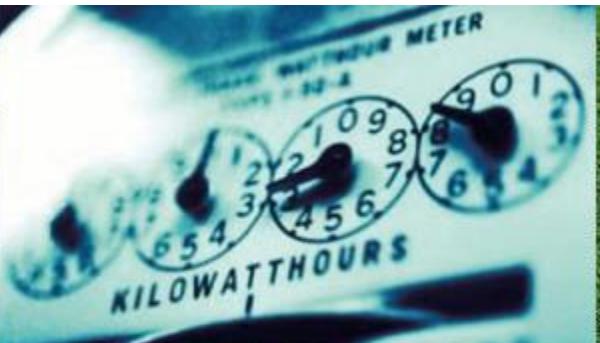


# Pumped Storage Hydro Valuation Program

Presented by: Patrick Balducci (Argonne National Laboratory)

2023 U.S. DOE Energy Storage Finance Summit

January 26, 2023



# Pumped Storage Hydro (PSH) Valuation Team

## Valuation Guidance & Techno-Economic Studies and Tool for Pumped Storage Hydropower



**Argonne National Laboratory (Argonne)**



**Idaho National Laboratory (INL)**



**National Renewable Energy Laboratory (NREL)**



**Oak Ridge National Laboratory (ORNL)**



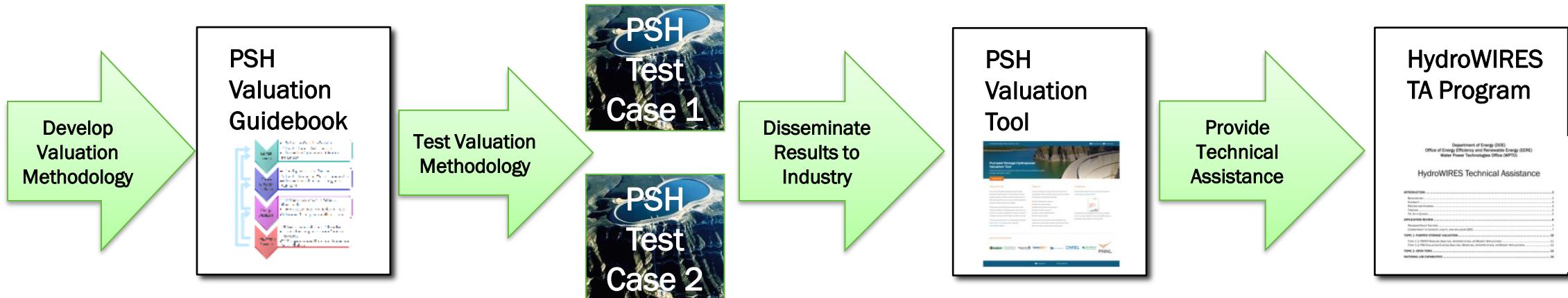
**Pacific Northwest National Laboratory (PNNL)**

# Program Goals and Objectives

**Objective:** Advance the state of the art in the assessment of value of PSH plants and their role and contributions to the power system

**Specific goals:**

1. Develop and test a comprehensive and transparent valuation guidance that will allow for consistent valuation assessments and comparisons of PSH projects
2. Transfer and disseminate the PSH valuation guidance to the hydropower industry, PSH developers, and other stakeholders
3. Provide technical assistance (TA) to the hydropower industry (\$4 million TA program)



# Techno-Economic Studies

A variety of analyses were carried out to assess the costs and benefits of various PSH services and contributions to the grid

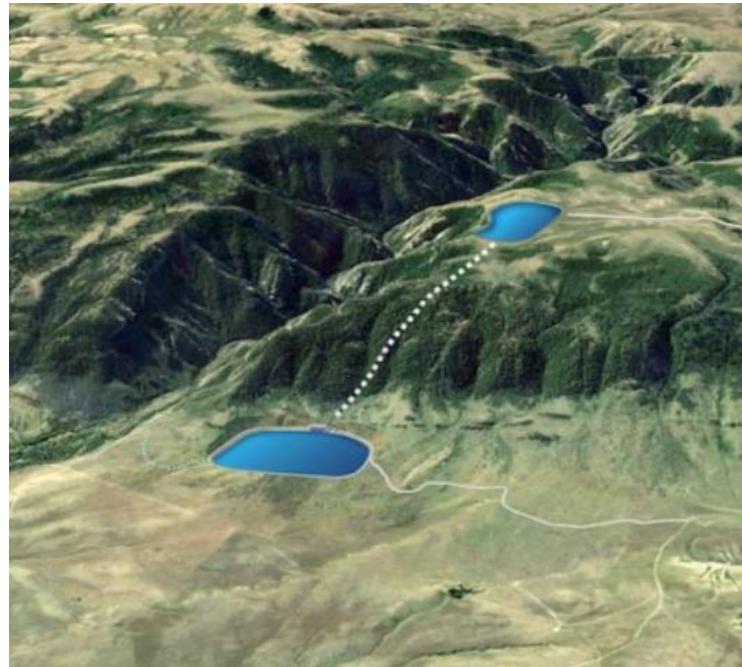
- Bulk power capacity and energy value over PSH lifetime
- Value of PSH ancillary services (regulation service, contingency reserves, etc.)
- Power system stability services (inertial response, governor response, transient and small signal stability, voltage support)
- PSH impacts on reducing system cycling and ramping costs
- Other indirect (system-wide or portfolio) effects of PSH operations (e.g., PSH impacts on decreasing overall power system production costs, benefits for integration of variable energy resources, and impacts on power system emissions)
- PSH transmission benefits (transmission congestion relief, transmission investments deferral)
- PSH non-energy services (water management services, socioeconomic benefits, and environmental impacts)

# The Project Team Collaborated with Two Industry Partners

## Absaroka Energy

### Banner Mountain PSH

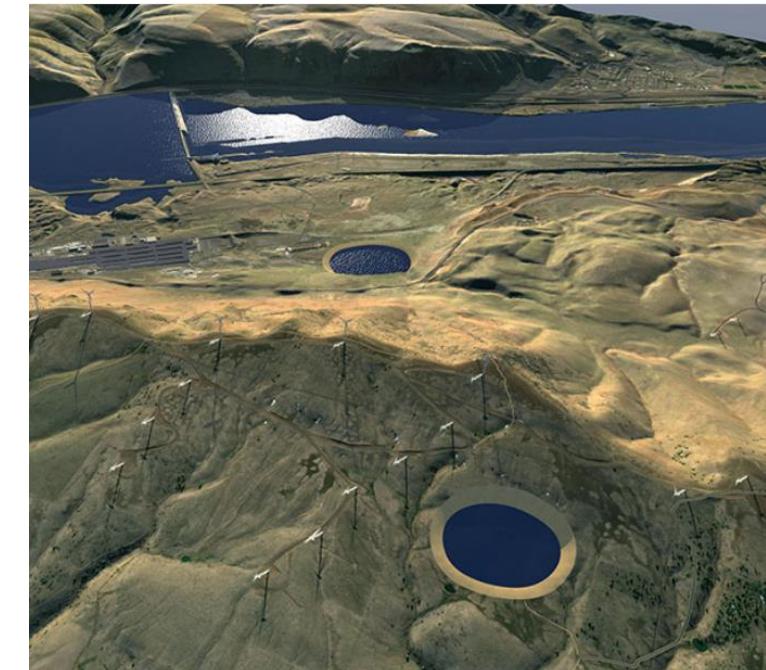
- 400 MW, quaternary technology
- Closed loop
- Site near Casper, WY



## CIP & Rye Development\*

### Goldendale Energy Storage Project

- 1,200 MW, adjustable speed technology
- Closed loop
- Site just north of OR/WA border



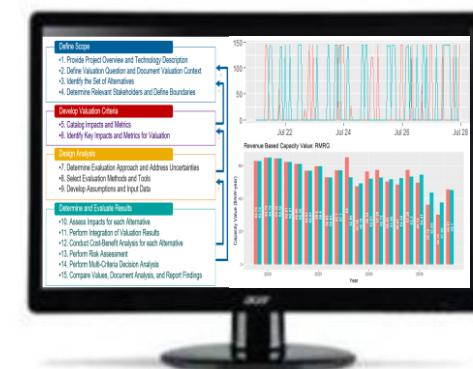
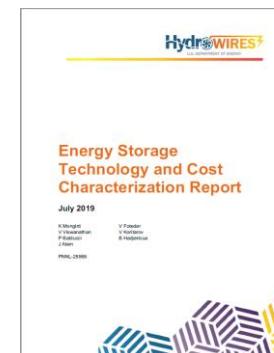
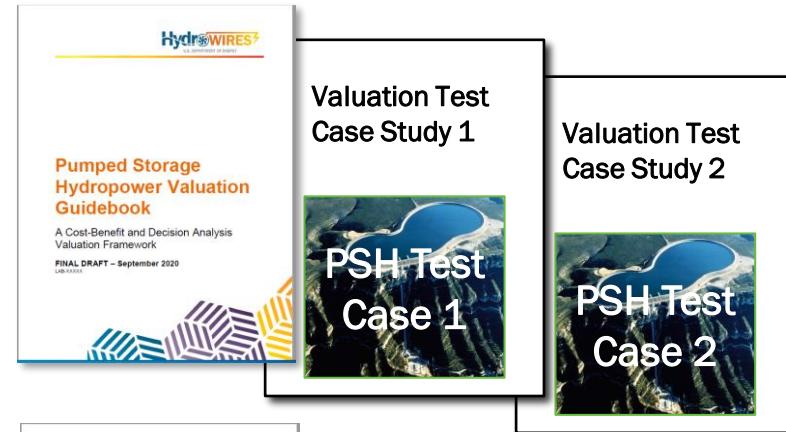
\*CIP = Copenhagen Infrastructure Partners

# Key Products of the PSH Valuation Project

- PSH Valuation Guidebook (published)
- Two technical reports illustrating test case studies for actual PSH projects (complete)

- Energy storage cost and performance study (published)

- PSH valuation tool to help the users navigate the PSH valuation process (<https://pshvt.egs.anl.gov/>)



# PSH Valuation Tool

- PSH valuation tool provides step-by-step valuation guidance for PSH developers, plant owners or operators, and other stakeholders
- PSH tool advances the state of the art in evaluating a broad set of use cases from three perspectives: owner/operator, system, and society
- PSH tool has several advanced features:
  - Embedded price-taker model
  - Multi-criteria decision analysis (MCDA) tool
  - Embedded financial worksheets and benefit-cost analysis (BCA) model
  - Embedded price-influencer model

Pumped Storage Hydro Valuation Tool

User Manual | Guidebook

Pumped Storage Hydropower Valuation Tool

A step-by-step tool to assess the value of services provided by pumped storage hydropower plants

Launch Tool

About the Tool

As an energy storage technology, pumped storage hydropower (PSH) supports various aspects of power system operations. However, determining the value of PSH plants and their many services and contributions to the power system has been a challenge.

This decision tree-based tool provides step-by-step valuation guidance for PSH developers, plant owners or operators, and other stakeholders to assess the value of existing or potential new PSH plants and their services.

This tool was funded by the U.S. Department of Energy's Water Power Technologies Office under the HydroWIRES initiative.

Features

- Value of bulk power capacity
- Value of energy arbitrage
- Value of production cost reductions
- Value of ancillary services
- Power system stability benefits
- Transmission benefits

Guidebook

The methods outlined in this tool are documented in a PSH valuation guidebook (PDF).

The methods in the guidebook were used to complete techno-economic studies of two proposed PSH plants in Goldendale, WA and Banner Mountain, WY.

Sponsors and Partners

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy Argonne NREL Idaho National Laboratory NREL Oak Ridge National Laboratory PNNL

Contact Us

Privacy/Security

PSH Valuation Tool Home Page

# Price-taker Model

- PNNL adapted its Battery Storage Evaluation Tool (BSET) to PSH
- Embed BSET within the tool
- Tool provides:
  - Optimization across single or multiple services customized by users
  - Optimization without perfect foreknowledge of prices; operations based on historical prices or price predictions
  - Power and energy limit specifications
  - Model can be used to determine optimal power capacity and energy ratings

Category	Use Case
Bulk Energy	Energy Arbitrage
	Capacity
Ancillary Services	Frequency Regulation
	Spin / Non-Spin
Transmission	Upgrade Deferral
	Congestion Relief
Distribution	Upgrade Deferral
	Volt-VAR
Customer Energy Management	Power Reliability
	TOU Charge Management
	Demand Charge Management

Price-taker Model Use Cases

# MCDA Tool

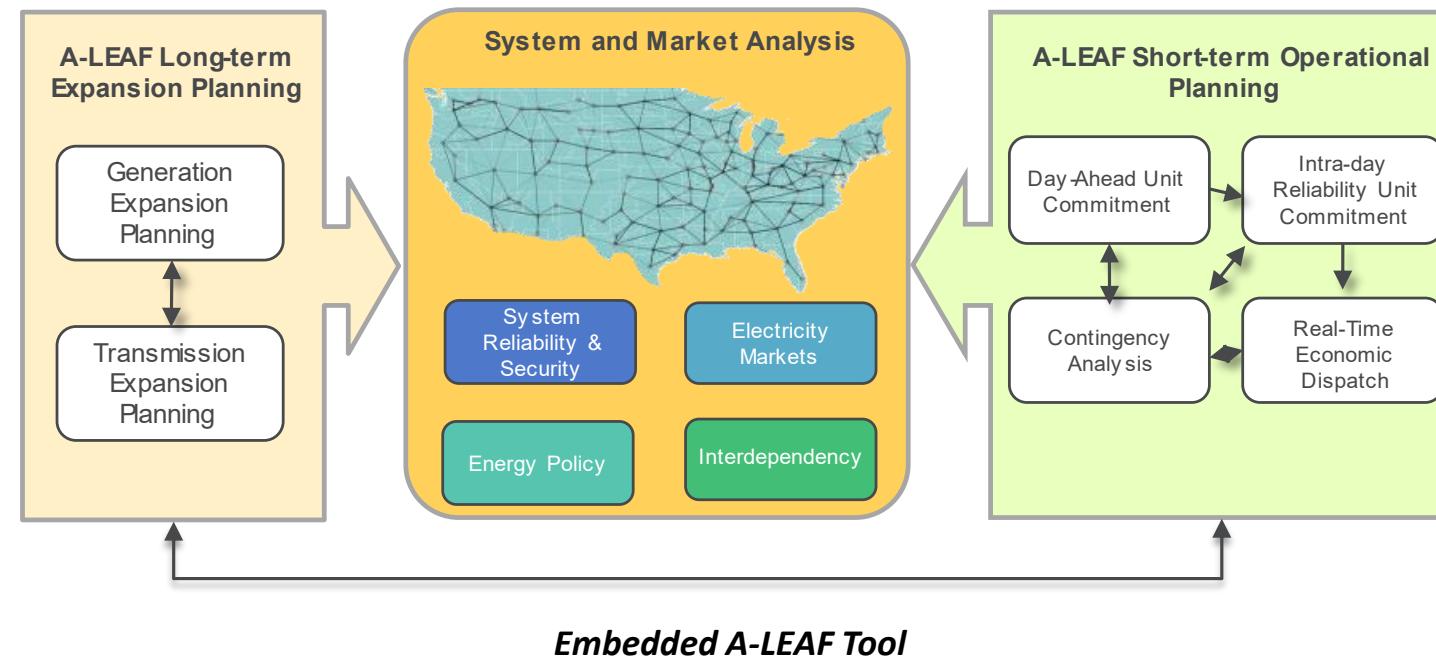
- Choosing among different alternatives with multiple attributes
- Many PSH impacts are not easily monetized and must be expressed in physical units or qualitatively
- How to compare different alternatives that are described by both monetized and non-monetized impacts?
- A decision-support system can help decision-makers choose among different alternatives defined by multiple attributes

Entered Optimization Goal and Bounds of Measurement Scale									
	Alternative 1			Alternative 2			Alternative 3		
Metric 1	NPV	Lower Bound	-40.0	Upper Bound	60.0	Goal	Maximize	45	85
								30	70
								40	80
Metric 2	VER Curtailments	Lower Bound	0.0	Upper Bound	50.0	Goal	Minimize	30	40
								40	20
								45	10
Metric 3	Interruption Cost	Lower Bound	0.0	Upper Bound	30.0	Goal	Minimize	15	50
								22	27
								19	37
Metric 4	Environmental Score	Lower Bound	0.0	Upper Bound	5.0	Goal	Maximize	4	80
								2	40
						Average			
	NPV	Value	85	Weight	0.222	Weighted Scores	18.88	Value	70
	VER Curtailments		40		0.188		7.50	Weight	0.222
	Interruption Cost		50		0.289		14.47	Weighted Scores	15.55
	Environmental Score		80		0.301		24.08	Value	10
								Weight	0.188
								Weighted Scores	3.75
								Value	37
								Weight	0.289
								Weighted Scores	7.72
								Value	60
								Weight	0.301
								Weighted Scores	10.61
								Value	80
								Weight	0.222
								Weighted Scores	17.77
								Value	60
								Weight	0.301
								Weighted Scores	18.06
	Performance Index			64.93			39.06		
							48.31		

PSHVT MCDA Tool

# Argonne Low-carbon Electricity Analysis Framework (A-LEAF)

- Integrated national-scale power system simulation framework developed at the Argonne National Laboratory, used to analyze various issues related to the evolution of the nation's power system.
- Suite of least-cost generation & transmission expansion, unit commitment, and economic dispatch models
- Determine system optimal generation portfolio and hourly or sub-hourly unit dispatch under a range of user-defined input assumptions for technology characteristics and system/market requirements



