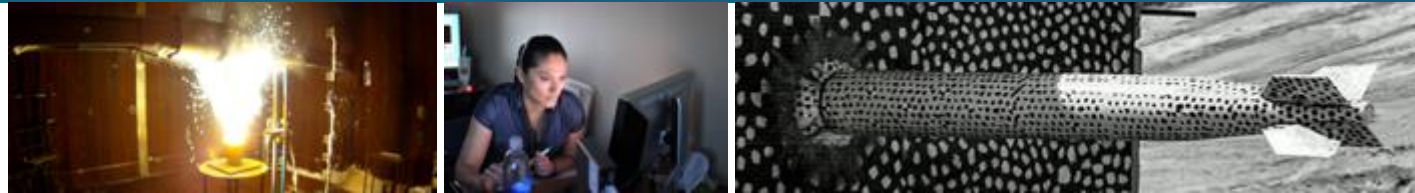


VALUATION OF ENERGY STORAGE: PROBLEMS, METHODOLOGIES, AND SOFTWARE TOOLS



PRESENTED BY

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Sandia National Laboratories



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SAND2024-03411PE



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

- 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

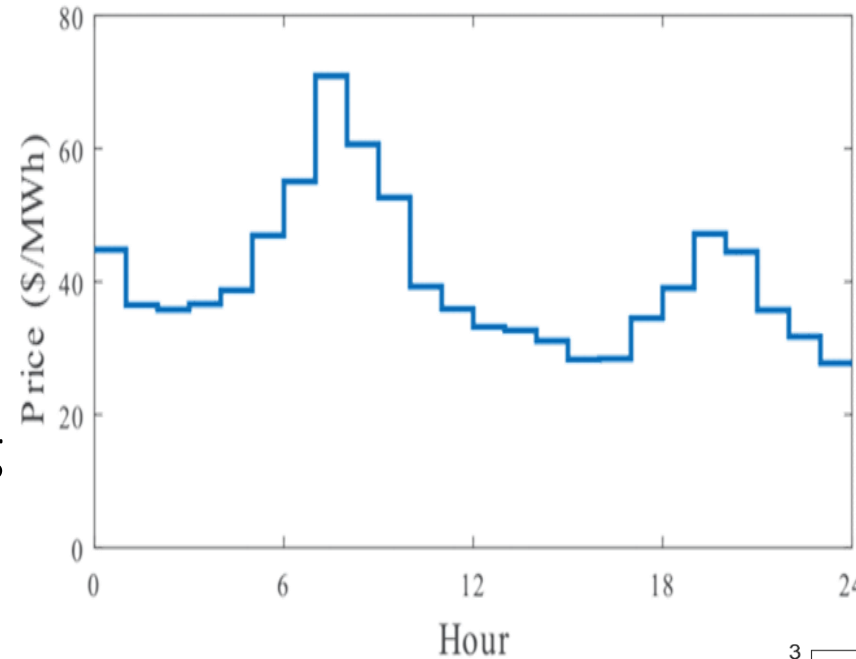
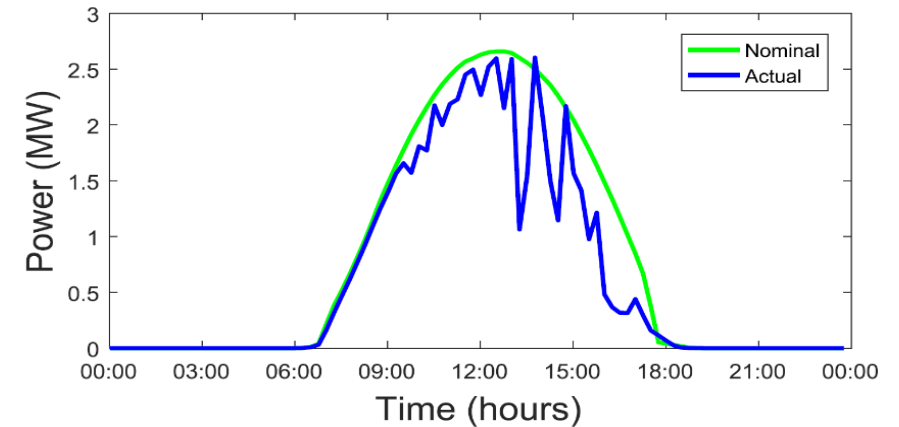


