Energy Storage Valuation: A Review of Use Cases and Modeling Tools

Vinod Siberry, Di Wu, Dexin Wang, Xu Ma

Technical Report
Publication No. DOE/OE-0029
June 2022

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

U.S. DEPARTMENT OF ENERGY

Disclaimer

Table of Contents

Introduction and Purpose

An enticing prospect that drives adoption of energy storage systems (ESSs) is the ability to use them in a diverse set of use cases and the potential to take advantage of multiple unique value streams. The Energy Storage Grand Challenge (ESGC) technology development pathways for storage technologies draw from a set of use cases in the electrical power system, each with their own specific cost and performance needs. In addition to the need for cost and performance improvements for storage technologies, there is a need for robust valuation methods to enable effective policy, investment, business models, and resource planning. Numerous storage valuation tools are available to the public, many of which can analyze the value of an ESS project with inputs and characteristics that reflect a specific storage use case.

To effectively reach ESS stakeholders that may be interested in learning about valuation models, this report draws from publicly available tools developed by the Department of Energy (DOE) and frames their functionalities and capabilities within the context of three distinct use case families. This report examines three of the ESGC use case families in depth and provides a methodology in which interested stakeholders can determine which DOE modeling tool is best suited to value ESS for their specific case. The high-level objectives for this report are as follows:

- Provide specific sub-use cases for each use case family for further characterization.
- Provide technical parameters and relevant data for three example use cases that could be used in a valuation tool.
- Identify a list of publicly available DOE tools that can provide energy storage valuation insights for ESS use case stakeholders.
- Provide information on the capabilities and different options in each modeling tool.
- Make conclusions on which tools are best suited for valuing certain functional/performance requirements and which tools might be applicable to other use cases.
- Show the methodology that informs a Model Selection Platform (MSP) framework that educates stakeholders on different DOE models and provides a streamlined way to choose the right model that most closely matches their needs. This framework will follow the structure in shown Figure 1.

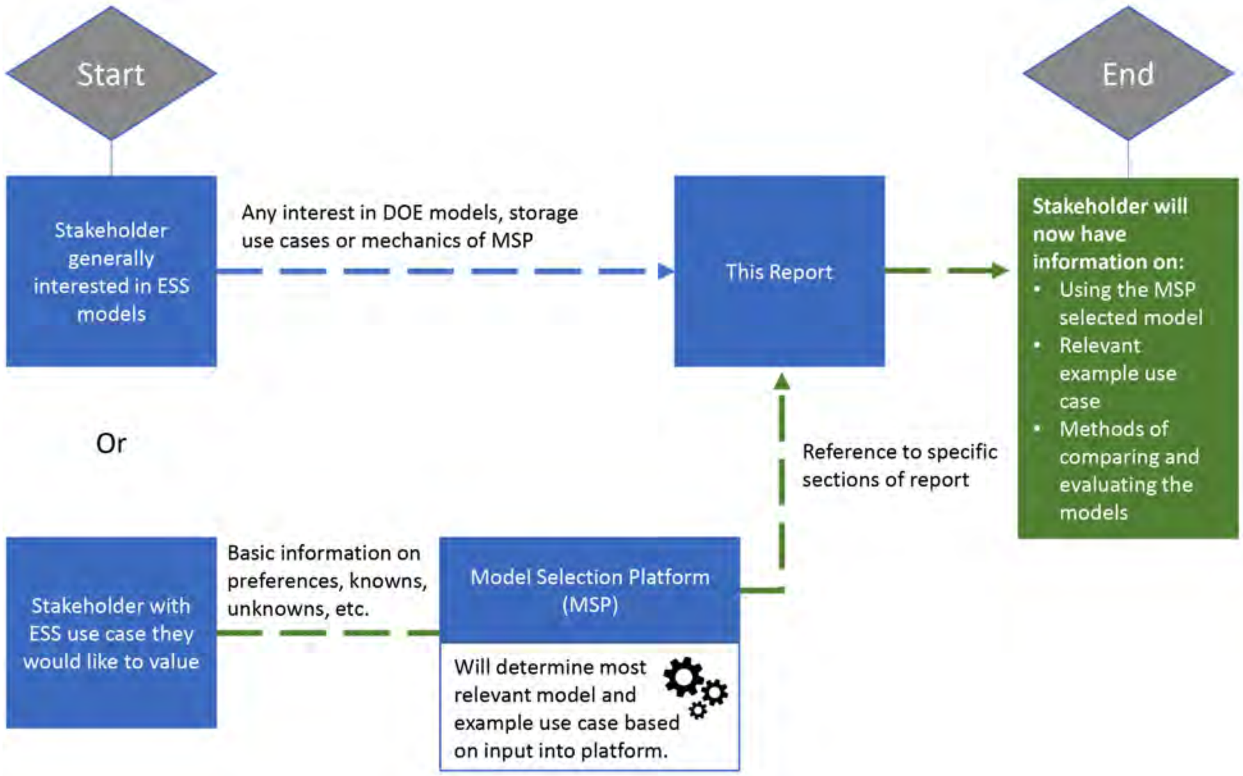


Figure 1: Objective Framework

Use Case Family Characterization

Introduction

This report examines three of the use case families that were formulated as a part of the ESGC roadmap effort to inform future DOE research and development activities in the field of energy storage. These three families are described below and in the Technology Development section of the roadmap[1]:

- **Facilitating an Evolving Grid:** The ability of the U.S. electric power system (i.e., the electric grid) to reliably meet customer demand is crucial to our economy and national security. The increasing adoption of variable renewable energy (VRE) and dynamic changes in customer demand, as well as stresses from weather, physical, and cyber threats, highlight how enhanced grid flexibility can ensure the continued reliability, resilience, and security of the electric power system.
- **Critical Services:** Sectors that provide critical services include the defense industrial base sector, emergency services sector, government facilities sector, and health care and public health

[1] DOE ESGC Final Roadmap: https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf

sector. An extended loss of power to facilities in these sectors could lead to unacceptable public health and safety risks, especially following disaster-related power outages. Similarly, many companies and manufacturers require the ability to resume and maintain operations in the event of an extended outage. The importance of these services reinforces the importance of sufficient energy supplies to these facilities during an extended outage.

- **Facility Flexibility, Efficiency, and Value Enhancement: Commercial and Residential Buildings:** This use case seeks to leverage opportunities to optimize energy production and usage in facilities, especially commercial and residential buildings. Optimized integrated processes can utilize high-performance, low-cost energy storage technologies to enhance the overall facility value to the owner, operator, and ultimately, the end consumer.

In this section, these three use case families will be further specified by sub-use cases that provide more detail about what these could look like in the context of using energy storage to support them. An example case study is included for each use case family to serve as a reference to a real-world example of storage being used in the respective sub-use case.

Facilitating an Evolving Grid

Provision of Ancillary Services

Case Study: Beacon Power Hazel Township Flywheel Plant Revenues in PJM

Description: 20 MW/5 MWh flywheel plant in Pennsylvania, New Jersey, and Maryland (PJM) territory to maximize revenue from energy arbitrage and frequency regulation in electricity markets based on historical prices.

Potential Parameters of Interest:

- Market rules and prices of frequency regulation, spinning/non-spinning reserves, and other market-based products from Independent System Operator/Regional Transmission Organization (ISO/RTO)
- Value to the system that, volt/var support, frequency response, ramping, black start, etc. provide often compared to cost of other assets that provide similar services, may inform value of bilateral contracts, power purchase agreement (PPA), or an energy storage tolling agreement

Provision of Peaking Capacity

Case Study: Value Proposition of Energy Storage for Sterling Municipal Light Department

Description: Economic analysis of the value of energy storage for the Sterling Municipal Light Department, including savings derived from the ISO-NE Forward Capacity Market (FCM), which incentivizes load-serving entities to minimize their load obligation during peak days/hours in the ISO region.