# How A-LEAF Works in the PSH Valuation Tool

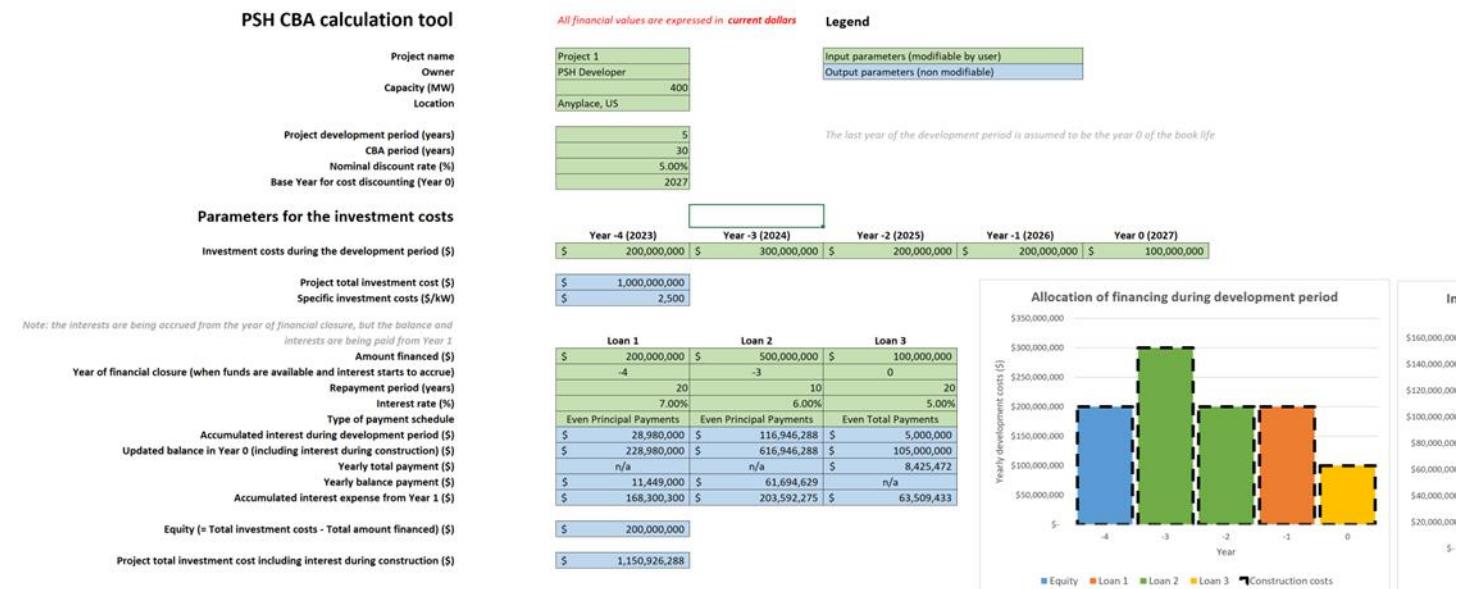
- **A-LEAF is embedded as an option**
  - Users can choose the current approach for estimating PSH values using multiple external tools or select the A-LEAF option
- **Data**
  - Users can use the default national scale dataset provided in A-LEAF
  - The tool supports users as they define input data for their own analysis
- **Alternative Scenarios**
  - Natural gas prices and technology costs
  - Environmental policies and tax credits
  - 134 balancing areas around US
- **Use Cases**
  - A-LEAF is customized to support several use cases in the PSH valuation tool

Category	Service
Bulk Energy Services	Electricity price arbitrage
	Bulk power capacity
Ancillary Services	Frequency regulation
	Contingency reserve
	Flexibility reserve
	Black start service
	Reduced power outages
Power System Indirect Benefits	Reduced electricity generation cost
	Reduced ramping of thermal units
	Reduced curtailments of variable generation
Transmission Infrastructure Benefits	Transmission upgrade deferral
	Transmission congestion relief
Energy Security Benefits	Fuel savings and diversification
	Major blackouts avoided

**A-LEAF Use Cases**

# BCA Calculator, Financial Worksheets, and Reporting

- BCA calculator runs the user through a series of data requests
- Model enables the user to define alternative scenarios, evaluate many use cases, and consider alternative debt structures, alternative depreciation methods, tax implications, salvage value, all capital and operations and maintenance costs, and refurbishment costs
- BCA calculator defines a benefit-cost ratio, discounted payback period, and an internal rate of return for each case
- The tool produces a report providing a technology overview, stakeholder engagement plan, use case and metrics, and results of the BCA and MCDA



**PSHVT BCA Calculator**

# Thank you! Questions?

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Contact:

**Patrick Balducci**

*Manager, Power Systems and Markets Research Group*

**ARGONNE NATIONAL LABORATORY**

**Cell: 503-679-7316**

**[pbalducci@anl.gov](mailto:pbalducci@anl.gov)**



# Energy Storage, DER, and Microgrid Project Valuation

## EPRI DER-VET™ Analysis in Action

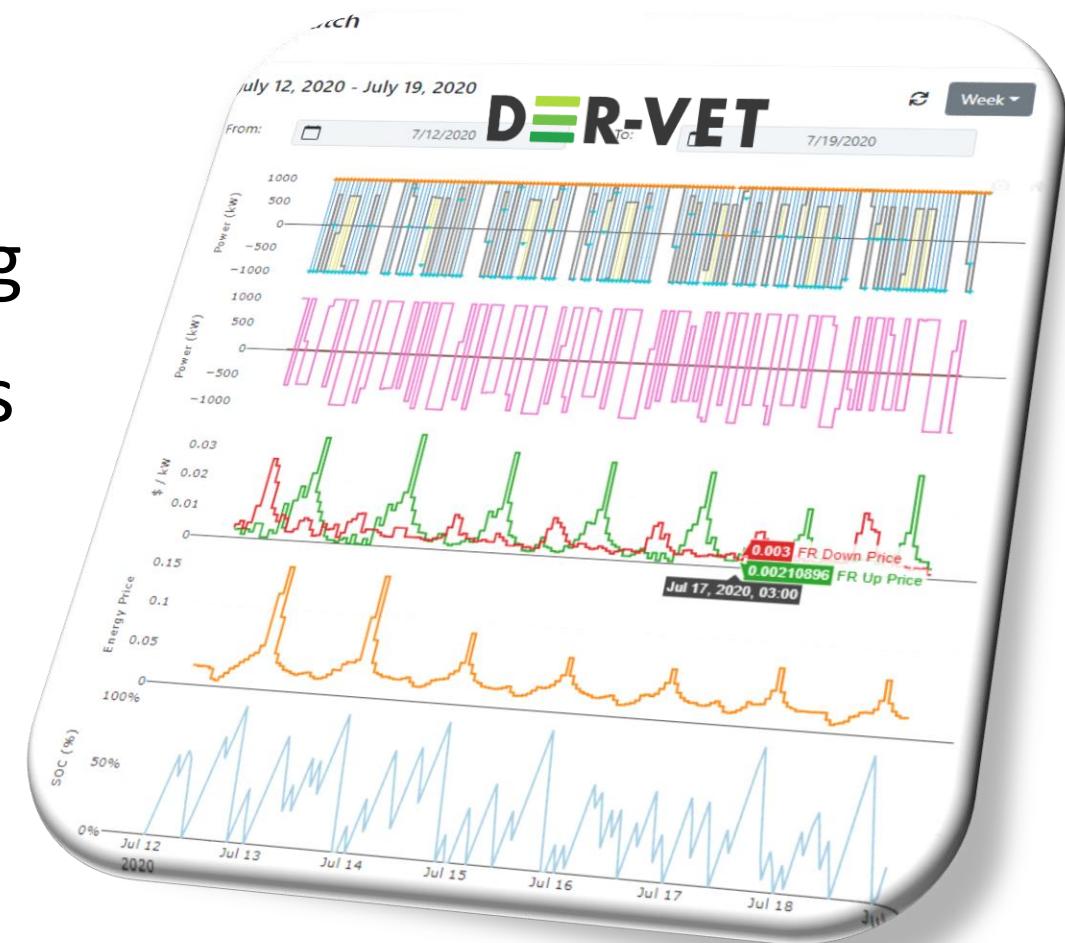
Eva Gardow  
[evgardow@epri.com](mailto:evgardow@epri.com)  
Technical Executive | EPRI

January 26, 2023

# The Challenges of Storage, DER\*, & Microgrid Modeling

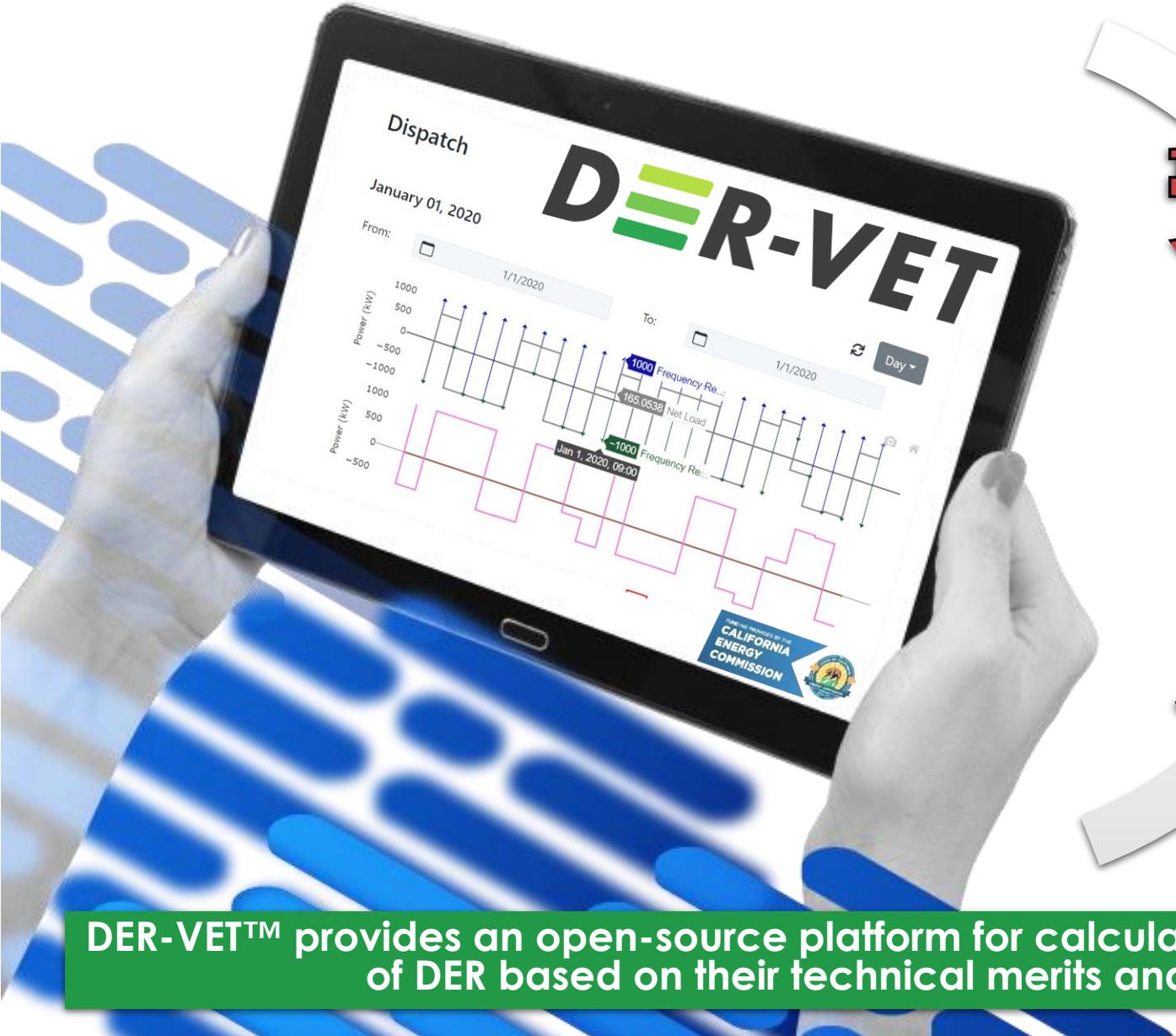
- Today's energy storage, DER, and microgrid deployments demand robust analysis for strategic planning
- Valuation of energy storage requires project-level analyses for specific applications and locations
- This is a complex co-optimization, decision-making process

\*DER: Distributed Energy Resources

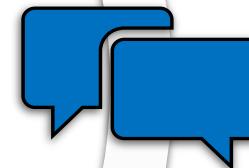


**EPRI's Distributed Energy Resources Value Estimation Tool,  
DER-VET™ addresses these challenges**

# The Solution: EPRI's DER-VET™



Bridges industry gaps in project-level energy storage, DER, and microgrid analysis with a publicly available tool and methodology



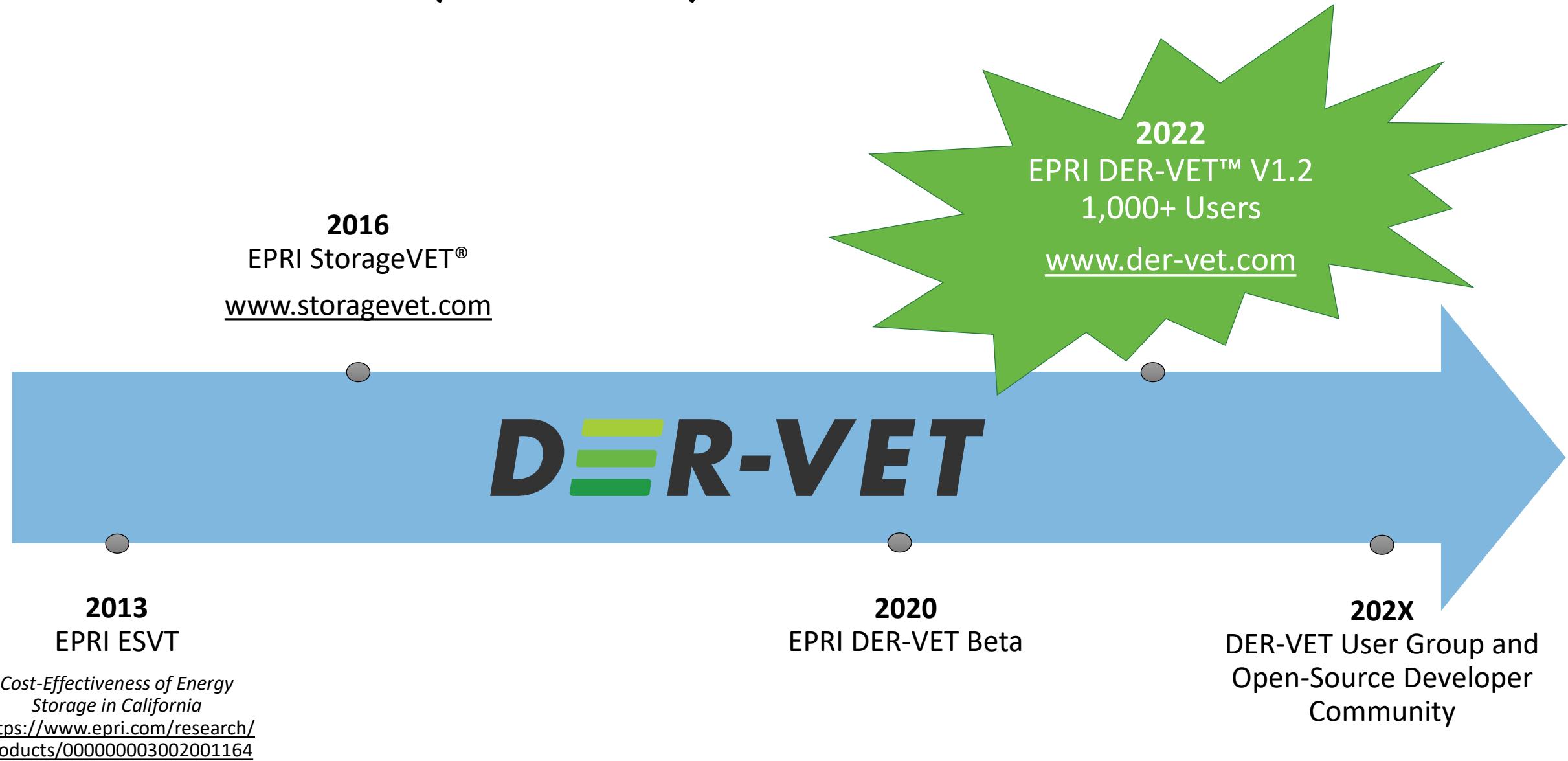
Creates a common and consistent communication tool among stakeholders



Evaluates various perspectives from customers values to grid values in any market; estimates benefits and costs of energy storage and other DER

DER-VET™ provides an open-source platform for calculating, understanding, and optimizing the value of DER based on their technical merits and constraints: [www.der-vet.com](http://www.der-vet.com)