Image Credit - Solar Power World



ENERGY STORAGE APPLICATIONS – FTM VS. BTM

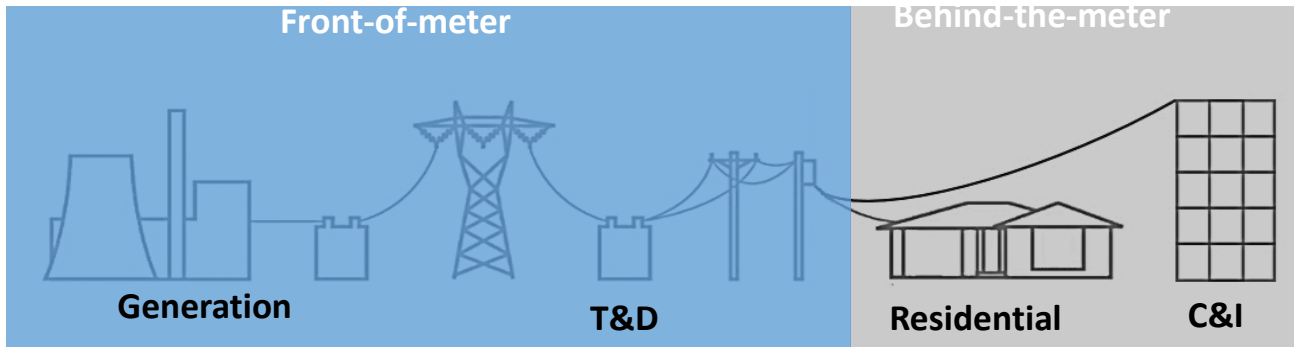
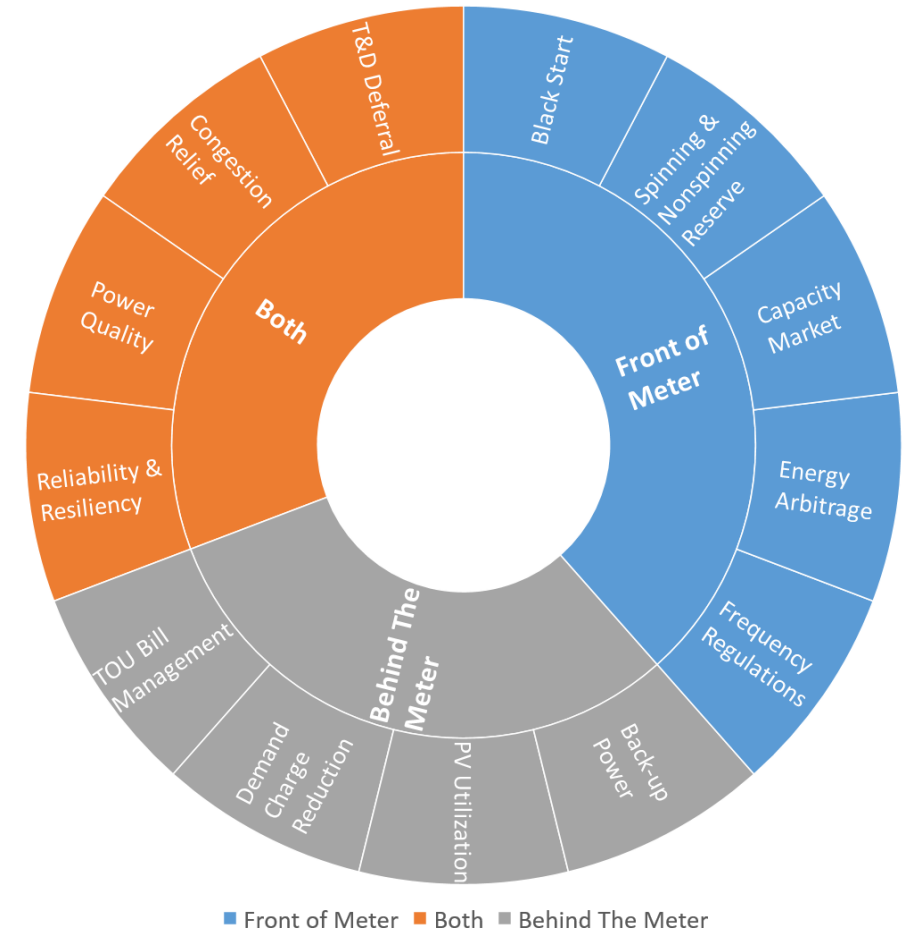


Image Credit: Navigant

- **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.



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?

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

subject to:

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

$$0 \leq s_i \leq \bar{S}$$

$$q_i^d + q_i^r + q_i^{ru} + q_i^{rd} \leq \bar{Q}$$

state of charge definition

state of charge limits

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

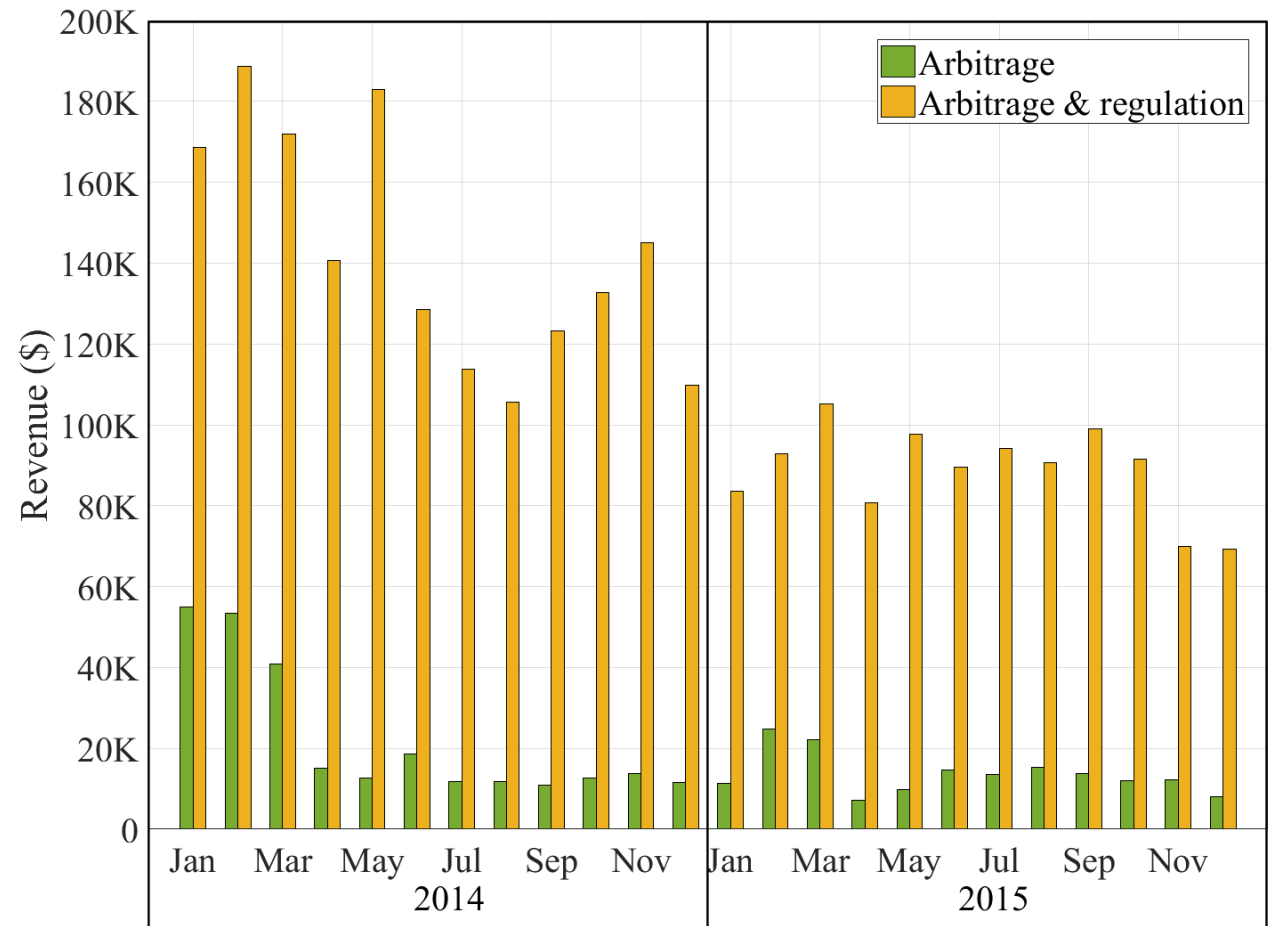
ENERGY STORAGE VALUATION – MARKET PROBLEM - EXAMPLE



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}	<i>R</i> ^{arb}	<i>R</i> ^{reg}	<i>R</i> ^{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





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 .

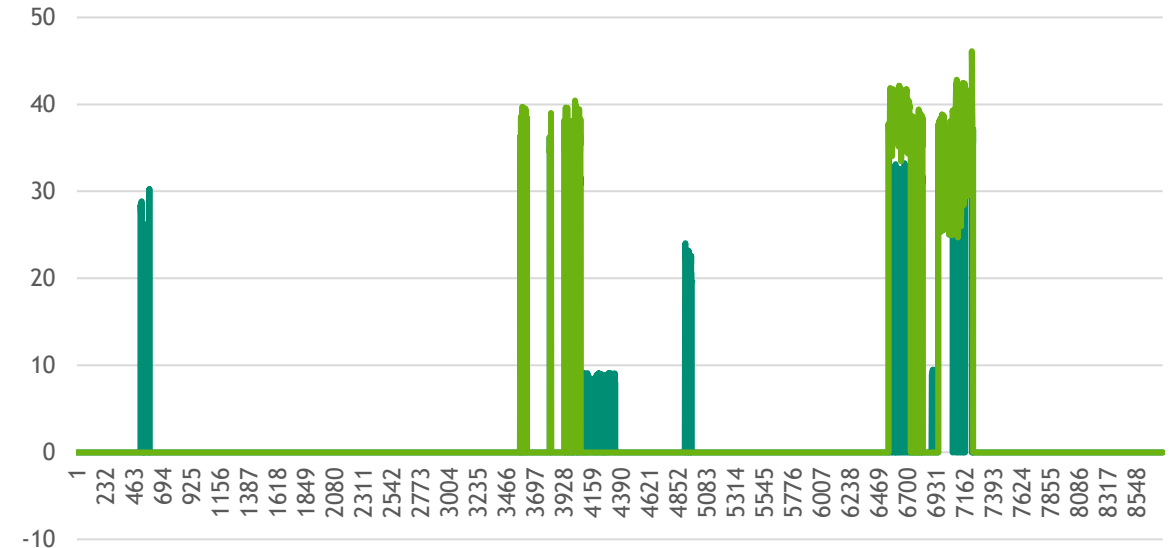
ENERGY STORAGE VALUATION – GENERATION PROBLEM - EXAMPLE



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.