Potential Parameters of Interest:

- ISO/RTO capacity market information and rules, cost of system operator capacity charges (See ISO-NE FCM charge), and potentially others
- Peaker plant emissions and associated rules (NO_x, CO_2, SO_2, etc.)
- Existing and proposed peaker plant power capacity, average longest start time, average hours per start, starts per year, costs metrics [fuel, operations and maintenance (O&M), etc.) for technology competing comparison

Transmission and Distribution Deferral

Case Study: Nantucket Island Submarine Transmission Cable Deferral

Description: To defer investment in another submarine transmission cable to meet expected peak summer load and serve the load during N-1 contingency event on Nantucket Island, MA, National Grid is installing 6 MW/48 MWh of battery energy storage system (BESS) along with upgraded combustion turbine generators (CTGs) on the island.

Potential Parameters of Interest:

- Cost of transmission infrastructure needed for specific case
- Value of transmission congestion contracts/financial transmission rights, cost of transmission charges that utilities pay to system operator (see ISO-NE RNS charges), and other locational marginal pricing (LMP) based costs
- Expected percent or hours of time that system will be needed for local reliability services
- Expected cost improvements associated with reducing customer outage times

Production Cost Optimization from System Operator/Planner Perspective

Case Study: Southern Company Energy Storage Study

Description: A production cost model was used to evaluate business cases for bulk electric energy storage under different scenarios in the Southern Company service territory. The evaluation involved a number of different ESSs of different sizes, ranging from larger pumped hydroelectric power plants to smaller bulk-scale battery systems, in providing energy time shifting, regulation reserve, and spinning reserve for production cost saving.

Potential Parameters of Interest:

- Utility generation asset data: resource type, rated power capacity, fuel costs (current and expected), O&M costs, start costs, average repair time, and other necessary unit characteristics/constraints
- Potential scenarios for storage to serve load based on peak and off-peak demand, types of generation, and demand seasonality and reserve requirements

Energy Smoothing and Shifting for VRE

Case Study: PNM Prosperity Energy Storage Project for PV Smoothing

Description: The Public Service Company of New Mexico (PNM) installed a 500 kW/350 kWh lead-acid battery with integrated supercapacitor (for energy smoothing) and a 250 kW/1 MWh lead-acid battery (for energy shifting) to facilitate the integration of their 500 kW photovoltaics (PV) resource. The smoothing battery was designed to smooth rapid fluctuations in solar PV output due to intermittent cloud cover, and the shifting battery was designed to shift the PV resource's output to better coincide with evening peak load.

Potential Parameters of Interest:

- PV plant power output standard deviation, ramp rate standard deviation, max-min reduction
- System efficiency metrics, including effects of AC-AC, DC-DC, balance of plant losses, etc.
- Metrics on predicting VRE resource availability (solar/wind energy potential and estimated variability on a given day)
- LMP data for day ahead and real time markets for arbitrage revenue potential

Critical Services

Microgrid Communities

Case Study: Revenues from Green Mountain Power Microgrid W/Storage

Description: This project is located at a former landfill site (Stafford Hills) outside of the town of Rutland, Vermont, in the vicinity of the Green Mountains National Forest in central Vermont. Green Mountain Power (GMP) is the electric utility company that serves this portion of Vermont. The system consists of 4 MW/3.4 MWh of lead-acid and Li-ion batteries, integrated with 2.5 MW of PV panels. The microgrid is designed for islanding; that is, it can operate independent of the utility electric grid using the installed PV and batteries. When connected to the grid, it generates and stores power for GMP, furthering renewable integration and providing peak shaving.

Potential Parameters of Interest:

- Grid connected, islanded, or capable of both
- Electrical load(s) of supported infrastructure, critical loads when microgrid must enter islanded mode to provide backup power
- Existing generation integrated into microgrid

Facility Flexibility, Efficiency, and Value Enhancement: Commercial and Residential Buildings

Residential Building

Case Study: BTM Storage Paired with PV for Bill Management and Demand Response

Description: The Hawaii Public Utilities Commission has approved the Hawaiian Electric Company's (HECO's) revised portfolio of demand response (DR) programs. The companies have released a grid services purchase agreement and subscribed an initial tranche of load into their DR programs. In collaboration with HECO, Pacific Northwest National Laboratory (PNNL) has evaluated distributed PV paired with BESSs for DR considering different tariff schedules and PV compensation programs across five islands. It was found that while the best resource configuration and potential economic benefits vary with tariff structure, a BESS paired with PV can be optimally dispatched to generate multiple value streams simultaneously. Compensation from DR programs is an important value stream to help increase the cost-effectiveness of the integrated system.

Potential Parameters of Interest:

- Building electricity usage profile
- Utility rates
- PV compensation programs
- Demand response programs
- BESS and PV techno-economic characteristics

Commercial Building

Case Study: Supermarket with Backup Generation

Description: This report discusses the costs and benefits of different generator types and configurations used in supermarkets in three different locations. PV and ESS is one of the options analyzed to see if it provides a cost-effective solution for this use case.

Potential Parameters of Interest:

- Building electricity usage profile
- Utility rates
- Cost of other technologies to provide similar backup power capabilities
- Value of lost load for facility

Behind-the-Meter (BTM) Aggregations

Case Study: Aggregate Flexible Building Loads for Grid Services

Description: This paper presents a framework for modeling, scheduling, and controlling flexible building loads to provide multiple grid services, such as energy shifting, peak load reduction, and ancillary services. A modeling method is proposed to characterize aggregate flexibility from building loads using a battery-equivalent model. Based on the flexibility model, a multi-period optimal scheduling formulation is developed to best utilize the flexibility from building loads and maximize total benefits from stacked value streams. Aggregate flexibility from residential air conditioners within a distribution feeder in the Southern California Edison system has been estimated and assessed.

Potential Parameters of Interest:

- Building parameters such as thermal resistance, thermal capacitance, temperature setpoint, and deadbands
- Outdoor air temperature
- Utility rates
- Grid service prices and dispatch signals

General Cost and Performance Parameters for Energy Storage Technologies

Introduction

For all of use cases and models, the parameters involved in evaluating an ESS's cost and performance are necessary and are often difficult to represent even using advanced metrics such as levelized cost of energy and levelized cost of storage. One of the efforts in the ESGC is a report titled "2020 Grid Energy Storage Technology Cost and Performance Assessment," which provides cost and performance estimates for six different ESS technologies by breaking down each technology into a standard set of parameters and categories. The general organization structure is found below:

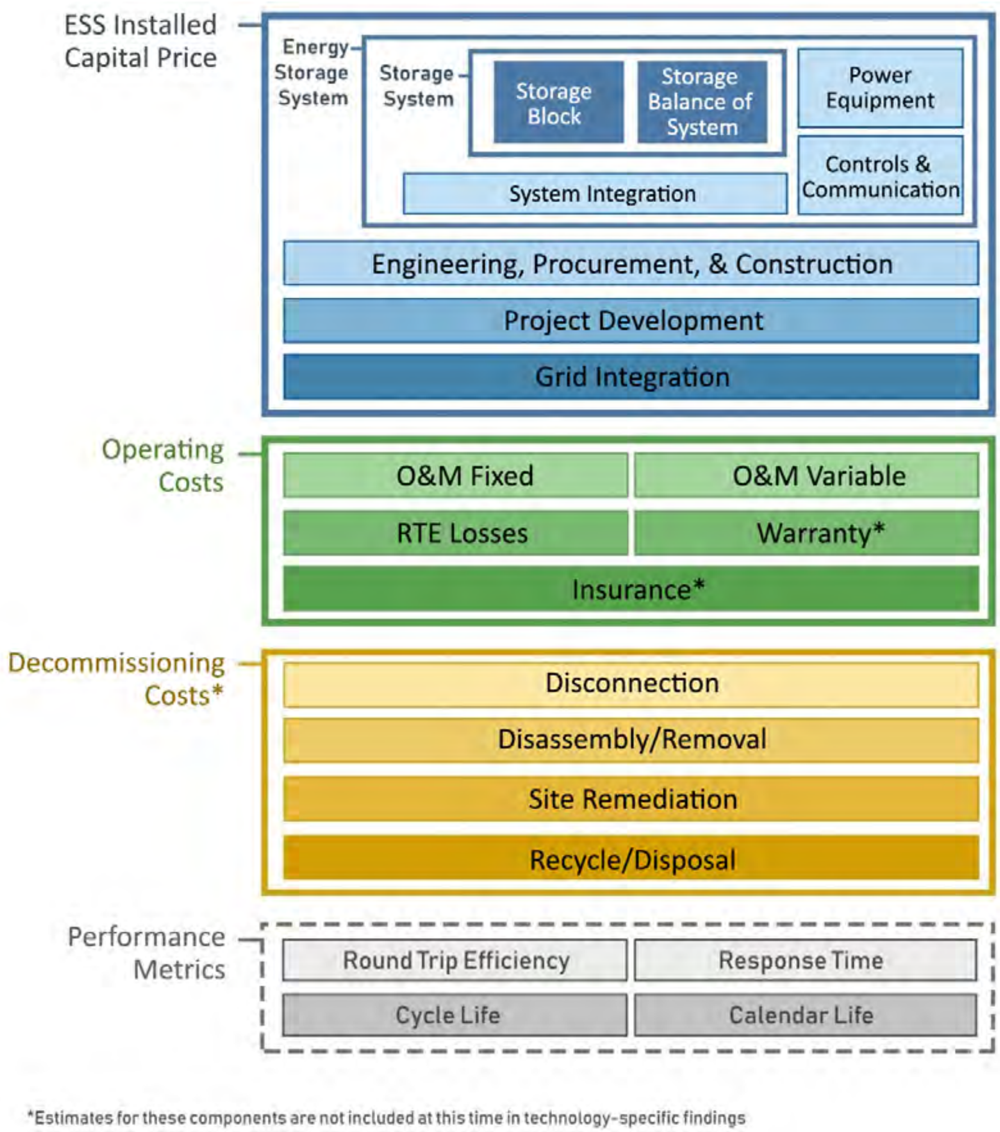


Figure 2: Breaking Down ESS Cost and Performance

This report provides current estimates for Li-ion, lead-acid, vanadium redox flow batteries, compressed-air energy storage (CAES), pumped storage hydro (PSH), and hydrogen ESS. Below is the list of performance and cost parameters used in the report, which provide a comprehensive view of the actual cost of a storage system.[2]

Installed Cost Components

- **Storage Block (SB) ($/kilowatt-hour [kWh]):** This component includes the price for the most basic direct current (DC) storage element in an ESS (e.g., for lithium-ion, this price includes the battery module, rack, and battery management system, and is comparable to an electric vehicle pack price).
- **Storage - Balance of System (SBOS) ($/kWh):** This includes supporting cost components for the SB with container, cabling, switchgear, flow battery pumps, and heating, ventilation, and air conditioning (HVAC).
- **Storage System ($/kWh):** This cost is the sum of the SB and SBOS costs and is an appropriate level of granularity for some studies.
- **Power Equipment ($/kilowatt [kW]):** This component includes bidirectional invertor, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, and software. This is the power conversion system for batteries, the powerhouse for PSH, and the power island/powertrain for CAES.
- **Controls & Communication (C&C) ($/kW):** This includes the energy management system for the entire ESS and is responsible for ESS operation. This may also include annual licensing costs for software. The cost is typically represented as a fixed cost scalable with respect to power and independent of duration
- **System Integration ($/kWh):** This is the price charged by the system integrator to integrate subcomponents of a BESS into a single functional system. Tasks include procurement and shipment to the site of battery modules, racks with cables in place, containers, and power equipment. At the site, the modules and racks are containerized with HVAC and fire suppression installed and integrated with the power equipment to provide a turnkey system.
- **Engineering, Procurement, and Construction (EPC) ($/kWh):** This includes non-recurring engineering costs and construction equipment as well as shipping, siting and installation, and commissioning of the ESS. This cost is weighted based on E/P ratio.
- **Project Development ($/kW):** These costs are associated with permitting, PPAs, interconnection agreements, site control, and financing.
- **Grid Integration ($/kW):** This is the direct cost associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers. For the last component, it could be a single disconnect breaker or a breaker bay for larger systems.

[2] 2020 Grid Energy Storage Technology Cost and Performance Assessment

Operating Costs

- **Fixed O&M ($/kW-year):** This includes all costs necessary to keep the storage system operational for the duration of its economic life that do not fluctuate based on energy throughput, such as planned maintenance, parts, and labor and benefits for staff. This also includes maintenance related to major overhauls, which depends on throughput.
- **Basic Variable O&M ($/megawatt-hour [MWh]):** This includes usage-impacted costs associated with non-fuel consumables necessary to operate the storage system throughout its economic life.
- **Round Trip Efficiency (RTE) Losses ($/kWh):** RTE is simply the ratio of energy discharged to the grid to the energy received from the grid to bring the ESS to the same state of charge (SOC). RTE is < 1 due to losses related to thermal management, electrochemical losses, power conversion losses, powertrain-related losses, energy conversion losses, evaporation, or gas/air leakage. This value for RTE losses is estimated through the cost of the additional electricity purchased or fuel required per unit kilowatt-hour of energy discharged due to the losses described.
- **Warranty ($/kWh):** Fees to the equipment provider for manufacturability and performance assurance of designated lifespan.
- **Insurance ($/kWh):** Insurance fees to hold a policy to cover unknown and/or unexpected risks. The terms of this cost may depend on vendor reputation and financial strength.

Performance Metrics

- **RTE (%):** This is the ratio of net energy that is discharged to the grid (after removing auxiliary load consumption) to the total energy used to charge the ESS (after including the auxiliary load consumption). Note that RTE for any technology depends on operating conditions.
- **Response Time (sec or min):** Measured as the time for an ESS to go from 0% to 100% rated power.
- **Cycle Life (#):** The cycle life for an ESS is a function of depth of discharge and measures the total number of cycles that an ESS can provide over its life.
- **Calendar Life (years):** Defined as the maximum life of the system regardless of operating conditions. For batteries, calendar life depends on the ambient temperature and SOC.
- **Duration Corresponding to Cycle Life (years):** Calculated by dividing the cycle life by the number of cycles per year, accounting for downtime.