# DER-VET's Past, Present, and Future



To download DER-VET, go to <https://www.der-vet.com/>

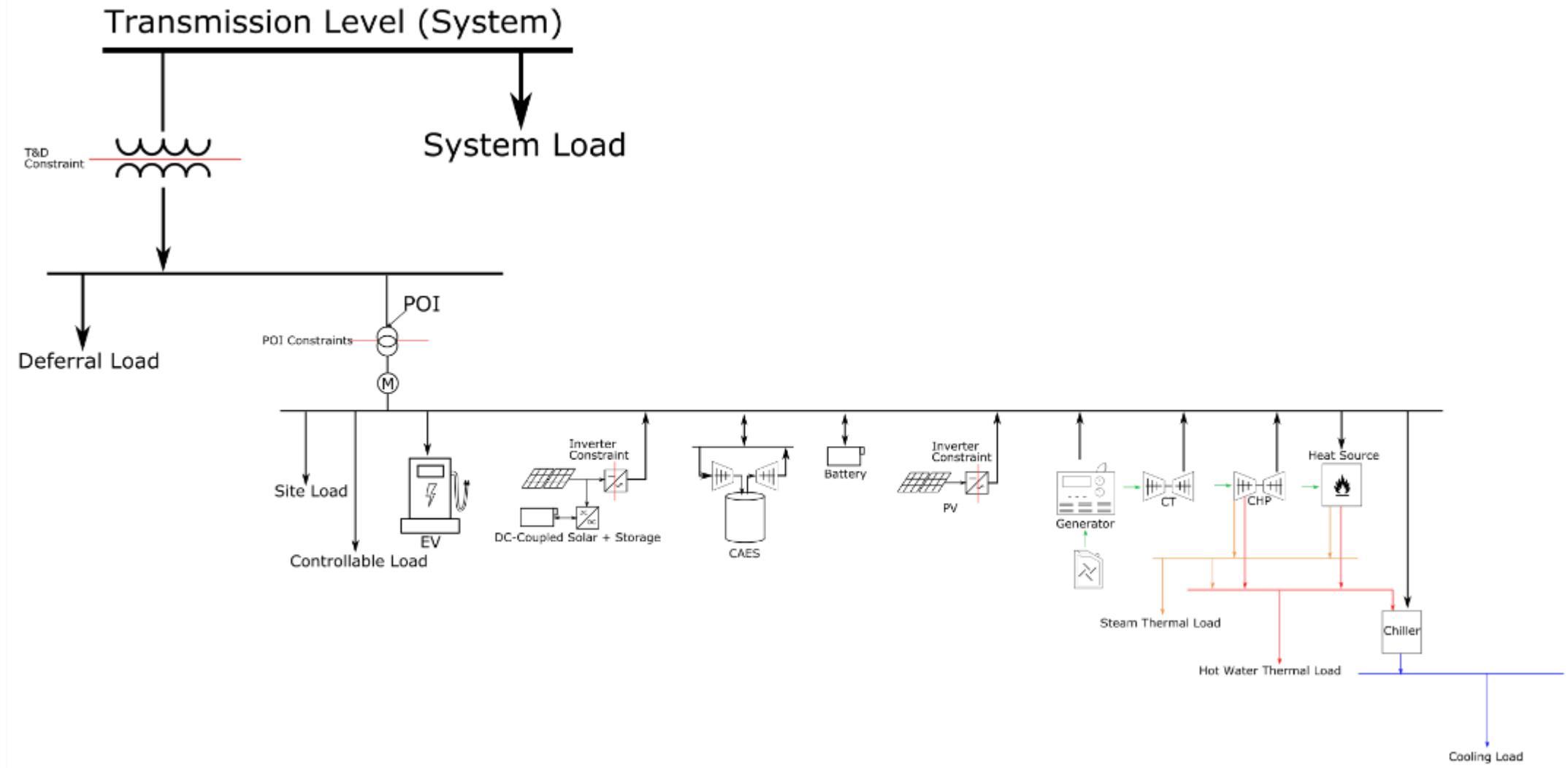
- Download the tool for free as it was developed with California Energy Commission funding
- [\*\*Software Release: DER-VET™ Version 1.2 \(Updated July 11, 2022\)\*\*](#)
- [\*\*DER-VET™ Overview Presentation \(September 2022\)\*\*](#)
- [\*\*DER VET User Guide\*\*](#)



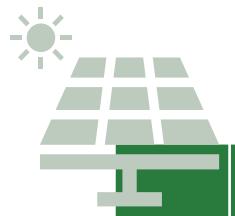
- **Get Involved**

- Engage with monthly Public ESIC Task Force Web Meetings. The Energy Storage Integration Council (ESIC), an open technical forum. More info can be found at [www.epri.com/esic](http://www.epri.com/esic).
- ESIC Working Group 1 DER-VET™ Task Force Meeting Recordings can be found at [www.der-vet.com/esictf](http://www.der-vet.com/esictf)
- The ESIC collaboration site contains live draft user documentation from the ESIC DER-VET™ Subgroup at [collab.epri.com/esic](http://collab.epri.com/esic).

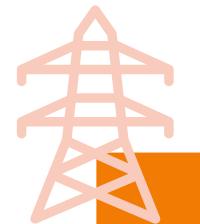
# Technologies in DER-VET



# Services in DER-VET



- Energy Time Shift
- Load Following
- Frequency Regulation
- Spinning Reserves
- Non-spinning Reserves
- Resource Adequacy Capacity



- Upgrade Deferral
- Reliability/Resilience



- Retail Energy Time Shift
- Demand Charge Reduction
- Demand Response
- Reliability/Resilience

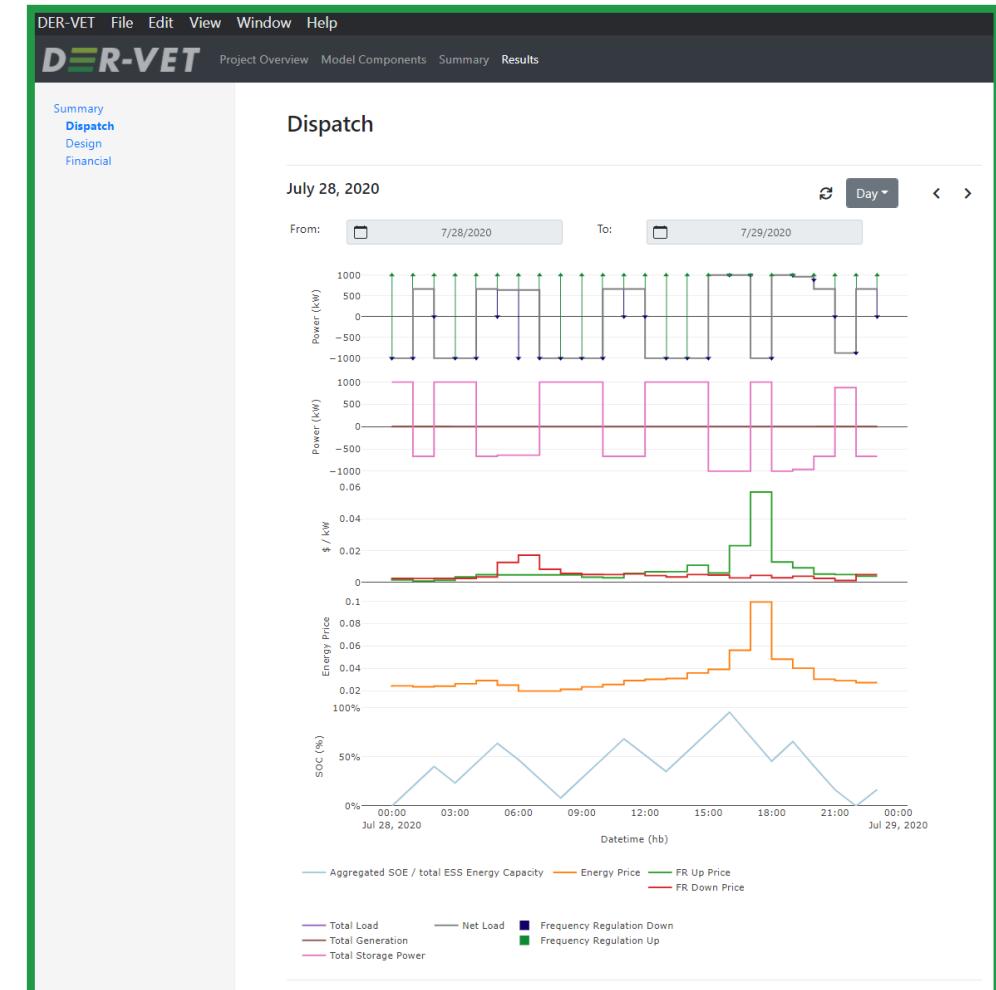
# Input and Output Examples in DER-VET

## DER-VET Project Configuration Example

The screenshot shows the 'Project Configuration' screen of the DER-VET software. The main area is titled 'Project Configuration'. It includes several sections:

- Name:** CAISO Pre-Defined Case
- Start Year:** 2020
- Analysis Window:**
  - Analysis Horizon Mode:** User-defined (selected)
  - Analysis Horizon:** 10 years
- Time Series Data:**
  - Data Year (Baseline):** 2020
  - Timestep:** 60 minutes
- Grid Domain:** Generation (selected)
- Ownership:** 3rd Party (selected)
- Run Configuration:** Output Folder (with a 'Select folder' button)

## DER-VET Dispatch Results Example





# Long Duration Energy Storage Case Study

# Long Duration Energy Storage (LDES) DER-VET Analysis

Type	Technology	Acronym	TRL
	Concrete Thermal Energy Storage	CTES	4
	Electro-Thermal Energy Storage	ETES	3
	Gravitational Energy Storage	GES	6
	Liquid Air Energy Storage	LAES	6
	Lithium-Ion Battery Storage	Li-Ion	9

## Base

- All technologies were run using the original pricing curves in each region for 4h for Li-Ion Benchmark as well as 6, 8, and 10h

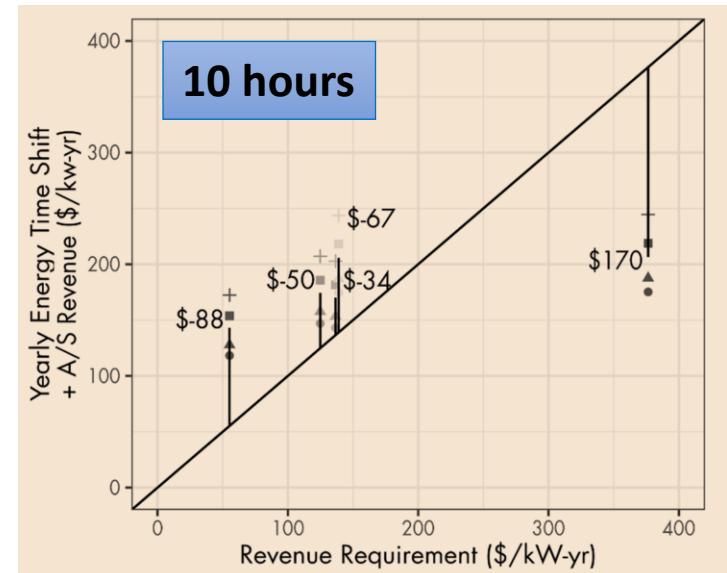
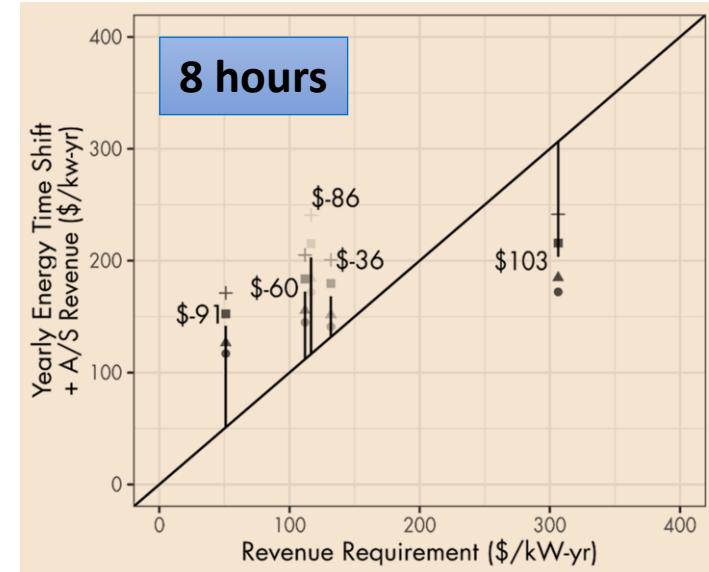
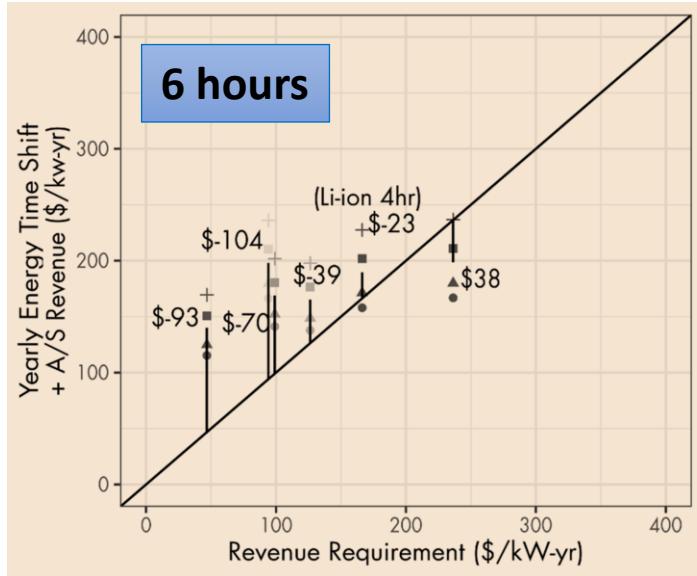
## Sensitivities

- Capital costs were adjusted +10% / -30%
- Energy prices were modified (mod) from their original (orig)
- RTE was adjusted +/- 5% points

Pricing	Orig								
RTE	Base	Base	Base	High	High	High	Low	Low	Low
Costs	Base	High	Low	Base	High	Low	Base	High	Low
Pricing	Mod								
RTE	Base	Base	Base	High	High	High	Low	Low	Base
Costs	Base	High	Low	Base	High	Low	Base	High	Base

Significant number of DER-VET cases: 1728 total

# DER-VET Results: Tech Duration vs. Revenue Requirements



Duration, hours	LDES A	LDES B	LDES C	LDES D	Li-ion
4	---	---	---	---	-23
6	-93	-39	-104	-70	38
8	-91	-36	-86	-60	103
10	-88	-34	-67	-50	170

Technology cost forecast is a key driver for LDES analysis



# Transmission Solar + Energy Storage Case Study

# LADWP Energy Storage + Solar Project

- Los Angeles Department of Water and Power (LADWP) required to study and procure energy storage
  - 100 MW, 4-hour battery energy storage system
  - 200 MW solar PV
  - Power Purchase Agreement (PPA) able to claim Federal Investment Tax Credit (FITC) incentive

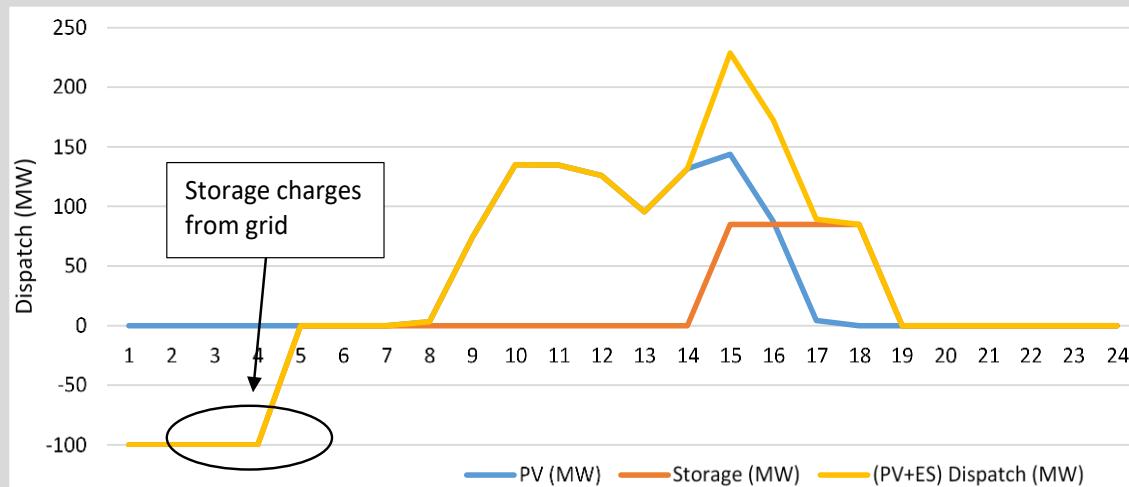
	Provide Energy Time Shift and Spinning Reserve	Restrict Charging from Grid	Restrict Charging from Grid and Discharge Min	Provide Frequency Response
Case #1	✓		✓	
Case #2	✓		✓	✓
Case #3	✓	✓		
Case #4	✓	✓		✓

LADWP Full Report: *Integrating Energy Storage System with Photovoltaic Generation: Analysis within Los Angeles Department of Water and Power (LADWP) Service Territory to Meet SB801 Requirements* at <http://www.ePRI.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002013007>