Unit 2 - Schedule



	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 – TRANSMISSION PROBLEM

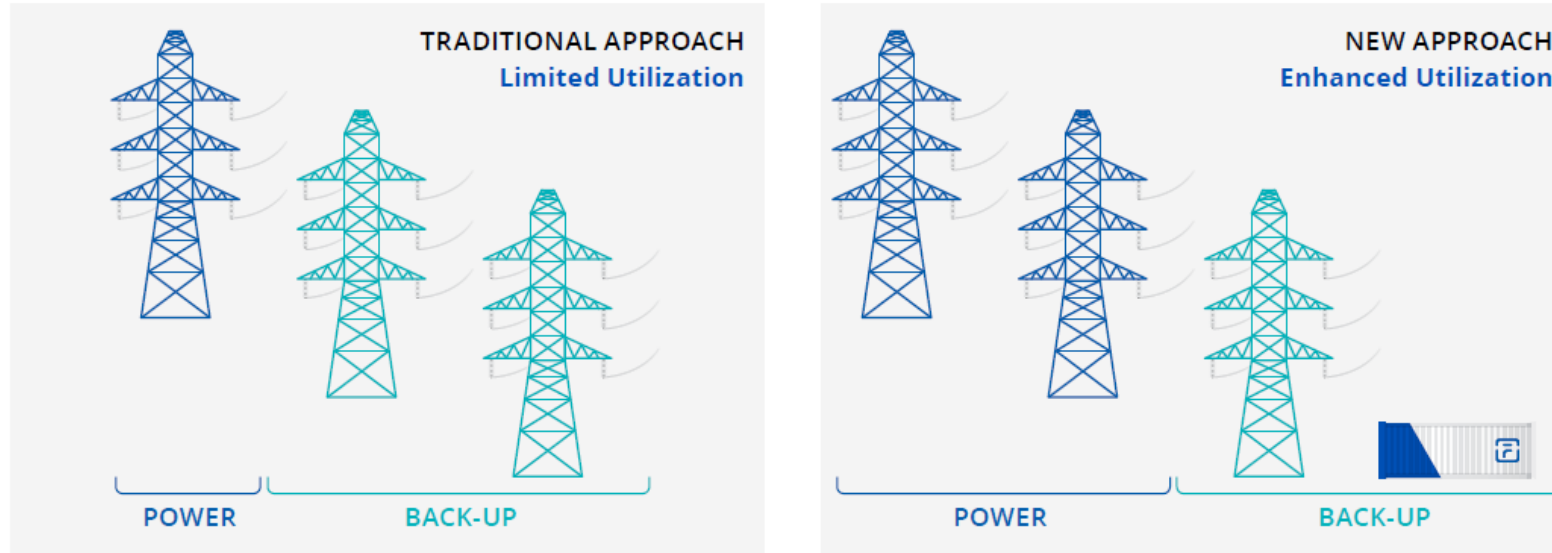
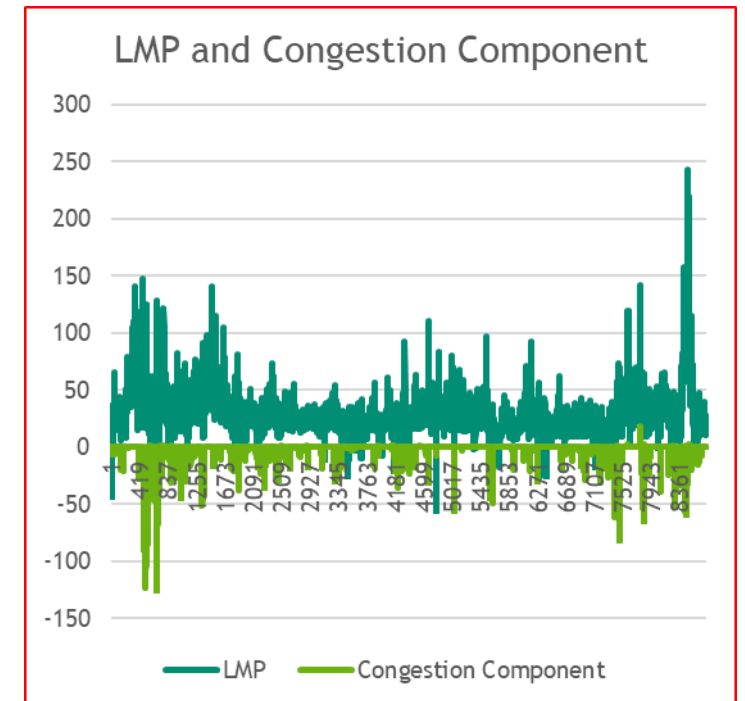
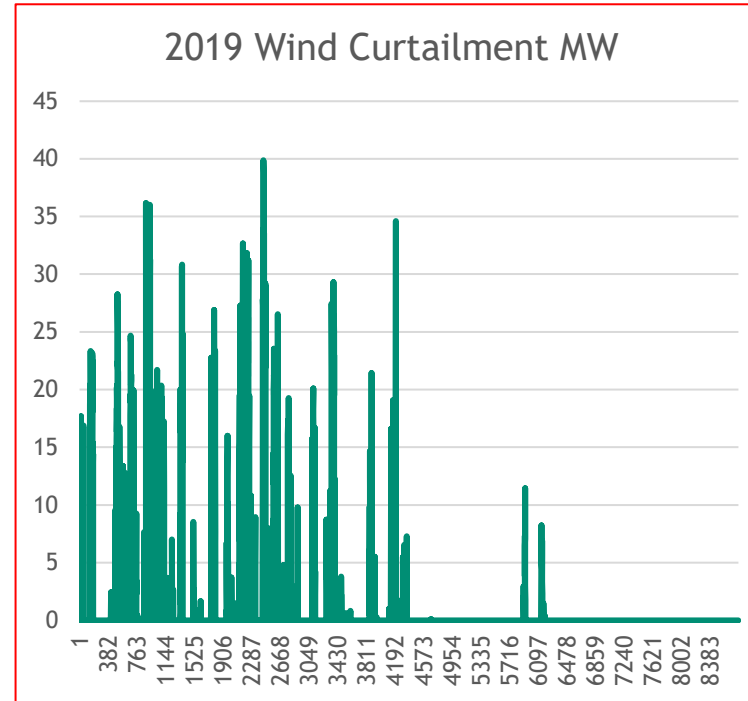
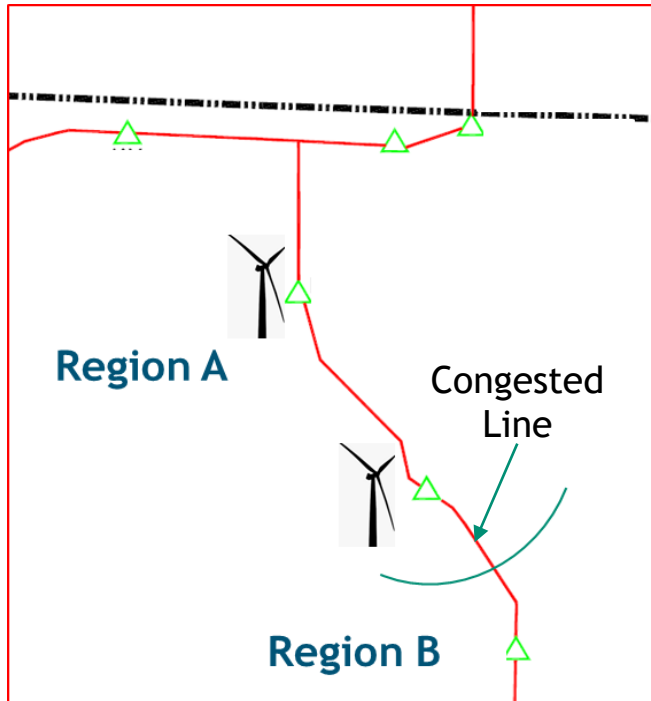