Overview of ESS Valuation Modeling

Introduction

Valuing energy storage is often a complex endeavor that must consider different polices, market structures, incentives, and value streams, which can vary significantly across locations. In addition, the economic benefits of an ESS highly depend on its operational characteristics and physical capabilities. Many of the value stacking opportunities for energy storage come from its ability to provide certain system services at both very short-term timescales (sub seconds to seconds) and medium-term (hours to days) time scales.[3] The physical limitations of an ESS must be respected and represented in a way that accurately captures their operational characteristics so that they can be fairly evaluated against other system assets. The complexity of correctly valuing ESSs comes not only from the devices themselves, but also the complexity introduced when evaluating multiple, potentially competing methods of gaining value from a given operational opportunity. Charging control could be very complicated due to the competition among various services for limited power and energy capacity, not only on a time step but also intertemporally. The landscape of stationary services that energy storage can provide is as follows:

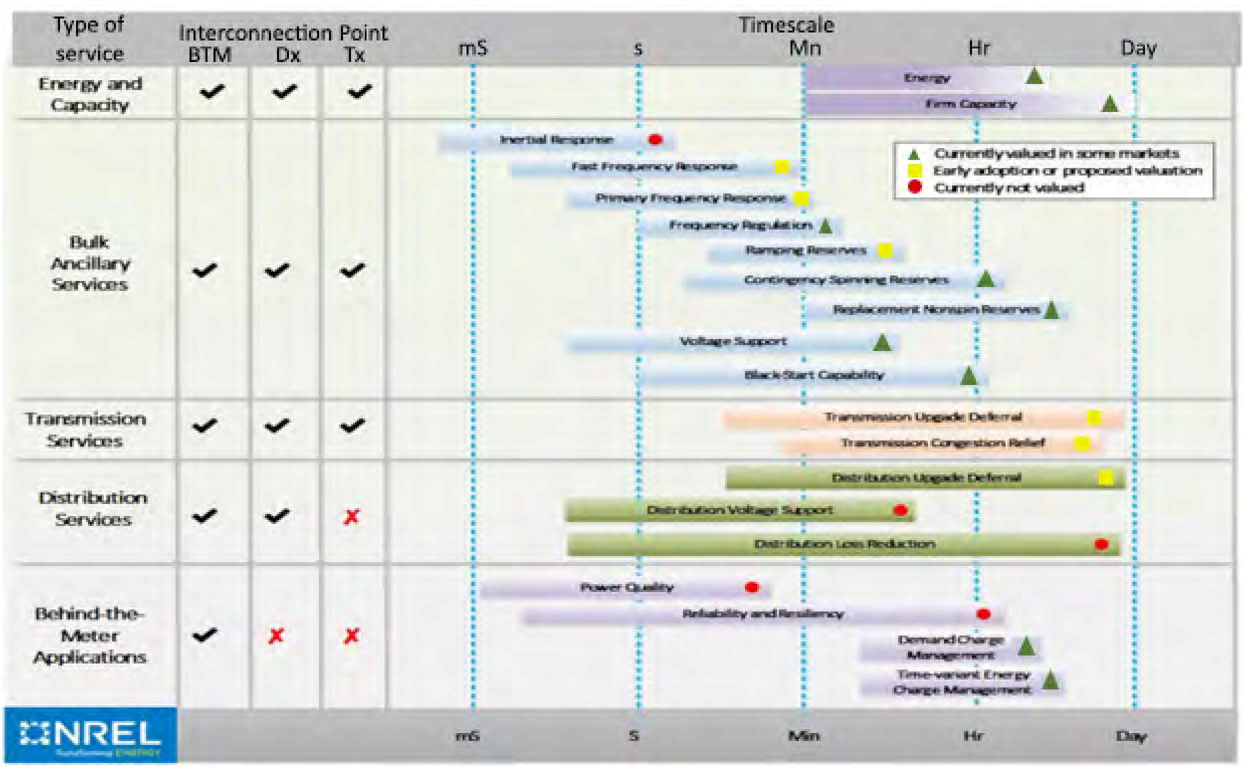


Figure 3: Timescale of Services Provided by ESS

[3] An Overview of Behind-the-Meter Solar-Plus-Storage Regulatory Design - Approaches and Case Studies to Inform International Applications (nrel.gov)

Category	Service	Value
Bulk energy	Capacity or resource adequacy	The ESS is dispatched during peak demand events to supply energy and shave peak energy demand. The ESS reduces the need for new peaking power plants and other peaking resources.
	Energy arbitrage	Trading in the wholesale energy markets by buying energy during off-peak low-price periods and selling it during peak high-price periods.
Ancillary services	Regulation	An ESS operator responds to an area control error (ACE) in order to provide a corrective response to all or a segment portion of a control area.
	Load following	Regulation of the power output of an ESS within a prescribed area in response to changes in system frequency, tie line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or established interchange with other areas within predetermined limits.
	Spin/non-spin reserve	Spinning reserve represents capacity that is online and capable of synchronizing to the grid within 10 minutes. Non-spin reserve is offline generation capable of being brought onto the grid and synchronized to it within 30 minutes.
	Frequency response	The energy storage system provided energy in order to maintain frequency stability when it deviates outside the set limit, thereby keeping generation and load balanced within the system.
	Flexible ramping	Ramping capability provided in real time, financially binding in five-minute intervals in California ISO (CAISO), to meet the forecasted net load to cover upwards and downwards forecast error uncertainty.
	Voltage support	Voltage support consists of providing reactive power onto the grid in order to maintain a desired voltage level.
	Black start service	Black start service is the ability of a generating unit to start without an outside electrical supply. Black start service is necessary to help ensure the reliable restoration of the grid following a blackout.
Transmission services	Transmission congestion relief	Use of an ESS to store energy when the transmission system is uncongested and provide relief during hours of high congestion.
	Transmission upgrade deferral	Use of an ESS to reduce loading on a specific portion of the transmission system, thus delaying the need to upgrade the transmission system to accommodate load growth or regulate voltage.
Distribution services	Distribution upgrade deferral	Use of an ESS to reduce loading on a specific portion of the distribution system, thus delaying the need to upgrade the distribution system to accommodate load growth or regulate voltage.
	Volt-VAR control	Volt–ampere reactive (VAR) is a unit used to measure reactive power in an alternating current (AC) electric power transmission and distribution system. VAR control manages the reactive power, usually attempting to get a power factor near unity.
	Conservation voltage reduction	Use of an ESS to reduce energy consumption by reducing feeder voltage.
Customer services	Power reliability	Power reliability refers to the use of an ESS to reduce or eliminate power outages to customers.
	Time of use (TOU) charge reduction	Reducing customer charges for electric energy when the price is specific to the time (season, day of week, time-of-day) when the energy is purchased.
	Demand charge reduction	Use of an ESS to reduce the maximum power draw by electric load in order to avoid peak demand charges.

Source: Modified from Akhil *et al.* 2015.

Figure 4: Description of Services Offered by ESS[4]

Not all these services are valued in a straightforward way, and existing modeling tools can often underestimate the true potential value of ESS. No models are currently capable of evaluating the full range of values described above and performing a co-optimization routine to estimate the maximum value provided by each service. In some cases, these values may not be captured through a market or ratemaking process. These system models rarely capture benefits at the sub-hourly level, do not address location-specific benefits, and often fail to characterize distribution- and customer-level benefits.[4]

The literature cited in the above section examines different storage valuation tools and their applicability to different ESS use cases. This report builds on this work with the overall objective to design a streamlined model selection process in which an end-user can find the most appropriate tool efficiently based on their use case(s) and preferences. In addition, the three example use cases designed in this report provides potential end-users with tangible applications to better understand how these tools work.

4 Assigning value to energy storage systems at multiple points in an electrical grid (rsc.org)

For a small-scale ESS, price-taker models are appropriate because the storage is too small to impact market prices or system dispatch. The price-taker option, however, may not be appropriate for an ESS that is large enough to affect the operation of the other resources in a system and market prices. In these cases, system-level analysis using production cost models is often required for valuation analysis. In addition to commercial tools such as Aurora, PLEXOS, and GridView, there are several cost-free DOE production cost models such as PRESCIENT and Resource Planning Model (RPM). While these tools do not directly generate ESS valuation results, the outputs – such as operation cost, prices, and dispatch results – could be used to estimate ESS economic benefits. This report focuses on the DOE price-taker valuation tools, including:

- QuEST
- REopt™
- DER-CAM
- System Advisor Model (SAM)
- Energy Storage Evaluation Tool (ESET™)

The tools examined in this report are not meant to serve as a comprehensive list of options that stakeholders must choose from, but rather as a collection of publicly available methods that uniquely approach valuing energy storage. In addition, this report provides insights and guidance on the methods used in each of these tools, as well as links to other technical resources for more accurate estimations. Future work on the MSP will include consideration and evaluation of other energy storage valuation tools.