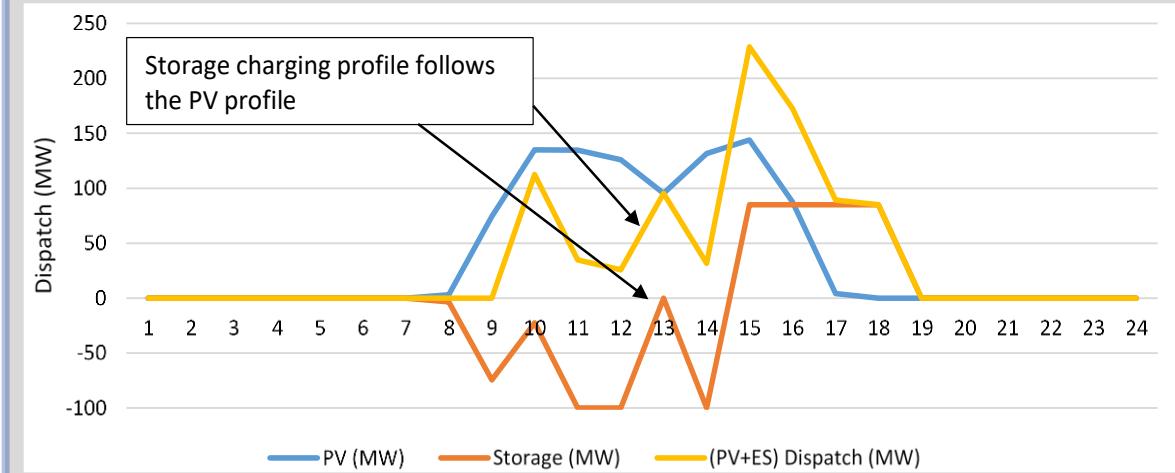
# LADWP Case Results - Dispatch

- Impact of grid charging constraints:

Unrestricted Storage Dispatch (Jan 11)



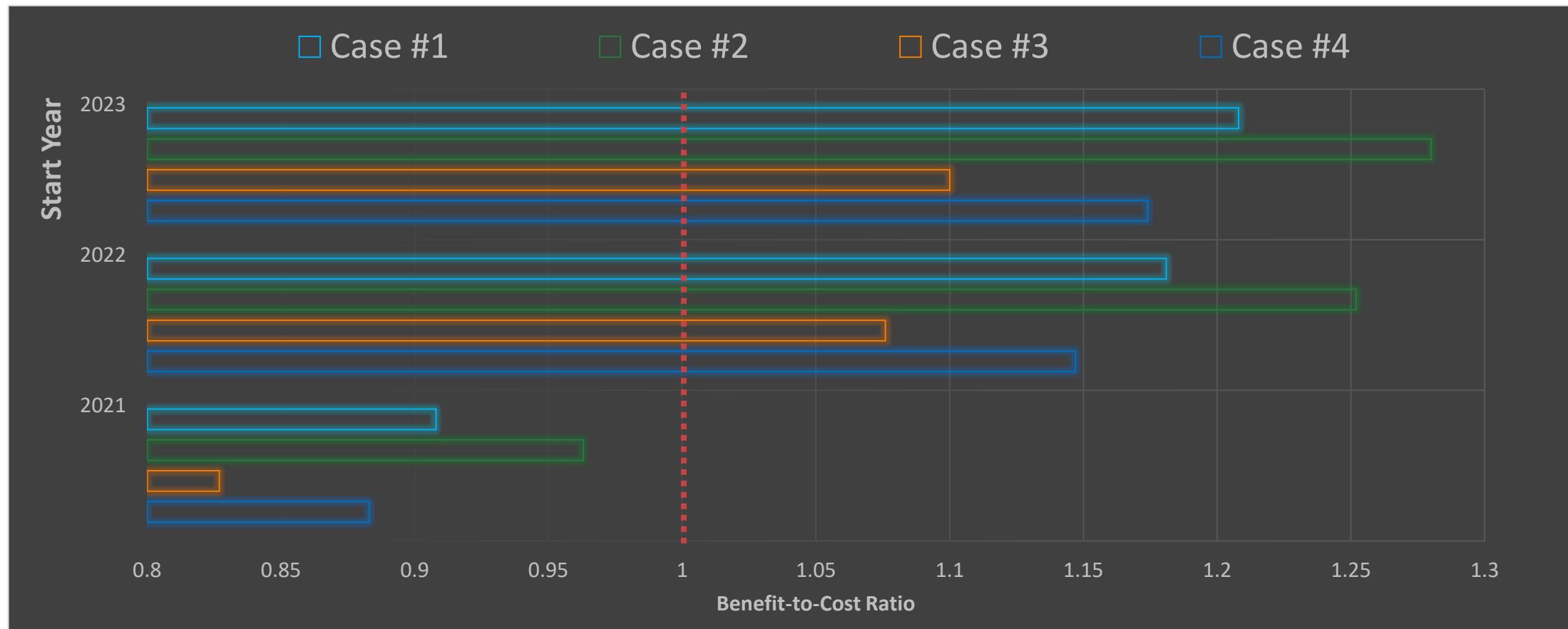
Restricted Storage Charging from Grid (Jan 11)



DER-VET Optimized Dispatch Outputs

# LADWP Case Results - CBA

- Several cases resulted in benefit-cost ratios greater than one for project start years after 2022 as illustrated in the graph below

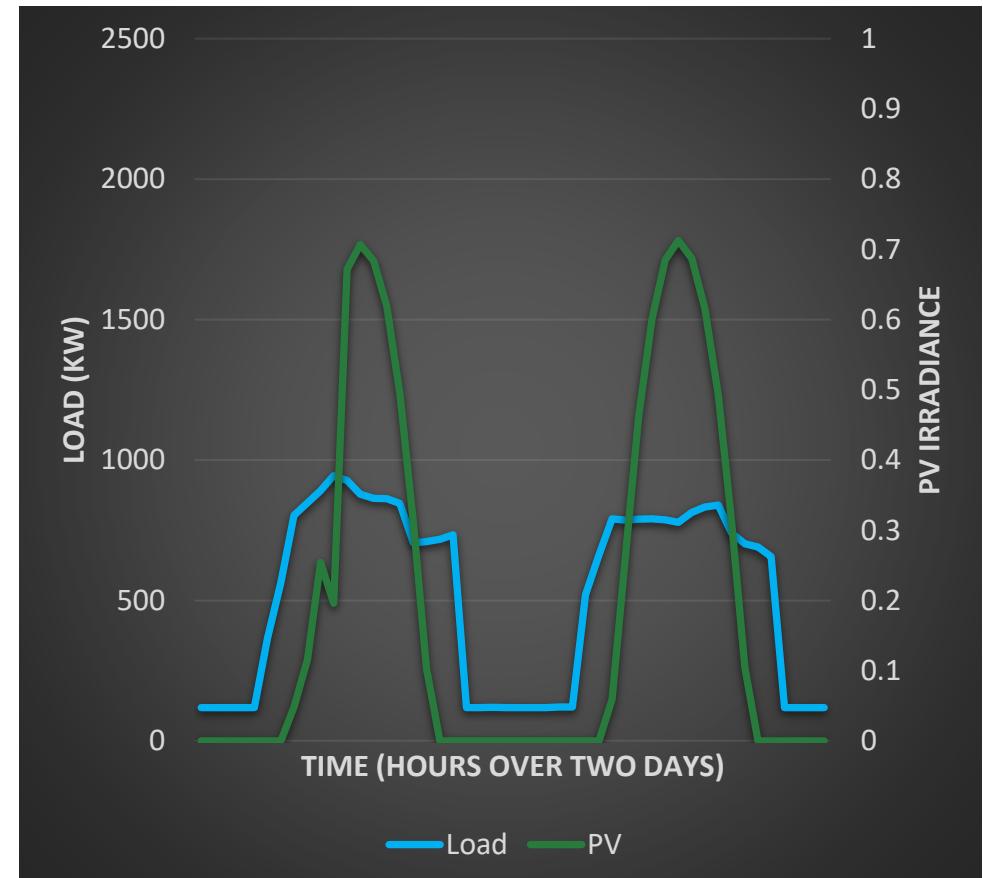




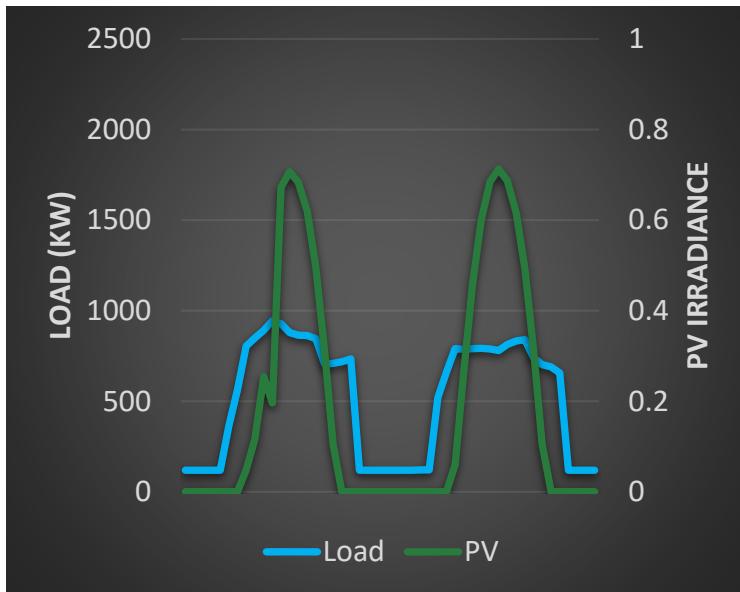
# **Microgrid Design for California Public Service Power Shutoffs (PSPS) Events**

# Microgrid Design - DER-VET Modeling Assumptions

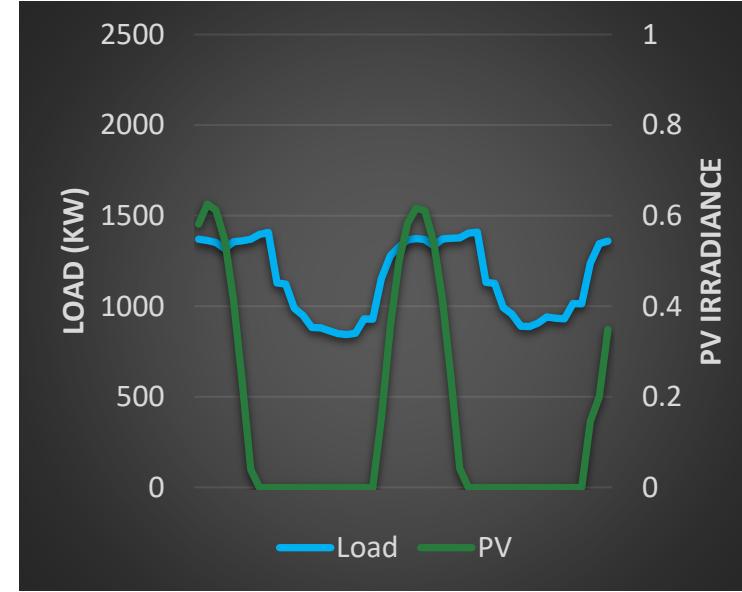
- Identify potential Public Safety Power Shutoff (PSPS) planned events and duration in California
- Solar PV plus battery energy storage microgrid technologies
- Initial storage state of charge at the start of outage event is 100% with advanced PSPS notifications



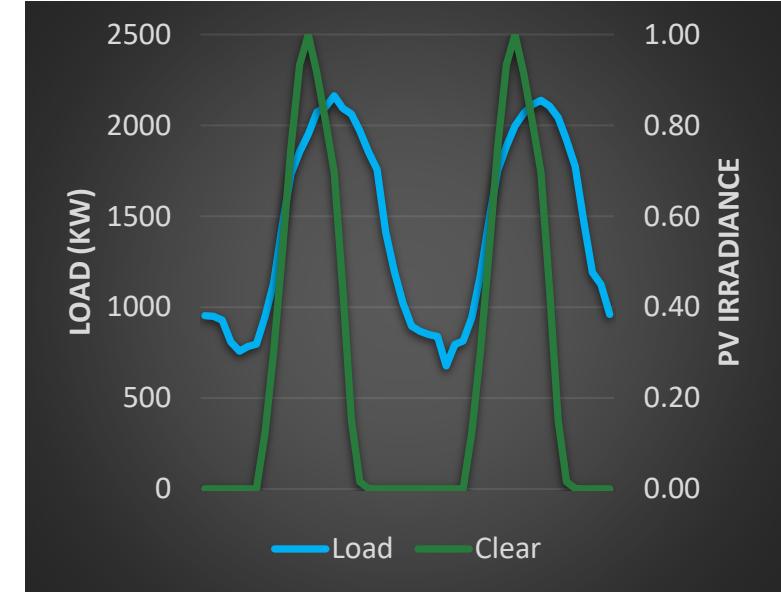
# Load and PV Profile



Peak load – 0.9 MW  
24hr load requirement – 13MWh  
36hr load requirement – 18MWh  
48hr load requirement – 25MWh



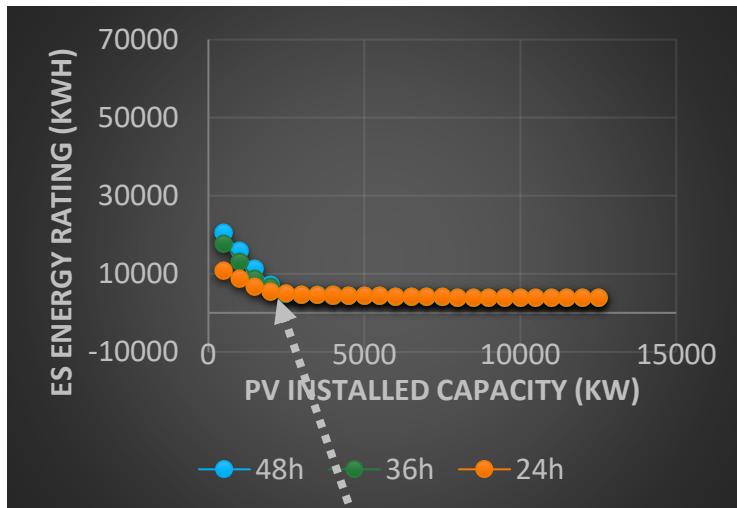
Peak load – 1.4 MW  
24hr load requirement – 28MWh  
36hr load requirement – 43MWh  
48hr load requirement – 55MWh



Peak load – 2.16 MW  
24hr load requirement – 35MWh  
36hr load requirement – 48MWh  
48hr load requirement – 76MWh

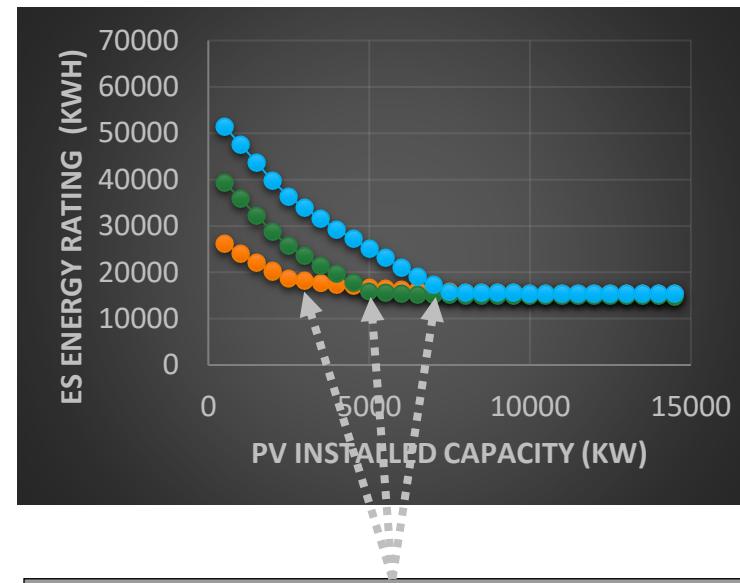
# Microgrid Sizing Results

## LA – Sec School



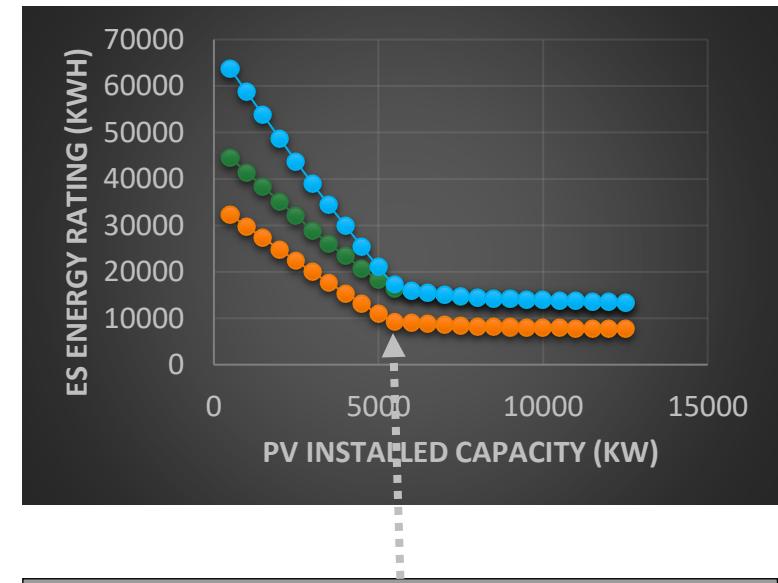
2.5MW PV +  
0.735MW/4.9MWh ES

## LA - Hospital



24h – 3.5MW PV+1.4MW/17MWh ES  
36h – 5MW PV+1.6MW/15MWh ES  
48h – 7.5MW PV+3MW/15MWh ES

## SCE Feeder

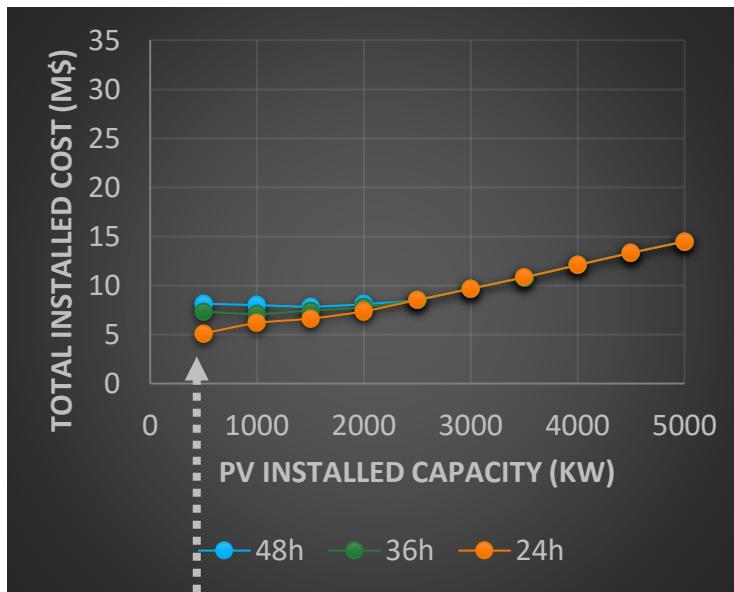


24h – 5.5MW PV+1.9MW/9.2MWh ES  
36h – 5.5MW PV+1.9MW/17.2MWh ES  
48h – 5.5MW PV +2 MW/17.2MWh ES

The energy storage and PV size corresponding to the knee point. Knee-point is a point where adding more PV does not affect the size of energy storage significantly.