Image Credit: FLUENCE- Storage as Transmission White Paper

- Maximize the benefits from cost-based 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 – TRANSMISSION PROBLEM - EXAMPLE

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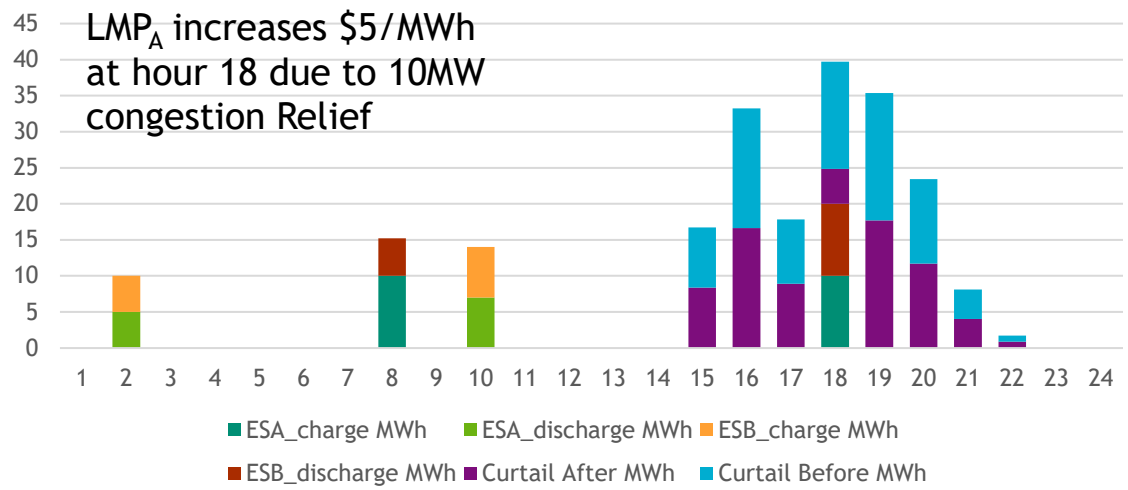


- Congestions make the marginal wind plant in region A curtail its output.
- Congestion component of LMP are negative indicating that if the congestions are relieved, more wind energy in region A can be sold to region B at higher LMPs
- In this case study:
 - Maximize the revenue for generators in region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