Overview of DOE Modeling Tools

QuESt

QuESt is a free, open-source, Python-based application suite for energy storage simulation and analysis developed at Sandia National Laboratories. QuESt currently consists of three distinct yet interconnected applications: QuESt Data Manager, QuESt Valuation, and QuESt BTM, which individually and collectively help project engineers and researchers evaluate ESSs for different use cases. Future releases will include applications for front-of-meter (FOM) analyses, microgrid operation and control, and energy storage project planning.

Access to QuESt

The source code of QuESt can be accessed at https://github.com/snl-quest/snl-quest. QuESt can also be installed from executables and run in both Windows and Mac OS systems. All projects will be saved and executed on a local computer. Internet connectivity is also required for QuESt Data Manager to download and manage market operation data for evaluation.

Eligible Technology Types

BESS (Li-ion battery, advanced lead-acid battery, vanadium redox flow battery, etc.), flywheel, and PV. The same model is used for different types of BESS and flywheel characterized by different parameters.

Key Input Parameters

- Energy and regulation prices from different ISO/RTO markets for grid services
- Hourly end-user load profiles for a typical year for BTM services
- Electricity tariff, demand charge rate, and other relevant price data (for BTM service)
- The site's PV generation profile for BTM services
- Energy storage physical characteristics, such as power and energy capacity, RTE, self-discharge efficiency

Key Output Results

- Optimal annual revenue by month or by grid service
- Optimal ESS dispatch
- Energy and demand charge reduction for BTM ESS

Functionality/Objective Type(s)

QuESt models optimally dispatch a BESS or flywheel to maximize the revenue from energy arbitrage and frequency regulation or minimize the electricity bill for BTM applications.

Modeling and Evaluation Methods

When evaluating ESS for grid services, the Valuation module maximizes the annual revenue from energy arbitrage and frequency regulation. It captures different market rules and revenue calculation methods used in different ISOs and RTOs for frequency regulation. When evaluation ESS for BTM services, the BTM module minimizes an end-user's electricity bill, which includes energy and demand charges. QuESt formulates different linear programming (LP) problems accordingly.

Renewable Energy Integration and Optimization (REoptTM)

The REopt™ techno-economic decision support platform is used by researchers at the National Renewable Energy Laboratory (NREL) to optimize energy systems for buildings, campuses, communities, microgrids, and more. It recommends the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, and energy performance goals. REoptTM capabilities are available through a free REopt Lite™ web tool evaluation or a custom REoptTM analysis. The REopt LiteTM web tool evaluates the economic viability of grid-connected solar PV, wind, combined heat and power (CHP), and storage at commercial and small industrial sites. It allows building owners to identify the system sizes and dispatch strategies that minimize the site's life cycle cost of energy. It also estimates the amount of time onsite generation and storage can sustain the site's critical load during a grid outage and allows the user to optimize energy resilience. REopt LiteTM enables users to screen the technical and economic potential of distributed energy technologies on their own or in combination with each other. The user can select default performance parameters or enter user-specified performance parameters that are consistent with the model architecture and assumptions.

Access to REopt Lite™

REopt Lite™ is a free, publicly available web version of the more comprehensive REopt™ model. The full REopt™ model is not available outside NREL. REopt Lite™ is available in three formats:

- Web interface: reopt.nrel.gov/tool. The web interface allows users to easily input data, run analysis, and view results for a single site in a graphical user interface.
- API: https://developer.nrel.gov/docs/energy-optimization/reopt-v1/. The API allows users and software developers to programmatically interface with the REopt Lite™ web tool. The API can be used to evaluate multiple sites and perform sensitivity analyses efficiently, and to integrate REopt Lite™ capabilities into other tools.
- Open source: https://github.com/NREL/REopt_Lite_API. The open-source code allows software developers to modify the REopt Lite™ code or host it on their own servers. It is licensed under BSD-3, a permissive license that allows for modification and distribution for private and commercial use.

Eligible Technology Types

PV, wind, CHP, electric and thermal energy storage, absorption chillers, and existing heating and cooling plants

Key Input Parameters

- Typical and critical load profiles, electricity tariff
- Financial parameters, including analysis period, discount rate, and escalation rate
- Grid emission factors
- Outage starting time and duration
- Capital, O&M, and fuel costs of various available technologies

Key Output Results

- Optimal selection and capacity of DER to be installed
- When and how the available DER should be dispatched (both to maximize economic performance and to meet resiliency and reliability targets)
- Detailed benefit and cost breakdown

Functionality/Objective Type(s)

REopt Lite™ evaluates the economic viability of distributed PV, wind, BESS, CHP, and thermal energy storage. It also enables users to identify system sizes and dispatch strategies to minimize energy costs and estimate how long a system can sustain critical load during a grid outage.

Modeling and Evaluation Methods

Formulated as a mixed-integer linear program (MILP), REopt Lite™ solves a deterministic optimization problem to determine the optimal selection, sizing, and dispatch strategy of technologies chosen from a candidate pool such that loads are met at every time step at the minimum life cycle cost. To identify the least-cost set of resources that can provide a site's energy services, the model weighs the avoided utility costs (grid-purchased electricity and purchased fuels) against the cost to procure, operate, and maintain additional on-site DER. The load, utility costs, and renewable resources are modeled for every hour of 1 year. It solves a single-year optimization to determine N-year cash flows, assuming constant production and consumption over all N years of the desired analysis period. All costs and benefits are discounted with the user-specified discount rate to present value using standard economic functions. By adjusting some inputs, the user can specify a system type and size rather than having REopt Lite™ solve for this.

Distributed Energy Resources Customer Adoption Model (DER-CAM)

DER-CAM is a powerful and comprehensive decision support tool developed at Lawrence Berkeley National Laboratory (LBNL) to find optimal DER investments in the context of either buildings or multi-energy microgrids. DER-CAM can be used to determine optimal portfolio, sizing, placement, and dispatch of a wide range of DER, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets.

Access to DER-CAM

DER-CAM is publicly available and free to use. Currently, DER-CAM can be installed and run in Windows. All projects are saved on a local PC and sent to LBNL servers for execution. Internet connectivity is required. DER-CAM Remote Desktop Interface is also available upon request, but is primarily for testing, evaluation, and educational purposes. All DER-CAM projects created are visible to all users.

Eligible Technology Types

Conventional generators, CHP units, wind generators, PV, solar thermal, batteries, electric vehicles, thermal storage, heat pumps, central cooling, and heating systems

Key Input Parameters

- The site’s hourly end-use load profiles for a typical year (electric, cooling, refrigeration, space heating, hot water, and natural gas loads)
- The site’s default electricity tariff, natural gas prices, and other relevant price data
- Capital, O&M, and fuel costs of various available technologies, together with the interest rate on customer investment
- Basic physical characteristics of alternative generating, heat recovery, and cooling technologies, including the thermal-electric ratio that determines how much residual heat is available as a function of generator electric output
- Information on the site’s topology and distributed heating infrastructure (only for multi-node models)

Key Output Results

- Optimal selection and capacity of DER to be installed
- Optimal placement of DER inside the microgrid (for multi-node models)
- When and how the available DER should be dispatched (both to maximize economic performance and to meet resiliency and reliability targets)
- Detailed cost breakdown of supplying end-use loads
- Detailed breakdown of carbon emissions associated with supplying end-use loads

Functionality/Objective Type(s)

DER-CAM can be used to determine optimal portfolio, sizing, placement, and dispatch of a wide range of DER, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets.