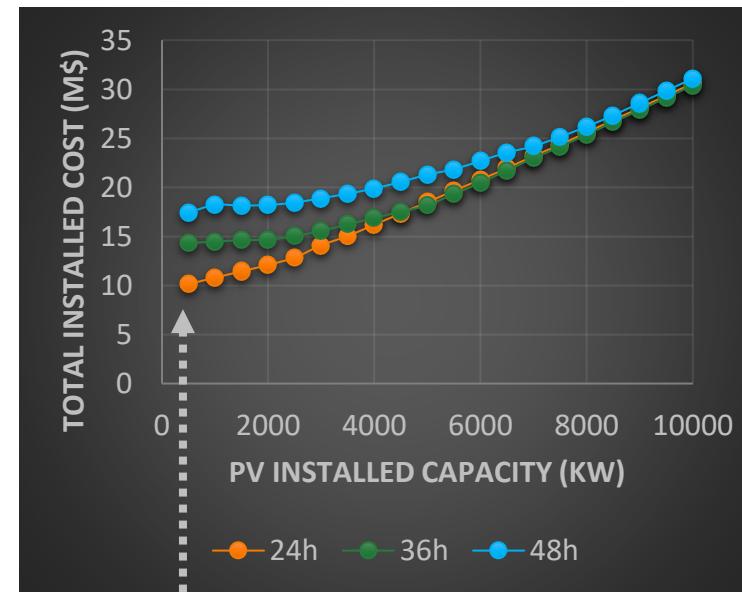
# Microgrid Cost Summary

## LA – Sec School



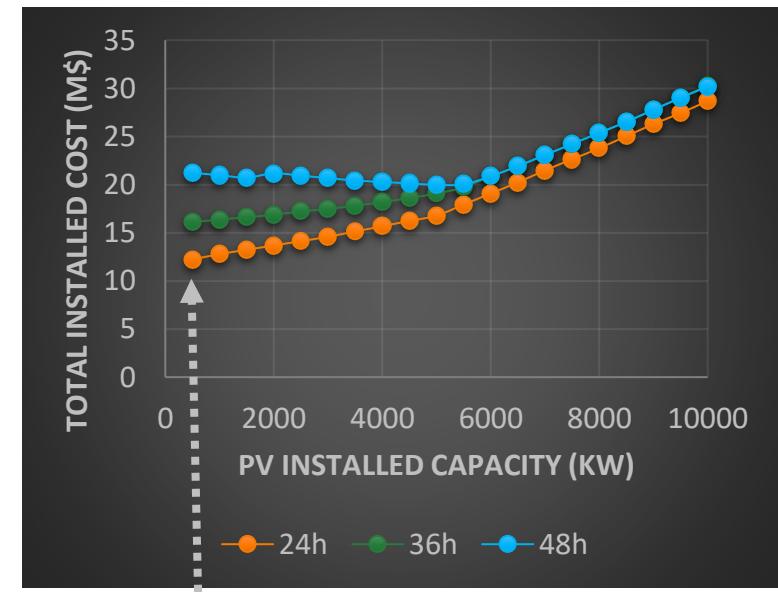
Min Cost of covering 24, 36, and 48hr outage – \$5M, \$7M, and \$8M

## LA - Hospital



Min Cost of covering 24, 36, and 48hr outage – \$10M, \$14M, and \$18M

## SCE Feeder



Min Cost of covering 24, 36, and 48hr outage – \$12M, \$16M, and \$22M



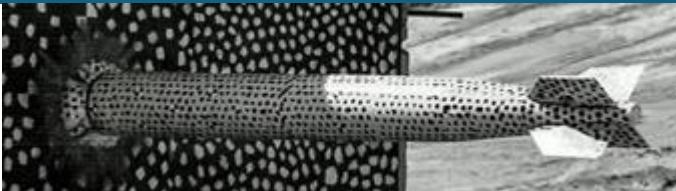
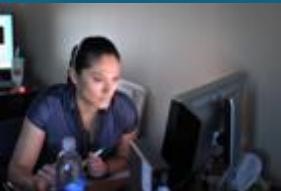
**Together...Shaping the Future of Energy®**





Sandia  
National  
Laboratories

## QuEST: Evaluation of Energy Storage



*PRESENTED BY*

Walker Olis

2023 DOE ENERGY STORAGE FINANCING SUMMIT



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

# Techno-economic Analysis of Energy Storage



- Identify revenue streams: what are the possible services/applications 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.
- Optimally size ESS.



# QuEST - Overview



QuEST

New or returning user?  
Take a quick tour

Sandia National Laboratories

**QuEST Valuation**  
Estimates value for an energy storage system providing ISO/RTO services. Uses historical data to determine the maximum amount of revenue that the energy storage system could have generated by stacking multiple services/value streams (e.g., ancillary services, energy arbitrage). This retrospective analysis estimates value from future cash flows.

Get started

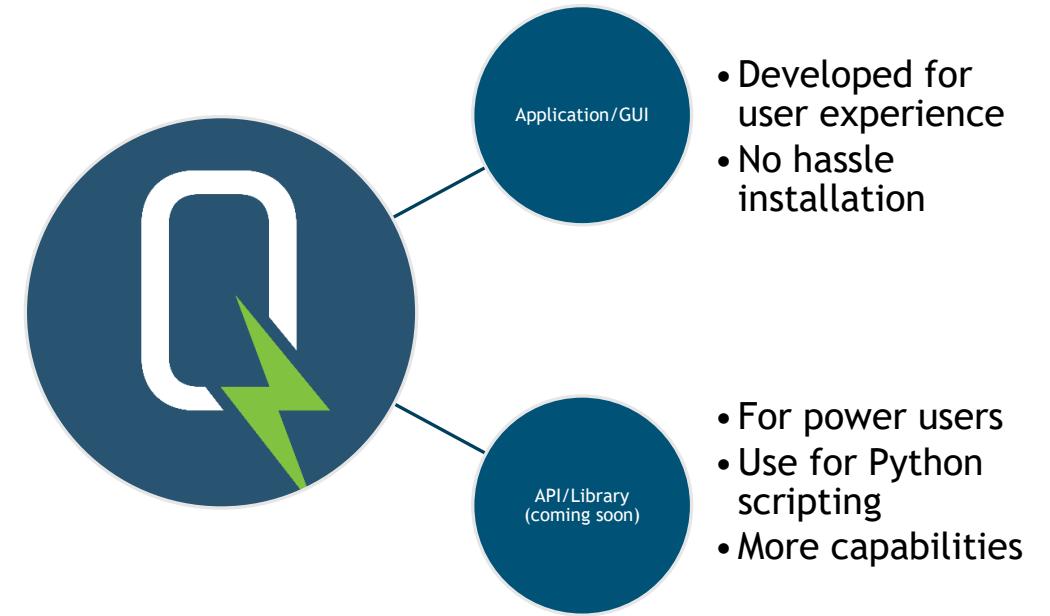
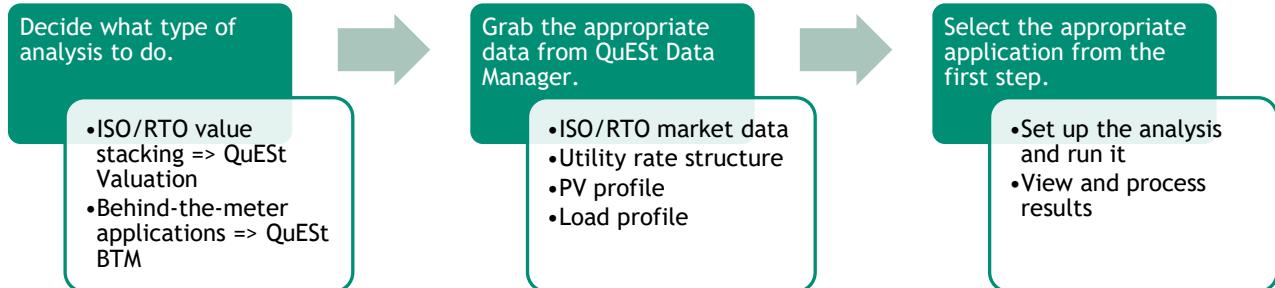
QuEST Data Manager  
QuEST Valuation  
QuEST BTM

QuEST Performance  
Technology Selection  
QuEST Equity

Version 1.6 available on GitHub: <https://github.com/snl-quest/snl-quest>

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U.S. DEPARTMENT OF ENERGY NNSA  
National Nuclear Security Administration



## Current (v1.6):

- QuEST Data Manager
- QuEST Valuation
- QuEST BTM
- QuEST Tech Selection
- QuEST Performance

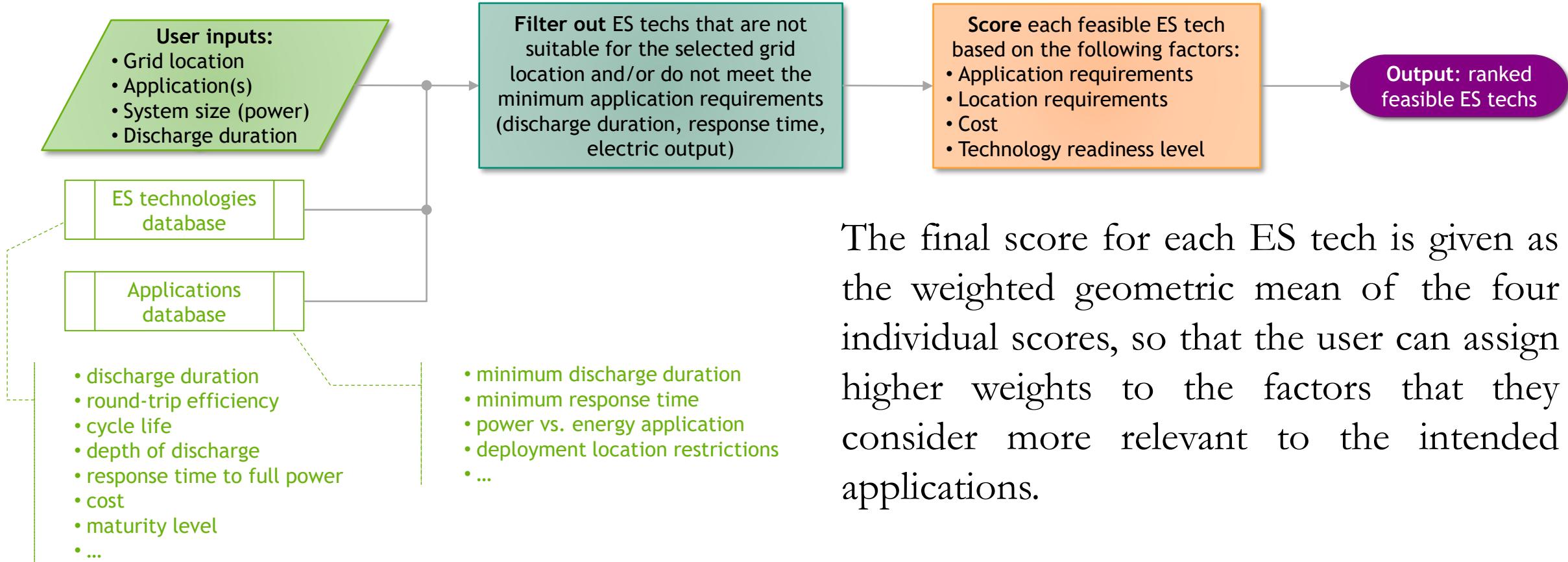
## Alpha Release:

- QuEST Equity

# Energy Storage Technology Selection



**Goal:** given a set of user selections, perform an initial screening to identify and rank feasible energy storage technologies for a given project.



The final score for each ES tech is given as the weighted geometric mean of the four individual scores, so that the user can assign higher weights to the factors that they consider more relevant to the intended applications.

# QuEST – Technology Selection



**Welcome to the energy storage technology selection wizard!**

This wizard will guide you through the process of identifying feasible energy storage technologies for a given project. Based on user inputs and pre-loaded databases that contain parameters to characterize multiple energy storage technologies and their grid applications, this tool identifies which storage technologies do not satisfy the minimum application requirements (such as discharge duration and response time). Then, the remaining feasible technologies are ranked to indicate their compatibility to the desired project.

The flowchart below depicts an overview of the steps performed during the energy storage technology selection analysis.

```

graph LR
    A["User inputs:  
- Grid location  
- Application(s)*  
- System size (power)*  
- Discharge duration*  
  
ES technologies database  
Applications database"] --> B["1st filter: remove ES techs that are not suitable for the selected grid location"]
    B --> C["2nd filter: remove ES techs that are not suitable for the selected application (based on discharge duration, response time, electric output)"]
    C --> D["Scoring: for each ES tech vs. application pair, assign a score for each of the following factors:  
- Application requirements  
- Location requirements  
- Cost  
- Technology readiness level"]
    D --> E["Scoring: compute combined feasibility score considering the previous factors"]
    E --> F["Output: ranked feasible ES techs"]
    style A fill:#90EE90,stroke:#008000,color:#000
    style B fill:#ADD8E6,stroke:#008000,color:#000
    style C fill:#ADD8E6,stroke:#008000,color:#000
    style D fill:#FFDAB9,stroke:#008000,color:#000
    style E fill:#FFDAB9,stroke:#008000,color:#000
    style F fill:#FF0000,stroke:#008000,color:#000
    
```

**User inputs:**  
 - Grid location  
 - Application(s)\*  
 - System size (power)\*  
 - Discharge duration\*

**ES technologies database**  
**Applications database**

\*These inputs have default values according to the selected grid location

**Get started**

**Energy storage technologies feasibility**

The plot below indicates whether each energy storage technology is a feasible option for your project.

	Grid location	Application requirements	Feasible?
Compressed-air energy storage	✗	✓	✗
Flow battery - Iron	✓	✓	✓
Flow battery - Zinc bromide		✓	✓
Flywheel - Long duration	✓	✓	✓
Flywheel - Short duration	✓	✗	✗
Lead-acid	✓	✓	✓
Lead-carbon	✓	✓	✓
Lithium-ion	✓	✓	✓
Lithium-ion iron phosphate	✓	✓	✓
Lithium-ion nickel-manganese-cobalt	✓	✓	✓
Nickel	✓	✓	✓
Pumped hydro storage	✗	✓	✗
Sodium	✓	✓	✓
Vanadium redox flow	✓	✓	✓
Zinc	✓	✓	✓

**Summary of user selections:**

- Grid location:** BTM: commercial/industrial
- Application:** Retail TOU energy charges
- System size:** 100 kW
- Discharge duration:** 4 hrs

**Previous** **Next**

**Ranking of feasible energy storage technologies**

The plot below depicts the feasibility score of each energy storage technology for your project; higher scores indicate a better match between a technology and the requirements of your project. The **Adjustments** box allows users to modify some settings used for computing the total feasibility scores.

	Application	Location	Cost	Maturity	Total
Sodium	0.5	0.5	0.5	0.5	0.5
Lithium-ion iron phosphate	0.5	0.5	0.5	0.5	0.5
Lithium-ion nickel-manganese-cobalt	0.5	0.5	0.5	0.5	0.5
Lead-acid	0.5	0.5	0.5	0.5	0.5
Lead-carbon	0.5	0.5	0.5	0.5	0.5
Vanadium redox flow	0.5	0.5	0.5	0.5	0.5
Flow battery - Iron	0.5	0.5	0.5	0.5	0.5
Flow battery - Zinc bromide	0.5	0.5	0.5	0.5	0.5
Zinc	0.5	0.5	0.5	0.5	0.5
Nickel	0.5	0.5	0.5	0.5	0.5
Pumped hydro storage	0.5	0.5	0.5	0.5	0.5
Compressed-air energy storage	0.5	0.5	0.5	0.5	0.5
Flywheel - Long duration	0.5	0.5	0.5	0.5	0.5
Flywheel - Short duration	0.5	0.5	0.5	0.5	0.5

**Summary of user selections:**

- Grid location:** BTM: commercial/industrial
- Application:** Retail TOU energy charges
- System size:** 100 kW
- Discharge duration:** 4 hrs

**Adjustments**

Weights for each category: ?