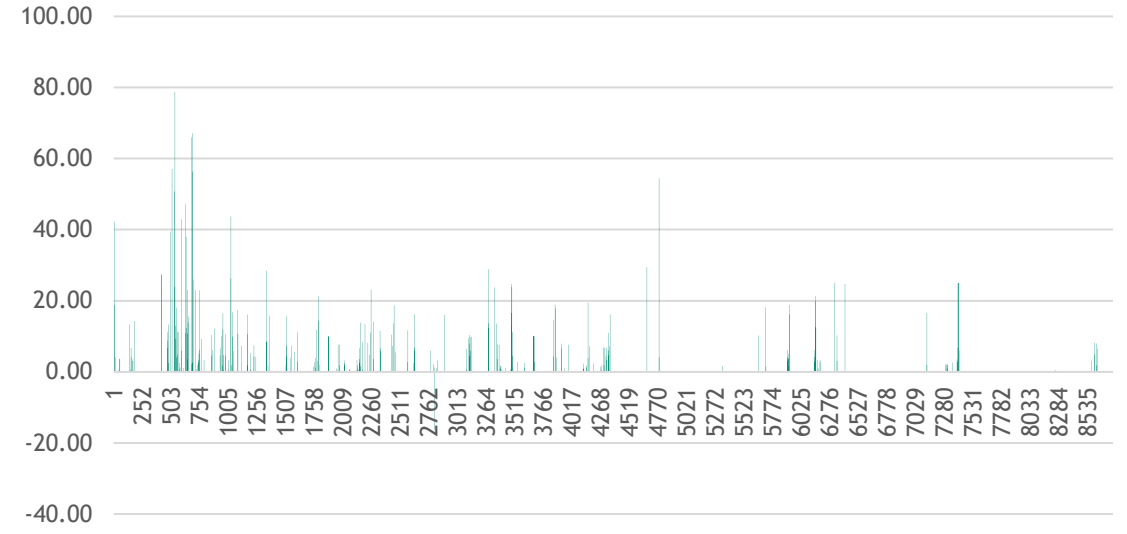
ENERGY STORAGE VALUATION – TRANSMISSION PROBLEM - EXAMPLE



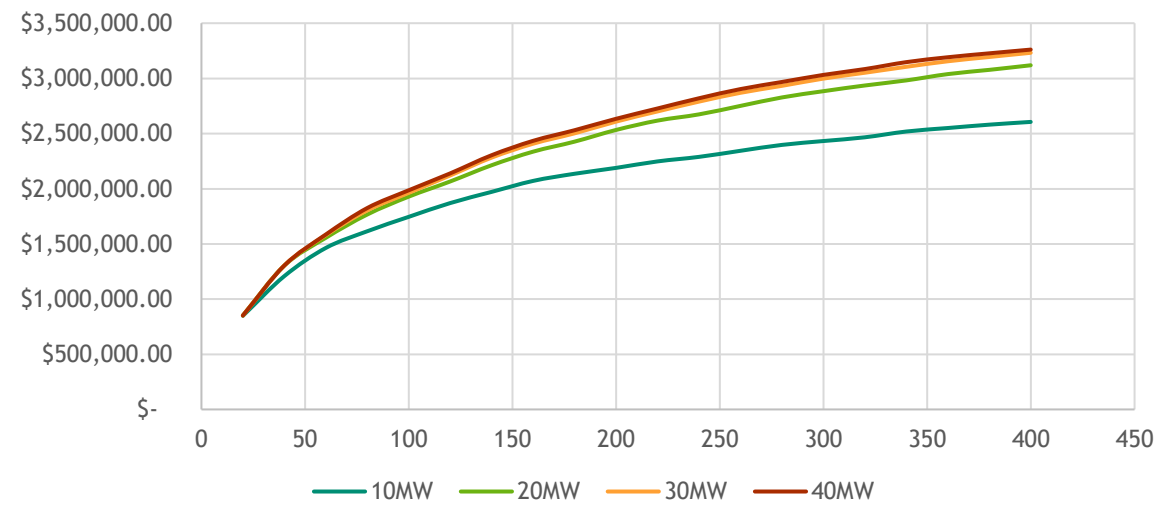
10MW/20Wh Case - Charge/discharge 24h Profile Example



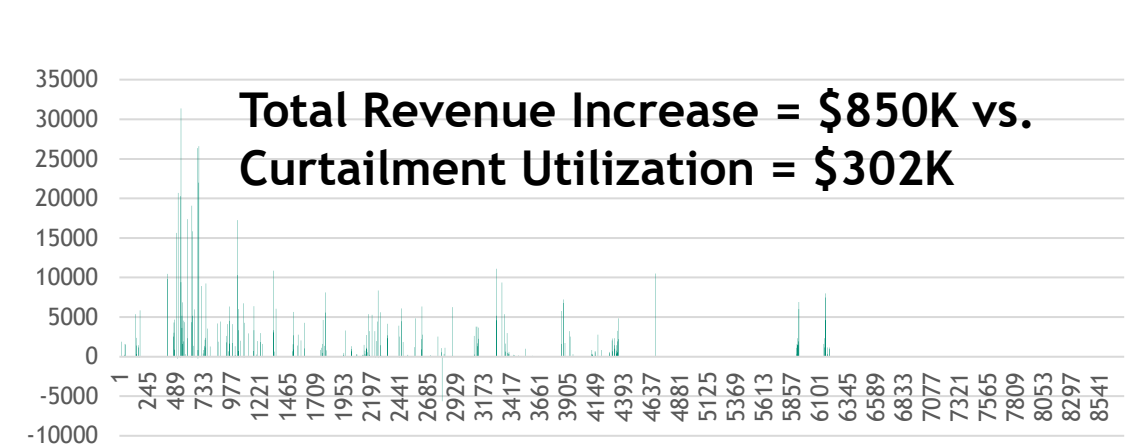
10MW/20Wh Case- LMP Improvement in \$/MWh



Congestion Relieve Revenue \$ vs. ESS size



10MW/20MWh Case - Region A Revenue Increase (\$)



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

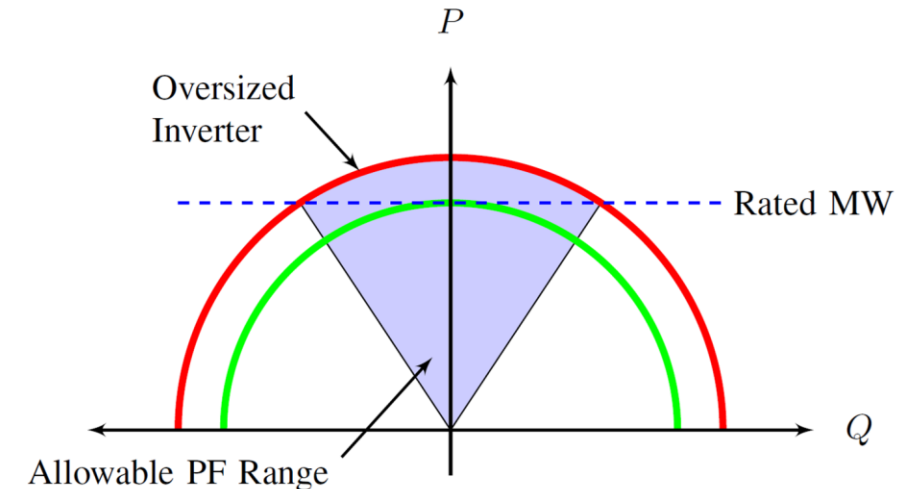
$$\min\{C_E^m + C_N^m + C_D^m\}$$

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 .