Modeling and Evaluation Methods

While the objective function of DER-CAM can be easily modified or even replaced by a multi-objective analysis, it is most commonly defined as a site's total annual cost of energy supply. Additionally, all value streams associated with the optimal DER dispatch determined by DER-CAM are considered in the objective function, in the form of both avoided costs and market participation. DER-CAM uses advanced mathematical modeling techniques to formulate the optimal multi-energy microgrid design problem as a MILP. Unlike simulation-based models or optimization models based on heuristic and non-linear formulations, DER-CAM can quickly find globally optimal solutions to this highly complex problem. The key challenge lies in developing and implementing linear formulations that adequately represent different non-linear phenomena, and DER-CAM achieves this using a wide range of techniques. Examples of advanced modeling solutions implemented in DER-CAM include linearized AC and DC optimal power flow algorithms, or multiple piece-wise approximations of non-linear efficiency curves.

System Advisor Model (SAM)

SAM is a techno-economic computer model that calculates performance and financial metrics of renewable energy projects. A renewable energy project is represented by a performance model and a financial model. The performance models are for PV systems with optional battery storage, concentrating solar power, solar water heating, wind, geothermal, and biomass power systems, and include a basic generic model for comparisons with conventional or other types of systems. The financial models are for projects that either buy and sell electricity at retail rates (residential and commercial) or sell electricity at a price determined in a PPA.

Access to SAM

SAM is publicly available and free to use. It can be installed and run on Windows, Mac, and Linux. All projects are saved on a local PC. When exploiting REopt™ for remote optimal sizing or dispatch, some data are sent to NREL servers. Internet connectivity is required for registration verification and remote optimization. All SAM projects created are visible to all users on the local system.

Eligible Technology Types

Only electrochemical ESSs are included in SAM's performance models. Supported battery types are lead-acid, Li-ion, vanadium redox flow, and all iron flow. Other types of batteries can be modeled by selecting "Lead Acid: Custom" or "Lithium Ion: Custom" and specifying the voltage, current, and capacity properties appropriate for the battery. SAM provides detailed component-level modeling of individual battery cells and power converters. Battery degradation, voltage variation, thermal properties, and other losses are also modeled.

Key Input Parameters

- Battery technical parameters: system- or cell-level power and energy capacity, power converter efficiencies, lifetime and degradation profile, voltage curve, thermal properties
- Electricity tariff: PPA or retail prices
- Automated or manual battery dispatch options
- Parameters related to other resources in the system: solar, wind, marine energy, biomass, geothermal, or fuel cell
- Weather data
- Financial parameters: capital costs, O&M costs, financing cost, tax, insurance, incentives, depreciation, etc.

Key Output Results

- Optimal size and dispatch schedule of the battery to be installed
- Annual performance metrics: revenue, cost, cash flow, usage, capacity factor, PV performance ratio
- Financial metrics: debt, equity, electricity bill savings, internal rate of return, net present value, levelized energy cost, etc.

Functionality/Objective Type(s)

SAM can model both FOM and BTM deployment of batteries. For FOM, PPA projects for power generation sell electricity through a PPA at a fixed price with optional annual escalation and time-of-delivery factors. Besides energy arbitrage, capacity and curtailment payments are also modeled for PPA projects. For BTM, residential and commercial projects generate electricity to reduce a building or facility’s consumption of electricity from the grid. SAM can model simple flat rates, monthly net metering, or complex rate structures with tiered time-of-use (TOU) pricing and demand charges.

Modeling and Evaluation Methods

There are four battery dispatch options: peak shaving, grid power target, battery power target, and manual. The peak shaving dispatch attempts to operate the battery to reduce peak demand over a forecast period, considering the load and solar resource over the period. Grid/battery power targets dispatch attempts to operate the battery in response to grid/battery power targets specified by the user. For the manual dispatch option, a user specifies the timing of battery charges and discharges using up to six dispatch periods and a set of weekday and weekend hour-of-day profiles by month. The manual dispatch controller assumes that the system meets the electric load before charging the battery.

Energy Storage Evaluation Tool (ESETTM)

ESET™ is a suite of modules and applications developed at PNNL to enable utilities, regulators, vendors, and researchers to model, optimize, and evaluate various ESSs. The tool examines a broad range of use cases and grid and end-user services to maximize the benefits of energy storage from stacked value streams. ESET™ models various ESSs with different levels of complexity and fidelity. ESET™ is based on a modular structure and is implemented in an encapsulated environment. It is designed to be easy to use without requiring knowledge of the modeling and optimization behind the tool.

ESET™ currently contains five modules to evaluate different types of ESSs, including BESSs, pumped-storage hydropower, hydrogen energy storage (HES) systems, storage-enabled microgrids, and virtual batteries from building mass and thermostatically controlled loads. Distributed generators and PV are also available in some applications.

- **Battery Energy Storage Evaluation Tool (BSET)**: BSET is a modeling and analysis tool enabling users to evaluate and size a BESS for grid applications. It models the technical characteristics and physical capability of a BESS. It also incorporates operational uncertainty into system valuation. Finally, it optimizes battery system operation to maximize stacked value streams from various grid and end-user services, considering trade-offs among these services.
- **Microgrid Asset Sizing considering Cost and Resilience (MASCORE)**: MASCORE is a modeling and analysis tool designed for optimal sizing of DERs in the context of microgrids, considering both economic benefits and resilience performance. It is based on a chance-constrained, two-stage stochastic approach to jointly determine optimal sizes of various DERs, including renewables, energy storage, microturbines, and diesel generators. MASCORE explicitly models the interaction between DER sizing at the planning stage and hourly or sub-hourly microgrid dispatch at the operating stage in both grid-connected and island modes, considering stochastic grid disturbances, load, and renewable generation.
- **Hydrogen Energy Storage Evaluation Tool (HESET)**: HESET is a valuation tool designed for HES systems toward multiple pathways and grid applications. It models economic and technical characteristics of individual components, multiple pathways of hydrogen flow, and a variety of grid and end-user services. It optimizes the operation of a HES system to maximize the economic benefits considering the coupling and trade-off among various pathways and grid services and performs the cost-benefit analyses.
- **Pumped-Storage Hydropower Evaluation Tool (PSHET)**: PSHET is an evaluation tool designed for PSH systems. It supports both fixed- and variable-speed PSH with different configurations, including separate and reversible pump/turbine and ternary sets. It models and optimizes PSH at the unit level in different operating modes to maximize economic benefits from a variety of grid and end-user services.
- **Virtual Battery Assessment Tool (VBAT)**: VBAT is an assessment tool designed to enable users to quantify the technical and economic potential of regional flexibility from different types of building loads in the U.S. The aggregate flexibility is characterized using a virtual battery that resembles simplified battery dynamics parameterized by charging/discharging power limits,

energy limits, and self-discharging rate. It captures the inherent ability of buildings to store heat in thermal mass, vary their power consumption, and shift the electric energy consumption to an earlier or later time, subject to customer requirements for comfort and convenience.

Access to ESET™

ESET™ is designed to be easy to use without requiring knowledge of the modeling and optimization behind the tool. A subset of features and capabilities of ESET™ are made publicly accessible as a web-based tool that can be used across a variety of platforms and devices. The web-based ESET™ can be accessed at https://eset.pnnl.gov/. It runs from a host server, eliminating the need for download, installation, and updates on local machines. The web interface allows users to create accounts, easily input data, run analysis, view results, and save analysis under their accounts. A more comprehensive and powerful version of ESET™ with additional functionalities and features is currently available for licensing.