Application: 1.00	Location: 1.00
Cost: 1.00	Maturity: 1.00

Target cost: ? 1000 \$/kWh \$/kW

**Update scores**

**Previous** **Next**

# 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?

$$\max \sum_i \left( \begin{array}{l} \lambda_i(q_i^d - \eta_c q_i^r) \\ \text{arbitrage} \end{array} + \begin{array}{l} q_i^{ru}(\lambda_i^{ru} + \delta_i^{ru}\lambda_i) \\ \text{regulation up} \end{array} + \begin{array}{l} q_i^{rd}(\lambda_i^{rd} - \delta_i^{rd}\lambda_i) \\ \text{regulation down} \end{array} \right) e^{-Ri}$$

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

# QuEST – Valuation Application

Select a market area to place the energy storage device in.

Different market areas can have different market structures, resulting in various opportunities for generating revenue.

**Market Areas:**

ERCOT	PJM	MISO
NYISO	ISONE	SPP
CAISO		

**IRC** (Independent Reliability Council)

**Previous** **Next**

Describe the type of energy storage device to be used.

Energy storage devices come in many forms and technologies. In this application, they are mainly modeled according to their power and energy ratings. Select an energy storage device template and/or customize your own.

**Li-ion Battery** Advanced Lead-acid Battery Flywheel Vanadium Redox Flow Battery

**Li-Iron Phosphate Battery**

self-discharge efficiency (%/h) 100.0  
round trip efficiency (%) 90.0  
energy capacity (MWh) 24.0  
power rating (MW) 36.0

**Li-ion Battery**  
Modeled after the Notrees Battery Storage Project in western TX.

**Previous** **Next**

Here's how the device generated revenue each month.

Revenue was generated based on participation in the selected revenue streams. The **gross revenue** generated over the evaluation period was **\$3,064,793.94**. The gross revenue from **arbitrage** was **-\$526,420.06**, an overall deficit. This implies participation in arbitrage was solely for the purpose of having capacity to offer regulation up services.

**Reports**

- Revenue (by month)
- Revenue (by stream)**
- Participation (total)
- Participation (by month)

**Generate report**

# 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?

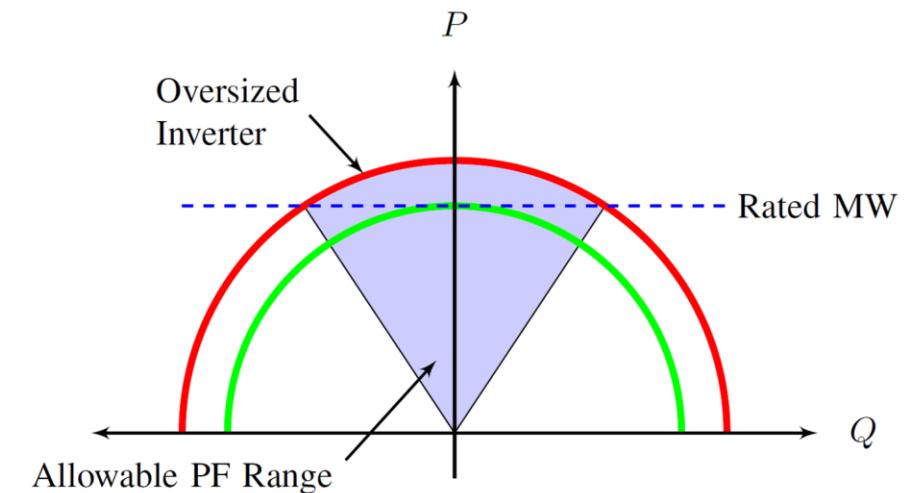
$$\min\{C_E^m + C_N^m + C_D^m\}$$

s.t. *energy storage and inverter constraints*

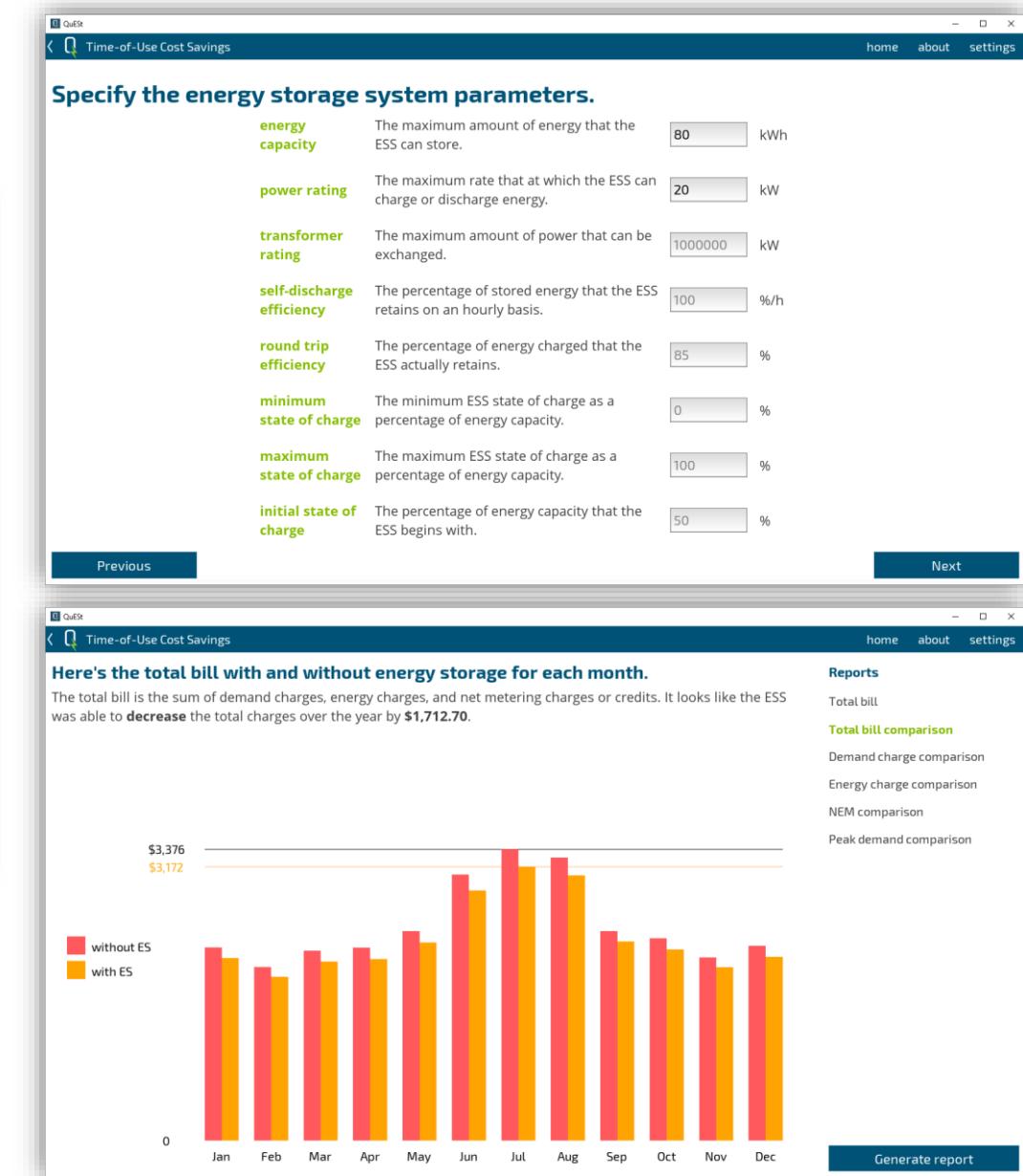
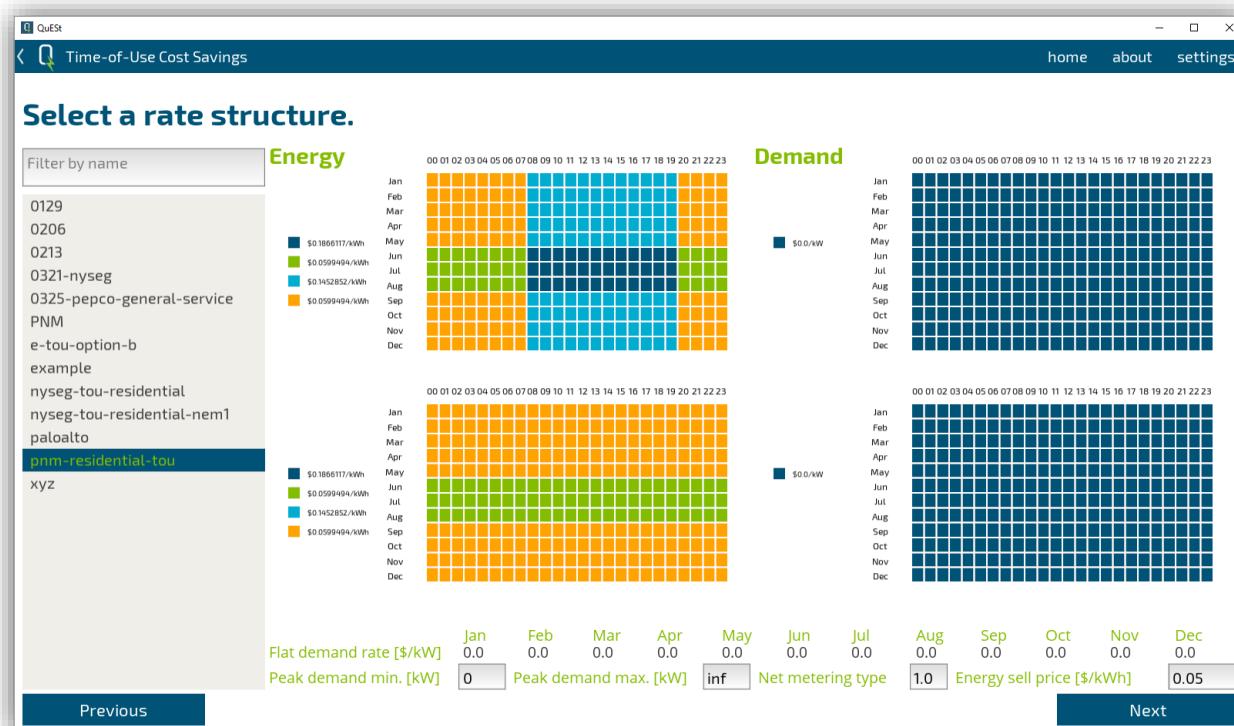
$C_E^m$  is the energy charge of period m

$C_D^m$  is the demand charge of period m

$C_N^m$  ( $\leq 0$ ) is the net metering charge of period m.

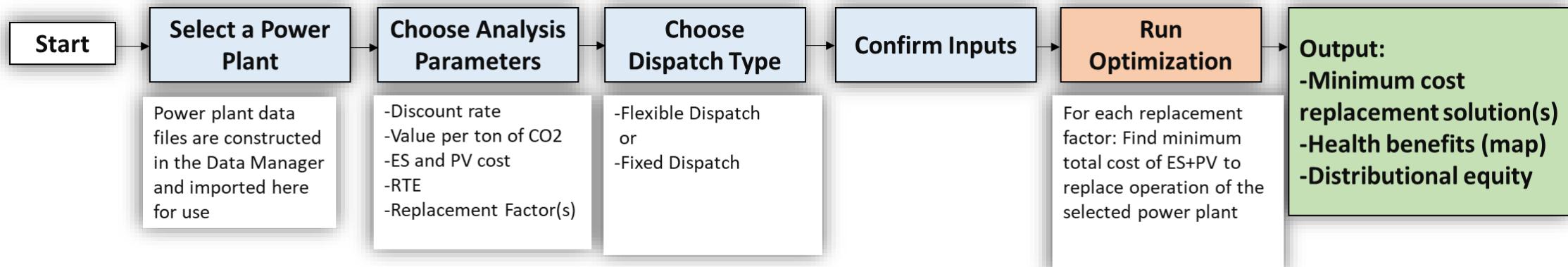
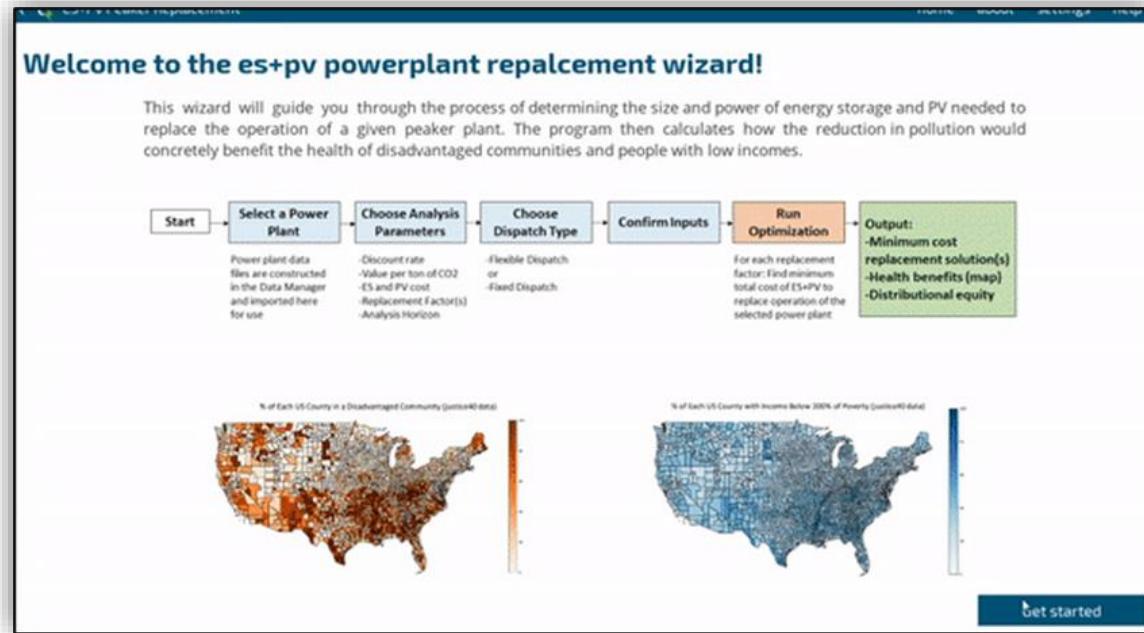


# QuEST – BTM Application





Given a Peaker loading profile, what are the optimal sizes of PV and storage for 1-to-1 replacement of that plant? What are the health and environmental benefits?



## Inputs

- Powerplant Data File
- Battery and Analysis Parameters
- Dispatch Type Assumption

## Outputs

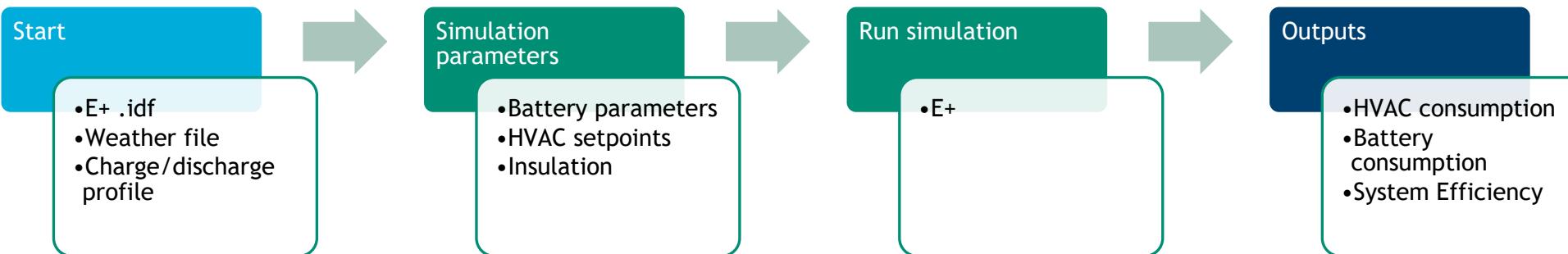
- Minimum capital cost solution(s)
- Health Benefits
- Distributional Impacts

# QuEST Performance



Given a charge/discharge profile of a BESS, how much energy is needed to run the HVAC that maintain system temperature within its operating range? How does this affect expected performance and location?

The screenshot shows the QuEST Performance Simulations interface. At the top, it says "Run performance simulations." Below are three input fields: "PTAC" (with "Select an input file" dropdown containing "1ZoneUncontrolled\_wESS\_hvactemplate\_ptacexp2.idf" and "container\_wESS\_ptac.idf"), "NY" (with "Select weather file" dropdown containing "nyc2020.epw"), and "Valuation Jul 18, 2022 12:46:53". A "Select battery profile" dropdown lists months from December to January. At the bottom, there are tabs for "Data", "Parameters", "Ready" (highlighted in green), and "Out".



# Example – QuEST Valuation and QuEST Performance



Example: 1MW, 1MWh Li-ion BESS located in NYC

Prerequisites:

- NYISO NYC zone prices
- NYC weather data
- E+

QuEST  
Wizard

Select a market area to place the energy storage device in.

Different market areas can have different market structures, resulting in various opportunities for generating revenue.

MISO      NYISO      SPP

[Previous](#)      [Next](#)

# Example – QuEST Valuation and QuEST Performance



The following screenshots illustrate the QuEST Valuation and QuEST Performance tools:

**QuEST Valuation (Left):**

- Home page with navigation links: QuEST Data Manager, QuEST Valuation (selected), QuEST BTM, QuEST Performance, Technology Selection.
- A "Get started" button.
- Sandia National Laboratories logo.
- DOE/NASA logos.
- Copyright notice: Copyright 2018 National Technology & Engineering Solutions of Sandia, LLC (NTESS). Under the terms of Contract DE-NA0003525 with NTESS, the U.S. Government retains certain rights in this software.