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: $pr = 0.04537$ [$\$/kWh$]

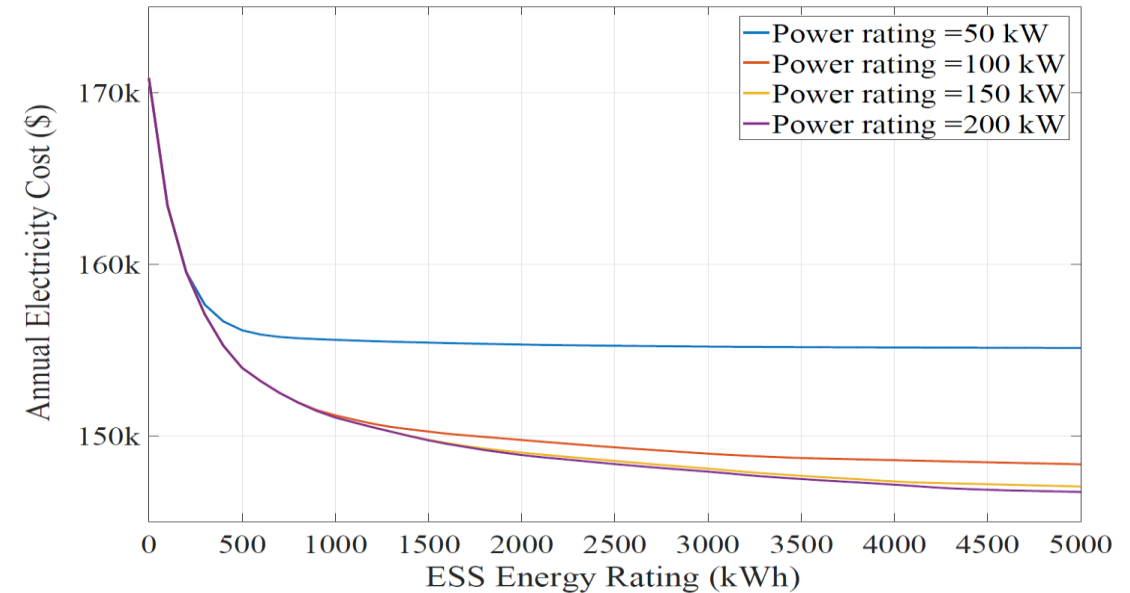
Peak-hour (6am-9pm) demand rate: $d_{pk} = 24.69$ [$\$/kW$]

Off-peak (9pm-6am) demand rate: $d_{opk} = 6.12$ [$\$/kW$]

Net-metering rate: $pr_s = 0.03$ [$\$/kWh$]

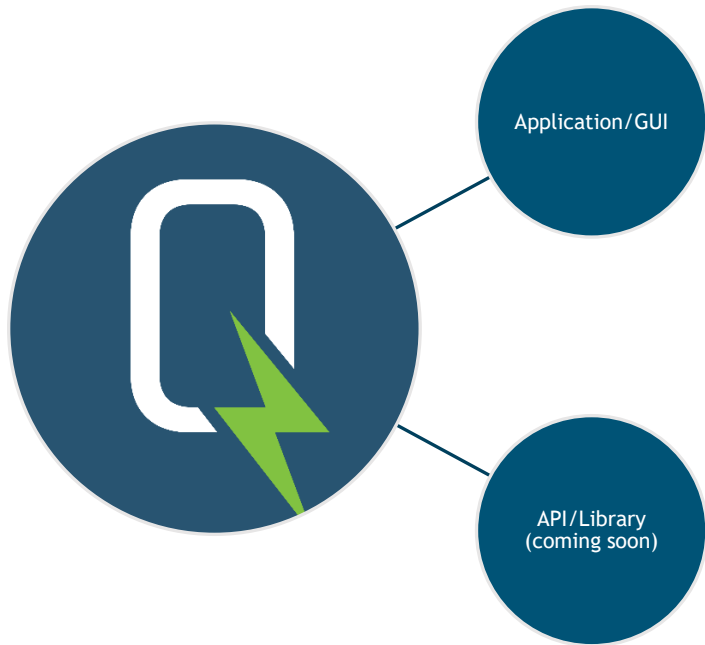
Case 1: TOU management without power factor correction

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

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- Energy storage analysis software application suite
- Version 1.0 publicly released in September 2018
- Version 1.6 available on GitHub
 - <https://github.com/sandialabs/sn1-quest>



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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

Decide what type of analysis to do.

- ISO/RTO value stacking => QuEST Valuation
- Behind-the-meter applications => QuEST BTM



Grab the appropriate data from QuEST Data Manager.

- ISO/RTO market data
- Utility rate structure
- PV profile
- Load profile



Select the appropriate application from the first step.

- Set up the analysis and run it
- View and process results

QuESt – Valuation Application

QuESt Wizard home about settings

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.

ERCOT	PJM	MISO
NYISO	ISONE	SPP
CAISO		

Previous Next

QuESt Wizard home about settings

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

QuESt Wizard home about settings

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)

Month	Arbitrage	Regulation
Jan	-\$10,000	\$370,000
Feb	-\$5,000	\$365,000
Mar	-\$10,000	\$360,000
Apr	-\$10,000	\$355,000
May	-\$10,000	\$350,000
Jun	-\$10,000	\$345,000
Jul	-\$20,000	\$340,000
Aug	-\$10,000	\$335,000
Sep	-\$10,000	\$330,000
Oct	-\$10,000	\$325,000
Nov	-\$10,000	\$320,000
Dec	-\$10,000	\$315,000

Generate report

QuESt – BTM Application



Time-of-Use Cost Savings

Select a rate structure.

Filter by name

- 0129
- 0206
- 0213
- 0321-nyseg
- 0325-pepco-general-service
- PNM
- e-tou-option-b
- example
- nyseg-tou-residential
- nyseg-tou-residential-nem1
- paloalto
- pnm-residential-tou**
- xyz

Energy

Legend: \$0.186617/kWh, \$0.0599499/kWh, \$0.1452852/kWh, \$0.0599499/kWh

Demand

Legend: \$0.0/kWh

Flat demand rate [\$/kWh] Jan 0.0 Feb 0.0 Mar 0.0 Apr 0.0 May 0.0 Jun 0.0 Jul 0.0 Aug 0.0 Sep 0.0 Oct 0.0 Nov 0.0 Dec 0.0

Peak demand min. [kW] Peak demand max. [kW] Net metering type Energy sell price [\$/kWh]

Previous Next

Time-of-Use Cost Savings

Specify the energy storage system parameters.