Eligible Technology Types

BESS, PSH, HES (electrolyzer, fuel cell, compressor, methanation reactor, hydrogen storage, etc.), flexible building load as a virtual battery, PV, conventional distributed generators

Key Input Parameters

- Financial parameters, including analysis period, discount rate, and escalation rate
- Prices and cost information for various grid services, such as energy, frequency regulation, spinning reserve, capacity value, transmission and distribution (T&D) upgrade deferral cost, DR incentive rates, and fuel costs
- Typical and critical load profiles and electricity tariff
- Survivability requirement and outage duration for resilience assessment
- Techno-economic characteristics of various available technologies, such as power and energy capacity (or range of power and energy capacity), operating range, efficiencies, and capital and O&M costs

Key Output Results

- Optimal sizing of various ESSs and other available technologies in BSET and MASCORE to maximize the net benefit from various value streams
- Optimal dispatch of ESS and other assets at either system or component level considering the trade-offs among various value streams
- Detailed benefit and cost breakdown and resilience level

Functionality/Objective Type(s)

ESET™ allows users to model, optimize, evaluate, and size various ESSs to maximize the benefits from stacked value streams, considering a broad range of grid and end-user services. The HESET module also models multiple energy delivery pathways of hydrogen in addition to grid services.

Modeling and Evaluation Methods

ESET™ consists of five applications for evaluating and sizing different types of ESSs. In general, appropriate modeling methods are developed to represent unique techno-economic characteristics of different energy storage technologies and capture rules and requirements for different grid and end-user services as well as competition among them for limited power and energy capacity. The exact modeling and optimization methods may vary by application and function (evaluation or sizing). Compared with the evaluation for a given size system, optimal sizing is generally more complicated, typically with additional assumptions made to simplify the problem. LP and MILP methods are used for most of the optimal dispatch and sizing problems. For problems that involve nonlinear models or stochastic optimization, advanced optimization techniques are used to generate their deterministic linearized equivalent or relaxed problems. Model predictive control is also often used to mimic the operational scheduling process and thereby improve assessment results. Forecast models are also integrated to capture operational uncertainty in valuation analysis. Other optimization methods such as bilevel optimization and dynamic programming are also used to tackle complicated evaluation and sizing problems.

Example Use Cases

This section provides three example use cases to illustrate how DOE tools can be used for storage valuations for three use-case families described earlier in this report: 1) facilitating an evolving grid; 2) critical services; and 3) facility flexibility, efficiency, and value enhancement. These examples are not intended to consider all the necessary parameters that end-users must analyze to define technically achievable benefits. The intent is to provide potential beneficiaries with an overview of the types of parameters that may go into these models and show how they are evaluated in DOE tools.

Energy Storage for the Grid

Introduction

While energy storage has attributes that provide tremendous flexibility to power systems, it is challenging to optimally use an ESS and fully capture its potential benefits from multiple grid applications. First, gaining value from a wide variety of services requires broad consideration. Services provided by energy storage have different purposes and vary based on the benefitting parties. Varying rules and requirements tied to each service must be fully considered to earn the given value. In addition, the economic benefits of an ESS highly depend on its operational characteristics and physical capability. The physical limitations of an ESS must be respected and represented in a way that accurately captures their operational characteristics so that they can be fairly evaluated against other system assets. Regulatory limitations may also allow or disallow certain kinds of operations at certain times. Lastly, it can be challenging to schedule and dispatch ESSs as necessary to provide the most value. The complexity of correctly valuing ESSs comes not only from the devices themselves but also from the complexity introduced when multiple, potentially competing applications of gaining value from a given operational opportunity are evaluated. Charging control could be very complicated due to the competition among various services for limited power and energy capacity, not only on a time step but also intertemporally.

Typical grid services that can be provided by an ESS are described as follows.

1) **Energy arbitrage:** Energy arbitrage or energy shifting refers to the operation of an ESS that generates electricity when the demand and/or electricity prices are high and consumes electricity when the demand and/or prices are low. Energy arbitrage can be performed in an electricity market to pursue revenue from energy trading or in a vertically integrated utility to reduce production cost. The economic reward is the price or cost differential between charging and discharging electrical energy, considering losses during charging/discharging operations.

2) **Frequency regulation:** The electric power system must maintain a near-real-time balance between generation and load. Balancing generation and load instantaneously and continuously is difficult because loads and generation are constantly fluctuating. Frequency regulation is required to continuously balance generation and load within a control area and thereby main system frequency and manage differences between actual and scheduled power flows between

control areas. Frequency regulation is the most valuable ancillary service. To provide regulation services, an ESS needs to respond rapidly to system operator requests for up and down movements by following automatic generation control signals. The economic benefits can be defined based on regulation prices in electricity markets or reduced costs of operating generators in vertically integrated utilities. Most markets have implemented pay-for-performance to calculate rewarding credit based on regulation capacity, regulation mileage, and performance factor/score. The exact calculation formula may vary from one ISO to another, but the main idea is the same.

3) **Spinning/Non-spinning reserve:** Contingency or operating reserves are called to restore the generation and load balance in the event of a contingency such as a sudden, unexpected loss of a generator. Any resource that can respond quickly and long enough can supply contingency reserves. An ESS can be used to provide both spinning and non-spinning reserves. Spinning reserve is provided by power sources already online and synchronized to the grid that can increase the output immediately in response to a major generator or transmission outage, and can reach full output quickly (e.g., 10 minutes). Considering the typical prices and required energy reserve, using an ESS to provide spinning reserve is generally more valuable than using it to provide non-spinning reserve. Unlike frequency regulation that is exercised from hour to hour, spinning reserve is not called upon unless a contingency occurs.

4) **Capacity and resource adequacy:** An important issue in power system planning is to ensure sufficient resources to meet future demand, either through capacity markets or integrated resource planning. Capacity is not actual electricity, but rather the ability to produce electricity in future years. ESSs can be used to provide peaking capacity since they are flexible and can be quickly dispatched with a high ramp rate to meet peak demands. The corresponding economic benefits are capacity payments for market participants or capacity charge reduction in a market environment or through bilateral contracts, or saving from replacing or reducing the need for new peaking resources in vertically integrated utilities.

5) **T&D upgrade deferral:** An ESS can play an important role by reducing the peak load on a specific portion of the T&D system, and thereby help defer or postpone specific projects and T&D system upgrades that otherwise would be needed earlier to meet the growing demands. Depending on the circumstances, the benefits can be quite significant, especially if the upgrade that is deferred is expensive. In most situations, an ESS for this application is only used for a small portion of the year when the load exceeds the T&D equipment's capacity. To receive the value from deferring a local T&D system investment/upgrade, an ESS must exceed a certain power output level during peak hours. The same ESS can be used for numerous other applications in the remaining time. The economic benefits can be estimated based on the T&D upgrade cost and the number of years an upgrade can be deferred.

Specification and Inputs

An energy storage assessment on Nantucket Island is used to demonstrate how to use the BSET app on the ESET™ platform developed at PNNL for a BESS valuation analysis. Nantucket Island, located off the coast of Massachusetts, has a fairly small resident population of approximately 11,000, which usually swells to 50,000 during summer. To meet the rise in energy demand in summer, and to improve reliability, National Grid will be deploying a 6 MW/48 MWh Li-ion ESS and replacing an on-island CTG with a new CTG capacity varying between 10 and 16 MW. Currently, Nantucket's electricity is supplied by two submarine supply cables (shown in Figure 5) with a combined capacity of 71 MW and two small CTGs. If one supply cable fails (N-1 contingency), the island would face energy shortage and outage threats during peak summer months. Since building a third submarine cable would cost between $105 and $205 million, deploying an ESS and a new CTG would lead to significant transmission deferral benefits. Other value streams are also considered, including energy arbitrage, frequency regulation, and spinning reserve. BSET can be used to determine optimal dispatch and define technically achievable benefits from the stacked value streams considering the trade-offs among various applications.