**Run multiple valuations with one click (Middle):**

- Two tabs: NYISO (selected) and Arbitrage.
- Sub-tabs: Data, Parameters, Go!
- Parameter inputs for Arbitrage valuation.

**Run multiple valuations with one click (Right):**

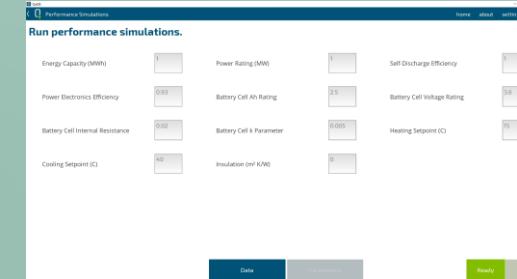
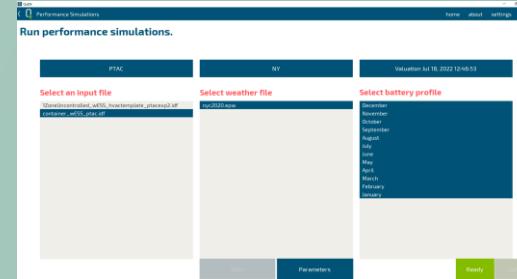
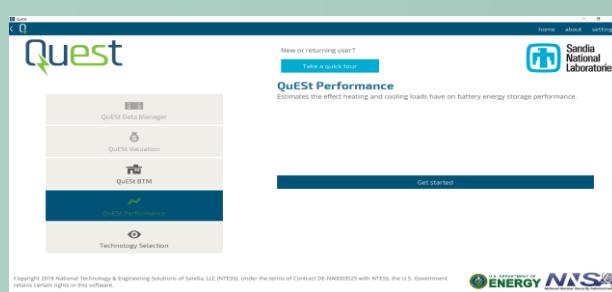
- Parameter inputs for self-discharge efficiency, round trip efficiency, energy capacity, power rating, initial state of charge, minimum state of charge, maximum state of charge, % of reg. bid reserved for discharging, % of reg. bid reserved for charging, frac. of reg. up capacity deployed, frac. of reg. down capacity deployed, performance score.
- Optional: parameter sweep section.
- Sub-tabs: Data, Parameters, Go!

**Task List:**

- Navigate to the QuEST Valuation tool.
- Click on the Batch Runs Button -> select NYISO from the pull down options -> select N.Y.C. from the node options -> select arbitrage from the pull down options -> select all months of the year.
- Click the Parameters tab. Change the energy capacity to 1 MWh and the power rating to 1 MW. Change the minimum state of charge to 5% and the maximum state of charge to 95%.
- Once everything looks correct, click Go! Once the simulations are finished, navigate back to the home page.



# Example – QuEST Valuation and QuEST Performance

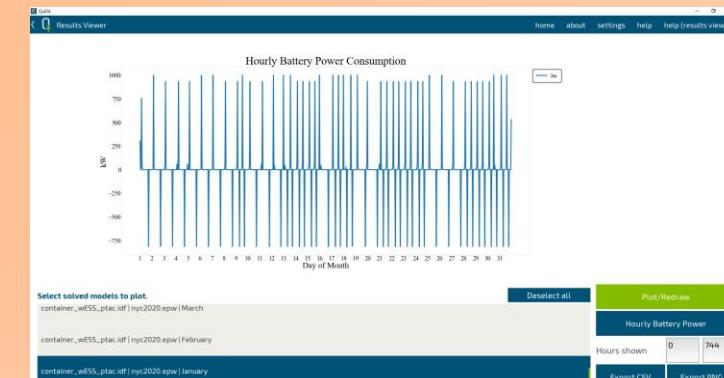
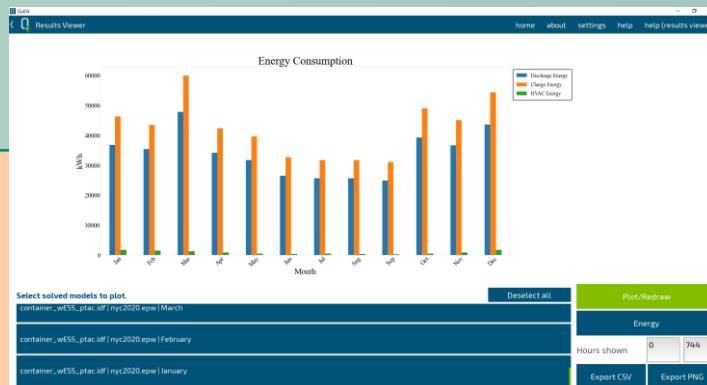


- Navigate to the QuEST Performance tool.

- Enter the Performance Simulations option. Select PTAC from the HVAC options. Select the provided input file describing a BESS in a shipping container. Select NY from the location dropdown. Select the weather file downloaded previously. Select the Valuation run from the Profile dropdown. Select the months available.

- Click the Parameters tab. Leave the default parameters as is, click the Ready button.

- The selections made will be displayed. If everything looks correct, press Go!



# Acknowledgements



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



Sandia National Laboratories

Thank You!

Tu Nguyen – [tunguy@sandia.gov](mailto:tunguy@sandia.gov)

Walker Olis – [wolis@sandia.gov](mailto:wolis@sandia.gov)



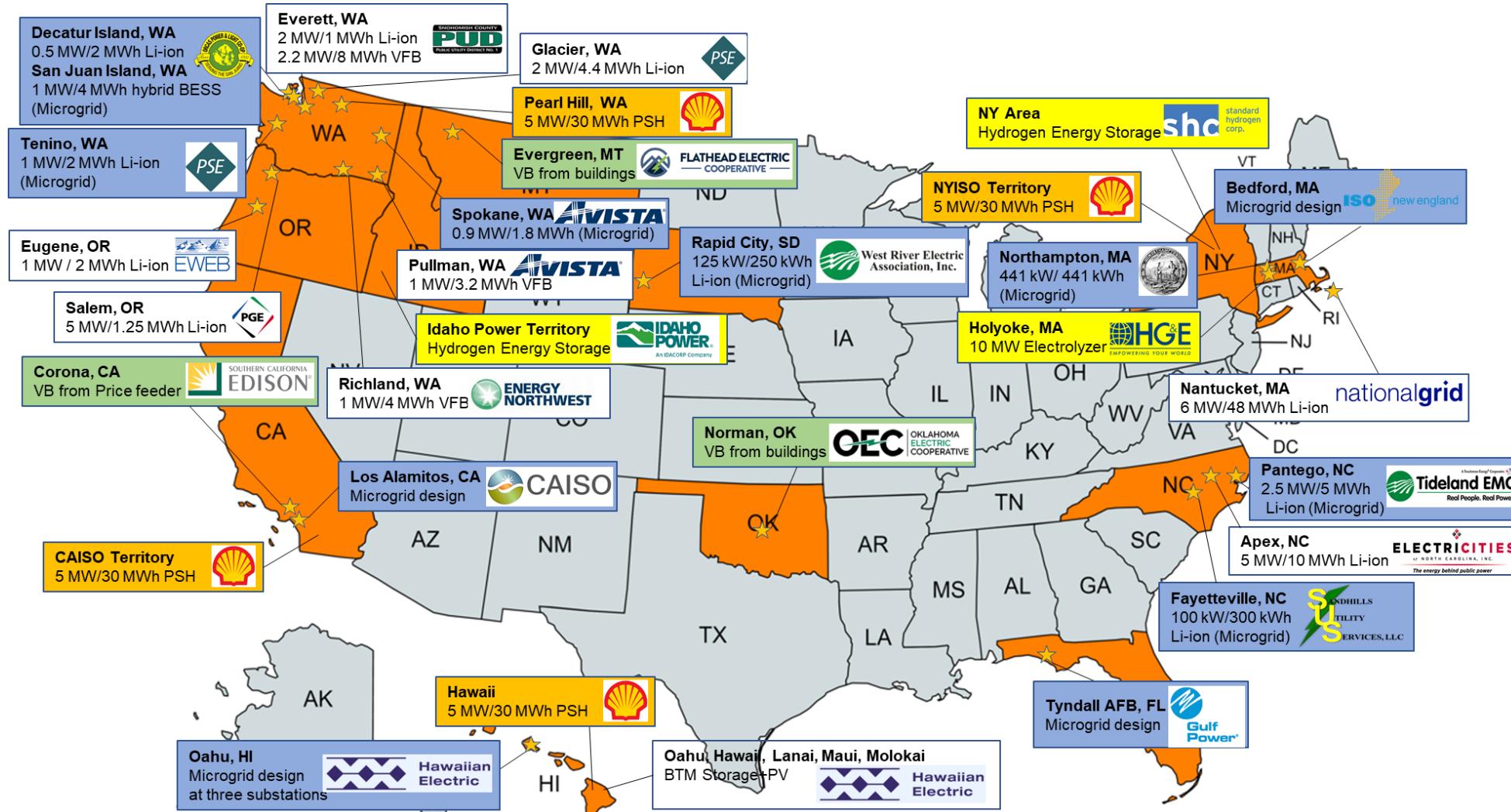
# Energy Storage Modeling and Valuation Tools

Dexin Wang, Senior Research Engineer  
Pacific Northwest National Laboratory

DOE Energy Storage Financing Summit  
January 26<sup>th</sup>, 2023



# PNNL Has Assessed Energy Storage and Microgrid Systems at More Than 30 Sites





Pacific  
Northwest  
NATIONAL LABORATORY

# Clean Energy Fund Grid Demonstration Projects



San Juan Island, WA (Microgrid)  
1 MW/4 MWh hybrid BESS+3.2 MW PV



Richland, WA  
1 MW/4 MWh Li-ion+4 MW PV



Tenino, WA (Microgrid)  
1 MW/2 MWh Li-ion+214 kW PV



CEF I

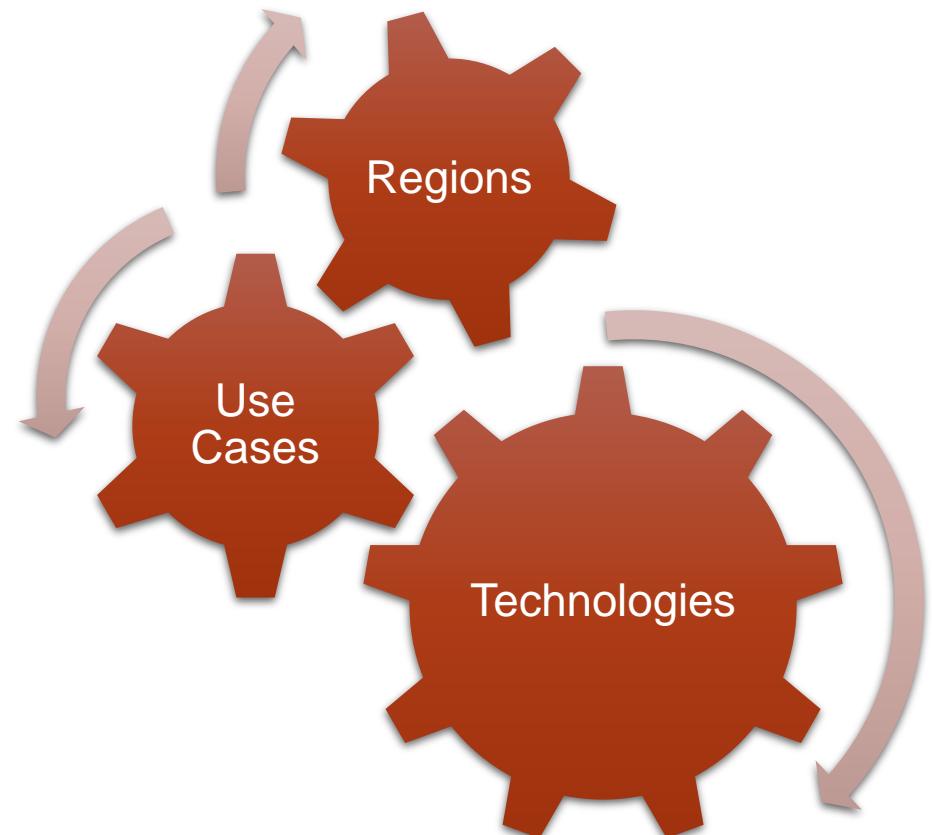
CEF II

CEF III

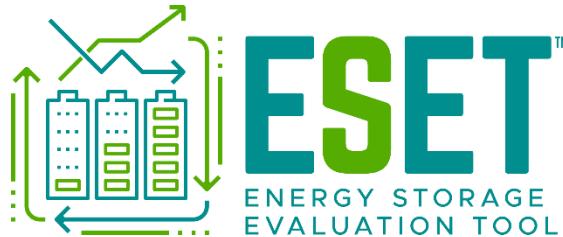
# Needs of Energy Storage Analytics

## Numerous Factors Affect Storage Valuation

- ESS physical capability
  - Energy storage technology, design, and characteristics
- Use cases
  - Vertically integrated utilities, electricity markets, distribution utilities, and large C&I customers
  - Bulk energy, ancillary service, transmission-level, distribution-level, and end-user services
- Regions and systems
  - Different generation mix, grid infrastructure, market structures/rules, distribution system capacity, and load growth rate



# ESET™ Overview



- Battery Storage Evaluation Tool (BSET)
- Microgrid Asset Sizing considering Cost and Resilience (MASCORE)
- Virtual Battery Assessment Tool (VBAT)
- Pumped-Storage Hydropower Evaluation Tool (PSHET)
- Hydrogen Energy Storage Evaluation Tool (HESET)

A suite of applications that enable utilities, regulators, vendors, and researchers to model, optimize, and evaluate various energy storage systems for stacked value streams



Web-based ESET: <https://eset.pnnl.gov>

# ESET Features

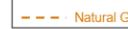
- **Various ESS models**
  - Different energy storage, hybrid, or microgrid systems
  - Appropriate levels of complexity and fidelity
  - Technical characteristics and physical capabilities
- **Advanced optimization and control methods**
  - Technically achievable benefits considering multi-dimensional couplings
  - Economic, environmental, and resilience
- **Built-in databases**
  - Electricity market prices
  - Utility rates
  - Renewables and building loads, and
  - Energy storage cost
- **Improved user experience design**

# User Experience Enhancements

- Heuristic evaluation against web application usability principles
  - Home page
  - Navigation
  - Account management
  - Modules

- Improvements
  - Better visibility of system status
  - Better organization of information with visual hierarchy
  - More informative and useful feedback
  - More consistent visual cues across ESET
  - Improved aesthetics and minimalistic design
  - New features that support more flexible inputs and better presentation of results

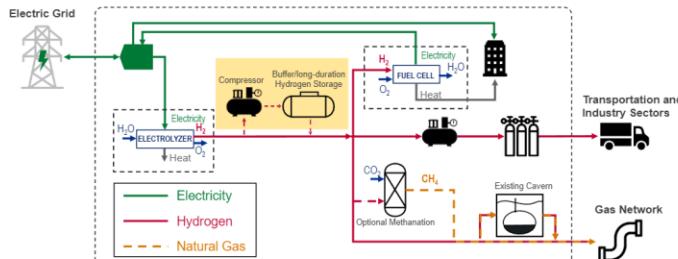
[← BACK TO EVALUATION TOOL HOME](#)
[SAVE PROGRESS](#)
[VIEW RESULT](#)
[RUN](#)

 Natural Gas

## Electrolyzer

Specs	Equipment Cost	Water Cost
Rated Power 5 MW	Installed Cost 1120 \$/kW	Minimum Charge 188.36 \$
Electricity Usage 56 kWh/kg	Fixed O&M 4 % of Installed Cost	Threshold 40 ton
Minimum Load 20 %	Charge Rate 4.709 \$/ton	
	Drainage Charge Rate 6.65 \$/ton	

## Dedicated Hydrogen Storage



The diagram illustrates a hydrogen energy system. It starts with an 'Electric Grid' providing 'Electricity' to an 'ELECTROLYZER'. The electrolyzer splits water (H<sub>2</sub>O) into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>). The hydrogen is stored in a 'Buffering-duration Hydrogen Storage' tank. The oxygen can be used in a 'FUEL CELL' to produce electricity and heat, or it can be sent to an 'Optional Methanation' unit where it reacts with CO<sub>2</sub> to produce methane (CH<sub>4</sub>). The hydrogen from storage can be transported via a 'Gas Network' to various sectors: 'Transportation and Industry Sectors' (via a truck), 'Existing Cavern' (via a tank), or 'Gas Network' (via a pipe). A 'Compressor' is also shown connected to the hydrogen storage tank.