- energy capacity**: The maximum amount of energy that the ESS can store. kWh
- power rating**: The maximum rate that at which the ESS can charge or discharge energy. kW
- transformer rating**: The maximum amount of power that can be exchanged. kW
- self-discharge efficiency**: The percentage of stored energy that the ESS retains on an hourly basis. %/h
- round trip efficiency**: The percentage of energy charged that the ESS actually retains. %
- minimum state of charge**: The minimum ESS state of charge as a percentage of energy capacity. %
- maximum state of charge**: The maximum ESS state of charge as a percentage of energy capacity. %
- initial state of charge**: The percentage of energy capacity that the ESS begins with. %

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Time-of-Use Cost Savings

Here's the total bill with and without energy storage for each month.

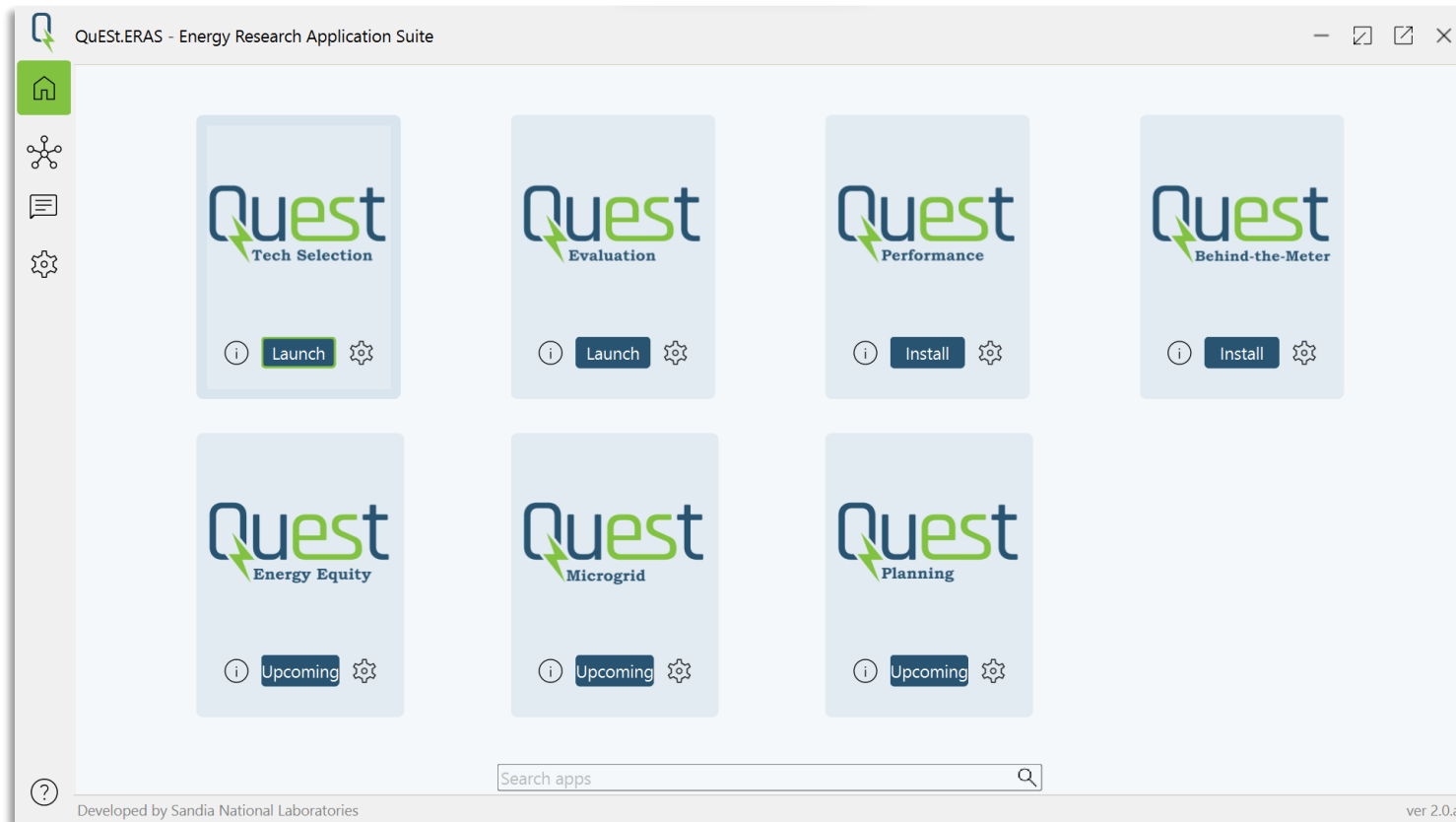
The total bill is the sum of demand charges, energy charges, and net metering charges or credits. It looks like the ESS was able to **decrease** the total charges over the year by **\$1,712.70**.

Month	without ES	with ES
Jan	\$3,376	\$3,172
Feb	\$3,376	\$3,172
Mar	\$3,376	\$3,172
Apr	\$3,376	\$3,172
May	\$3,376	\$3,172
Jun	\$3,376	\$3,172
Jul	\$3,376	\$3,172
Aug	\$3,376	\$3,172
Sep	\$3,376	\$3,172
Oct	\$3,376	\$3,172
Nov	\$3,376	\$3,172
Dec	\$3,376	\$3,172

Reports

- Total bill
- Total bill comparison**
- Demand charge comparison
- Energy charge comparison
- NEM comparison
- Peak demand comparison

Generate report



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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