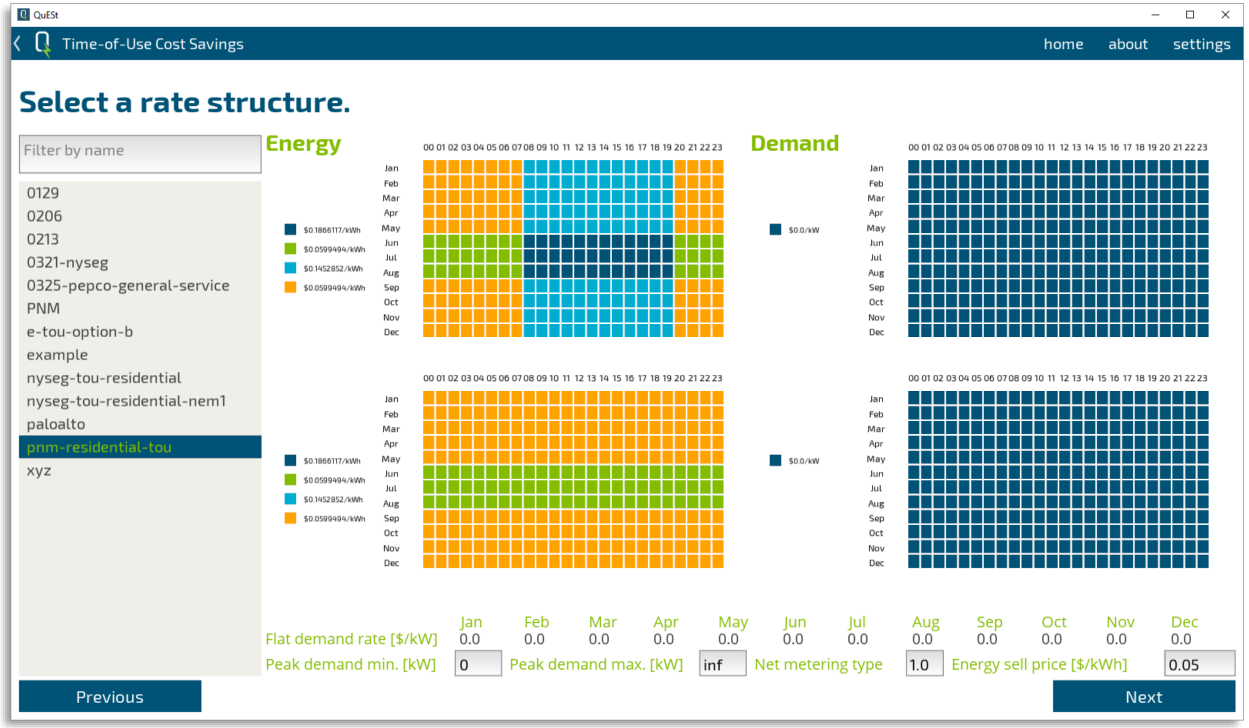
QuESt – Valuation Application

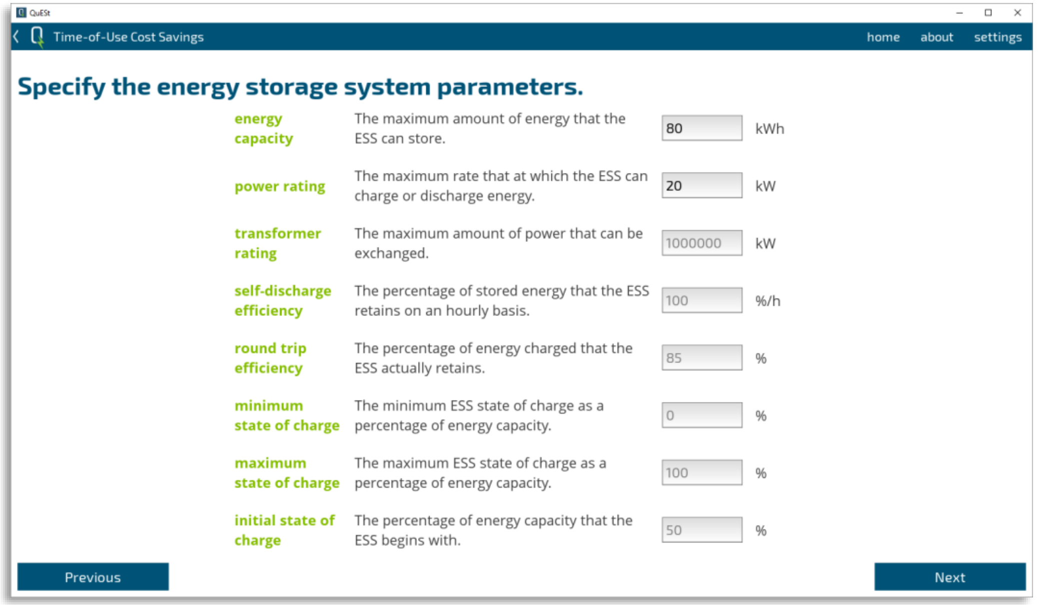


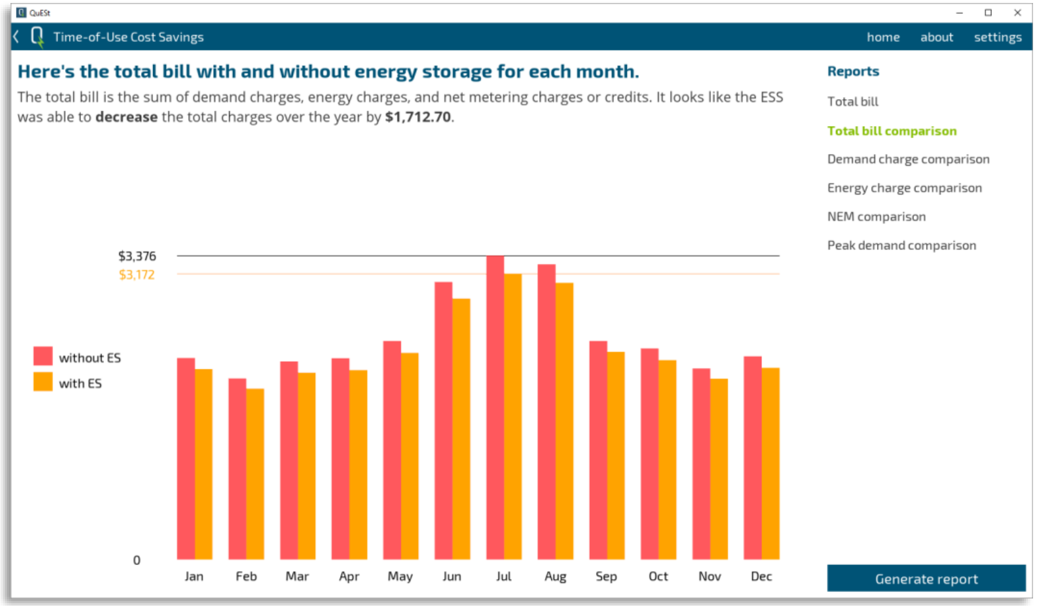




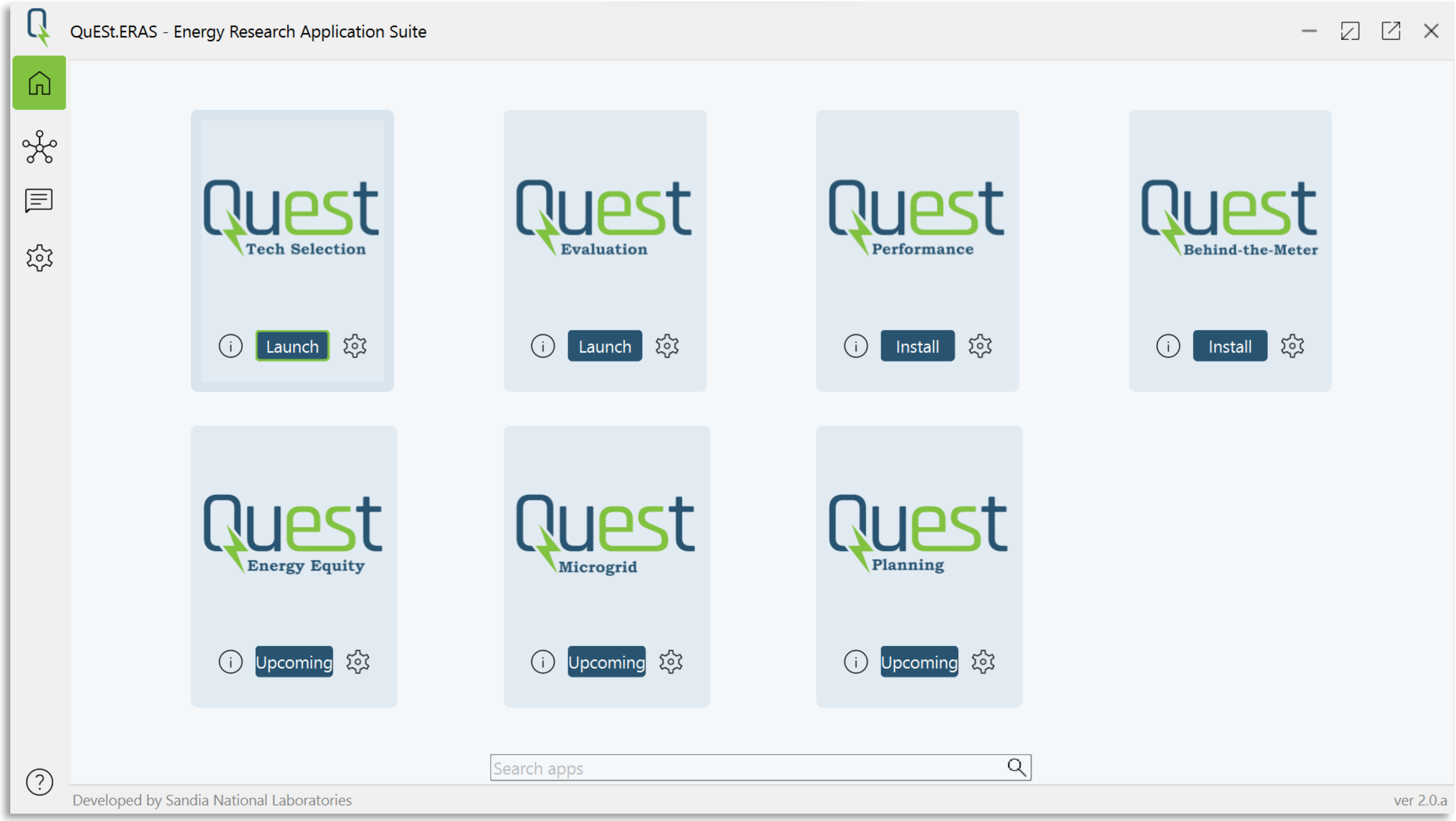
QuESt – BTM Application







QuESt 2.0



QuESt 2.0 includes 3 main components:

- QuESt App Hub works like an apps store that provides access points to multiple apps.
- QuESt Workspace provides an environment for integrating multiple apps into a work process
- QuESt GPT is a data analytic tool for the characterization and visualization of large datasets.

In Version 2.0, QuESt is being transformed from a software to a software platform.

Acknowledgements

Funding provided by US DOE Energy Storage Program directed by Dr. Imre Gyuk of the DOE Office of Electricity.

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