# Integrated Databases

- ISO market prices, including NYISO, ERCOT, SPP, ISO-NE, and CAISO (in progress)
  - Energy – LMP
  - Ancillary services: regulation (up, down, and mileage), spin/non-spin reserve
- Utility rate structures
  - *The Utility Rate Database (URDB)* – 3,833 EIA-recognized utility companies
  - Energy and demand charges: flat, time-of-use, tiered
- Typical building load profiles
  - *Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States* developed by NREL
- Detailed energy storage cost
  - *Energy Storage Cost and Performance Database* developed by PNNL

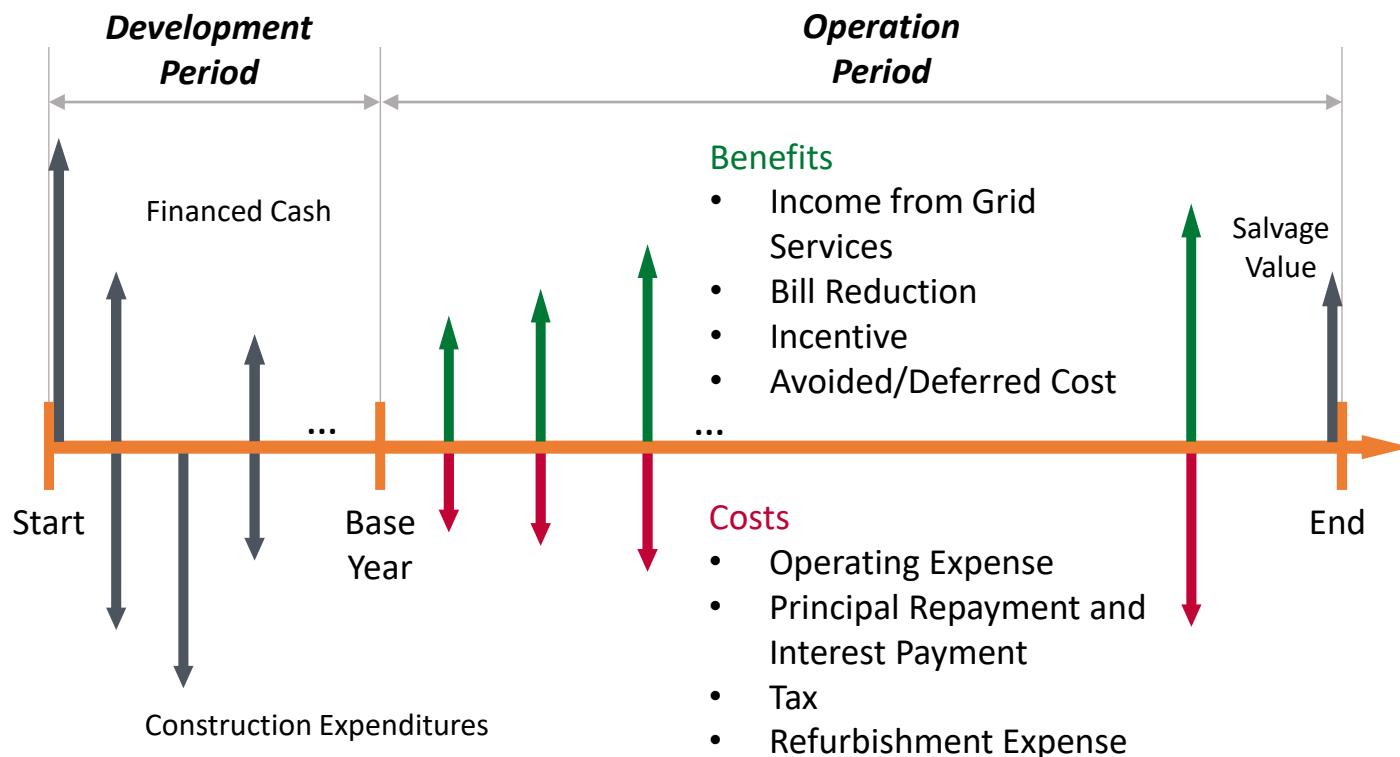




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Northwest  
NATIONAL LABORATORY

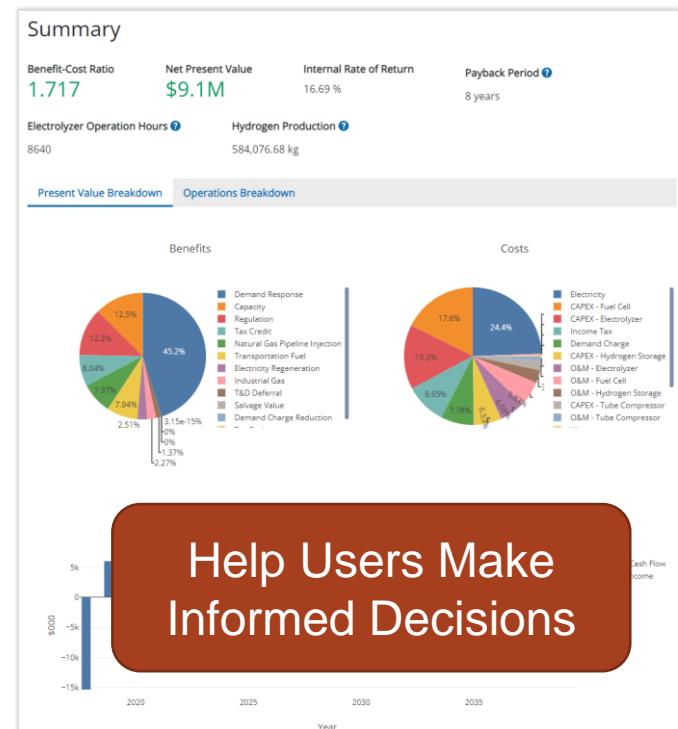
# Comprehensive Cost-Benefit Analysis Engine

- Typical Cash Flow for ESS Projects



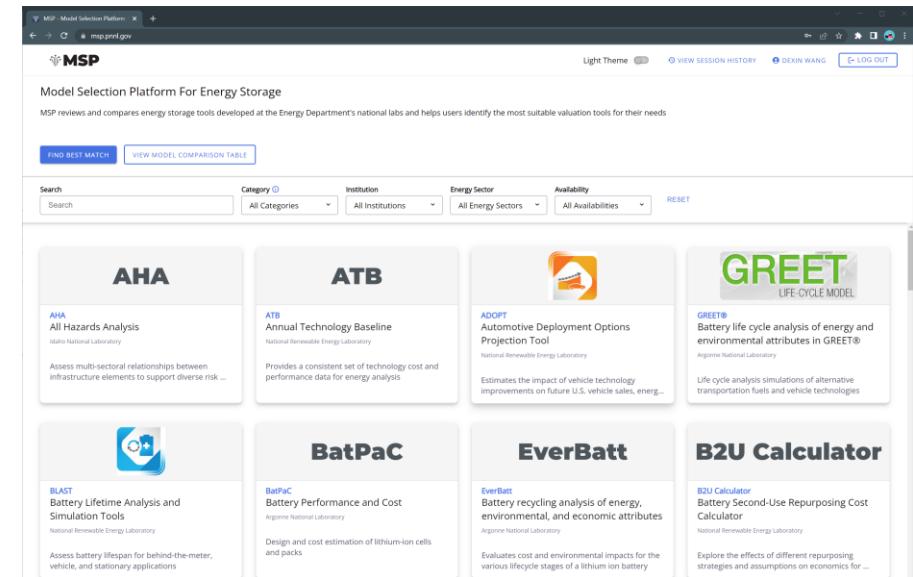
## Results

- BCR, NPV, IRR
- Itemized PV Benefits and Costs
- Net income over time
- Free cash flow over time



# Model Selection Platform for Energy Storage

- Not easy to tell
  - How are they different in terms of functionalities and capabilities?
  - Which one should I choose?
- MSP reviews and compares a list of tools and suggests the best-suited tools based on users' needs and requirements
- The core of MSP selection wizard is based on:
  - Specification discovery procedure
  - Scoring engine
- Progress in the last year
  - Includes 64 tools (up from 5 in previous release)
  - Production cost modeling (PCM) tools in selection wizard and comparison table



The screenshot shows the MSP web interface with a search bar and filters for category, institution, energy sector, and availability. Below the search area, there is a grid of tool cards:

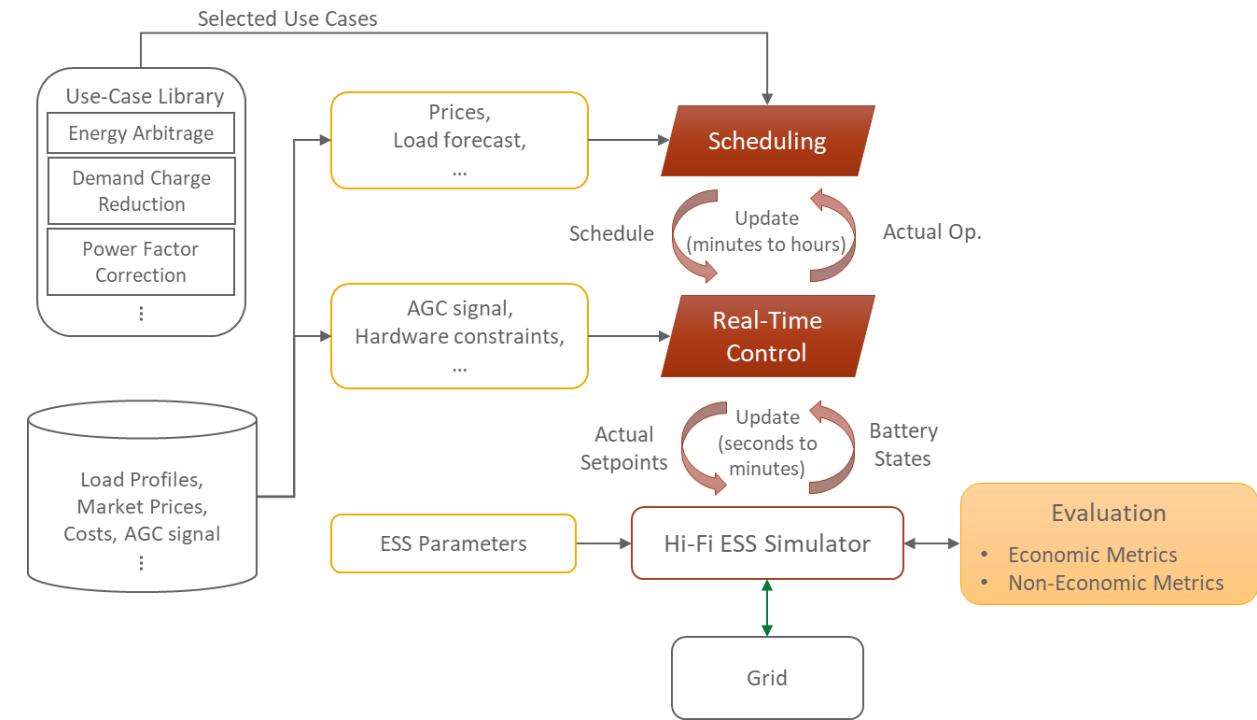
AHA	ATB	GREET LIFE-CYCLE MODEL
AHA All Hazards Analysis Idaho National Laboratory Assess multi-sectoral relationships between infrastructure elements to support diverse risk ...	ATB Annual Technology Baseline National Renewable Energy Laboratory Provides a consistent set of technology cost and performance data for energy analysis	GREET Automotive Deployment Options Projection Tool Argonne National Laboratory Estimates the impact of vehicle technology improvements on future U.S. vehicle sales, energ...
BLAST Battery Lifetime Analysis and Simulation Tools National Renewable Energy Laboratory Assess battery lifespan for behind-the-meter, vehicle, and stationary applications	BatPaC Battery Performance and Cost Argonne National Laboratory Design and cost estimation of lithium-ion cells and packs	EverBatt Battery recycling analysis of energy, environmental, and economic attributes Argonne National Laboratory Evaluates cost and environmental impacts for the various lifecycle stages of a lithium ion battery
B2U Calculator Battery Second-Use Repurposing Cost Calculator National Renewable Energy Laboratory Explore the effects of different repurposing strategies and assumptions on economics for ...		

<https://msp.pnnl.gov>

# ES-Control

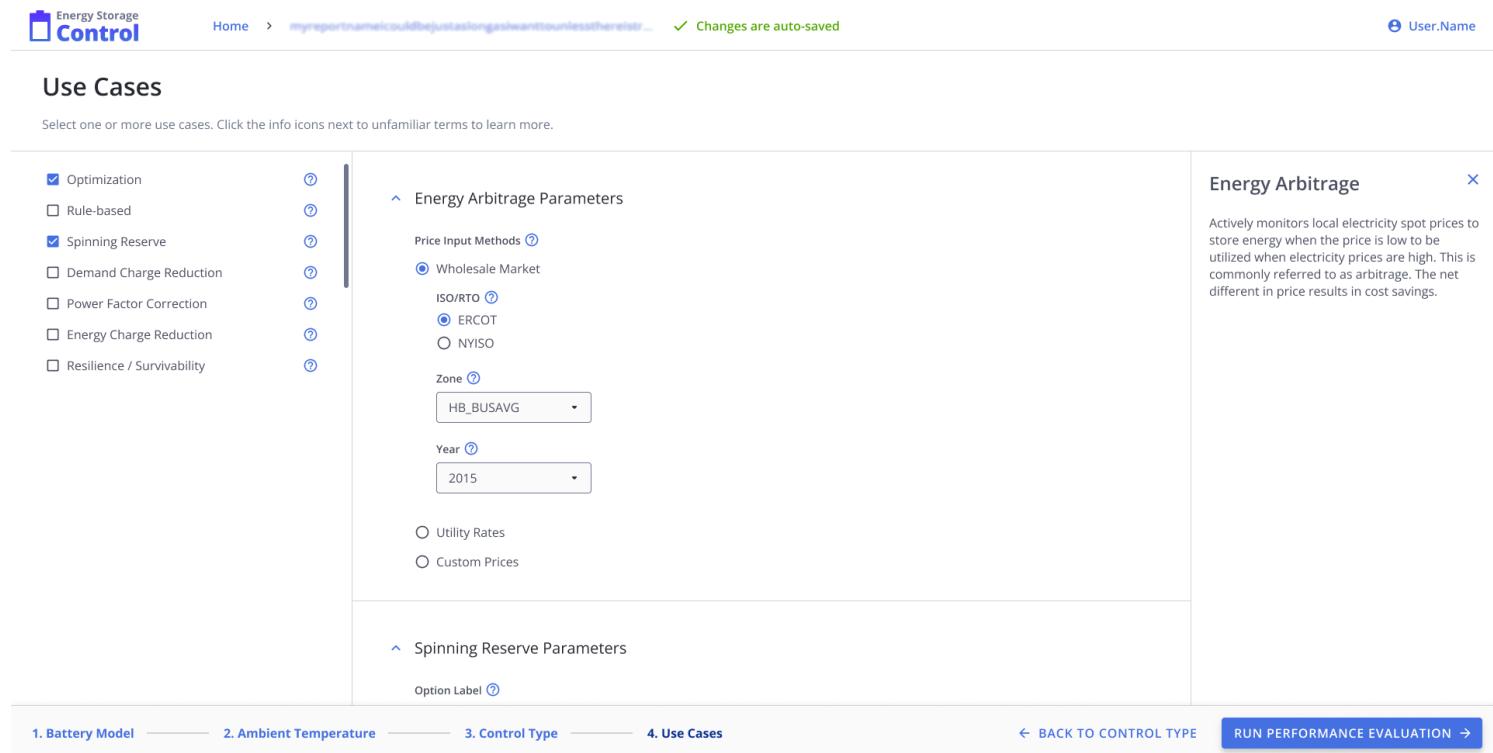
*ES-Control* is a platform for evaluation and testing of energy storage control strategies and algorithms with diversified time scales in a realistic setting, considering deployment options, use cases, and applications.

- Sandbox environment for modeling, control, simulation, and evaluation
- Representative built-in control strategies with adjustable parameters
- Open API for customized control
- Diversified energy storage models with different levels of complexity and fidelity
- Built-in database of energy storage costs, market prices, utility tariffs, etc.



# ES-Control (cont.)

- A web-based application
- Microservices architecture for rapid iteration and scalability
- Off-the-shelf AWS services for fast development and industry standard security



The screenshot shows a web-based application titled "Energy Storage Control". The top navigation bar includes links for "Home", "myreportnamecouldbejustaslongasitoulesstherestr...", and "User.Name". A green checkmark icon indicates "Changes are auto-saved".

The main content area is titled "Use Cases" and contains the following sections:

- Optimization** (checkbox selected)
- Rule-based** (checkbox unselected)
- Spinning Reserve** (checkbox selected)
- Demand Charge Reduction** (checkbox unselected)
- Power Factor Correction** (checkbox unselected)
- Energy Charge Reduction** (checkbox unselected)
- Resilience / Survivability** (checkbox unselected)

**Energy Arbitrage Parameters**

- Price Input Methods**:
  - Wholesale Market** (radio button selected)
  - ISO/RTO (radio button unselected)
  - ERCOT (radio button selected)
  - NYISO (radio button unselected)
- Zone**: HB\_BUSAvg
- Year**: 2015
- Utility Rates** (radio button unselected)
- Custom Prices** (radio button unselected)

**Spinning Reserve Parameters**

**Option Label**

At the bottom, there are tabs for "1. Battery Model", "2. Ambient Temperature", "3. Control Type", and "4. Use Cases". There are also buttons for "BACK TO CONTROL TYPE", "RUN PERFORMANCE EVALUATION", and a blue progress bar.

## Conclusions and Future Work

- System design and project development require appropriate energy storage models with a good balance between fidelity and complexity
- Advanced modeling and analytical methods and tools are required to define technically achievable benefits
  - Integrated forecasting and stochastic dispatch for modeling and addressing uncertainties
  - Ensemble machine learning for enhanced long-duration energy storage scheduling
  - Risk-aware scheduling to better balance economic and resilience benefits
- Additional research is needed to properly select, size, and value storage with different durations for future decarbonized grid
  - Electrification of transportation, building, and industry
  - Extreme weather conditions
  - Policy design and incentive mechanisms



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*Mission – to ensure a resilient, reliable, and flexible electricity system through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.*

<https://www.energy.gov/oe/activities/technology-development/energy-storage>

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# Thank You

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