Figure 5: The Two Submarine Supply Cables Connected with Nantucket Island

This example employs the most popular constant-efficiency model with static operating range for a BESS, in which a scalar linear system is used to resemble simplified dynamics of energy state parameterized by the rated power and energy capacity, charging/discharging efficiencies, lower and upper bounds of SOC. Other ESS specifications include lifetime, installed cost, and O&M cost. Inputs of grid services include energy price, regulation capacity and service prices, spinning and non-spinning reserve prices, capacity value, and T&D upgrade options and associated cost, among others. For cost-benefits analysis, various financial analysis parameters are needed, such as economic analysis life, discount rate, inflation rate, insurance rate, property tax rate, and federal and state income tax rate.

Analysis of the Use Case in ESET™

A step-by-step demonstration is provided as follows to carry out an economic assessment for the Nantucket ESS using BSET. First, we create a BSET project as shown in Figure 6.

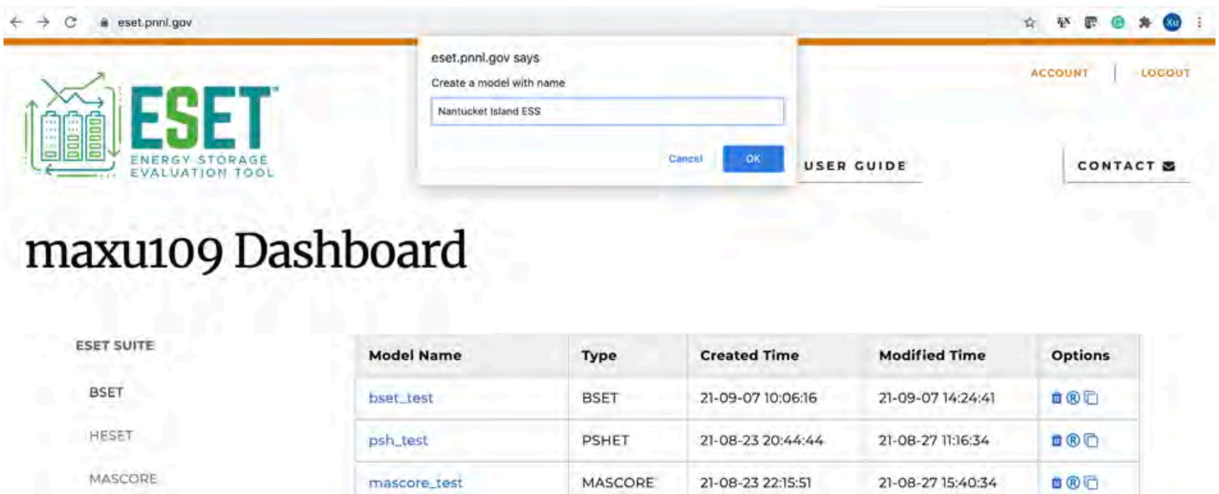


Figure 6: Create a BSET Evaluation Model for Nantucket Island

Default parameters and inputs are provided for a new project. These parameters and settings can be edited for a customized analysis. Specifically, the Nantucket Island ESS assessment can be modeled with *Grid Services* use case and *Evaluation* functionality. In this example, uncertainties in price forecasts are not considered and the *Price Forecasting* is unchecked. The Nantucket ESS is expected to have an economic life of 20 years with preventative maintenance being conducted throughout to ensure reliability. Therefore, we set the time horizon to 20 years for the financial analysis. Furthermore, a real discount rate of 6.85% is used to calculate the present-value costs and benefits. The simulation settings and financial analysis parameters used for this Nantucket ESS evaluation are shown in Figure 7. To simplify this analysis, other financial parameters (property tax rate, income tax rate, etc.) are not considered here.

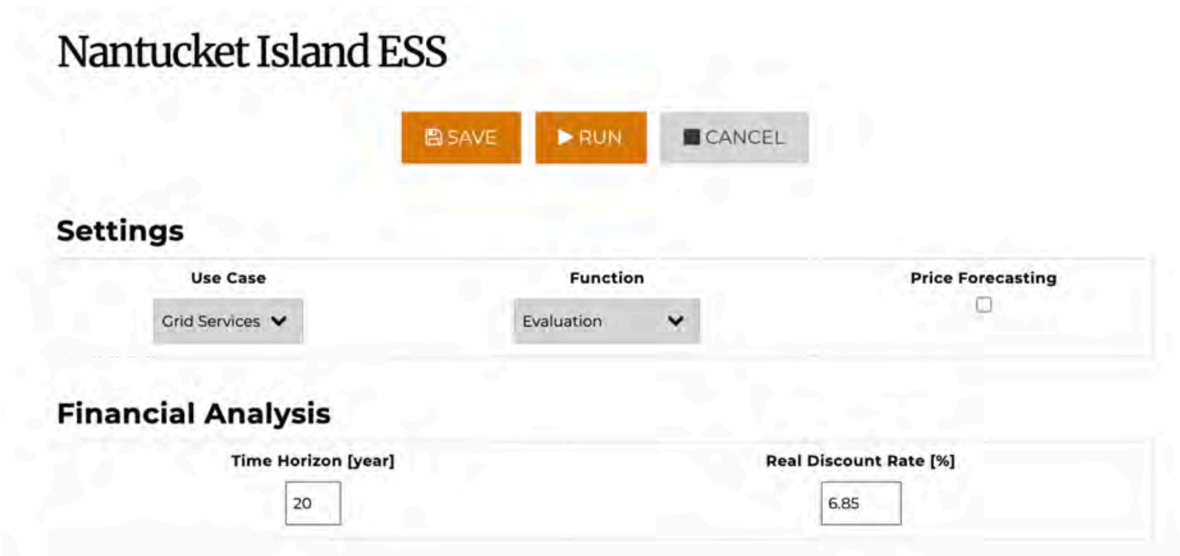


Figure 7: Simulation Settings and Financial Analysis Parameters

The Nantucket ESS is a 6 MW/48 MWh Li-ion Powerpack 2 System procured from Tesla, Inc. ESS charging and discharging efficiencies are both assumed to be 95%. The economic parameters, including energy and capacity cost and fixed investment cost, are also input below, as shown in Figure 8.

Figure 8: BESS Technical and Economic Parameters

In this example, four grid services are considered: arbitrage, frequency regulation, spinning reserve, and T&D upgrade deferral. The inputs include hourly energy price, regulation price, spinning reserve price, and T&D deferral events and upgrade cost, among others. Energy, regulation, and spinning reserve take hourly prices for a historical or representative year as inputs.

The frequency regulation market at ISO-NE has implemented a pay-for-performance policy to calculate rewarding credit based on regulation capacity, regulation mileage, and performance score. The capacity payment is calculated based on the capacity prices and regulation capacity. The mileage payment is calculated based on the mileage prices, regulation mileage, and performance score. Therefore, our inputs for regulation services include capacity and mileage prices and performance score. Since ISO-NE does not differentiable regulation up and regulation down for the capacity payment, we will not select the *Reg. Up & Down* checkbox in the simulation.

The inputs for upgrade deferral include existing load profile, load growth rate, existing infrastructure capacity, and planned upgrade cost. Based on the existing load profile and load growth rate, the peak demand for future years will be calculated and compared with the existing infrastructure capacity to determine the year when T&D investment needs to be made. Annual peak minimization problems are formulated and solved repeatedly inside BSET to determine the year when the T&D upgrade must be made. Based on the upgrade cost and the years when T&D investment needs to be made with and without the given ESS, present-value costs are calculated and T&D deferral benefits are estimated.

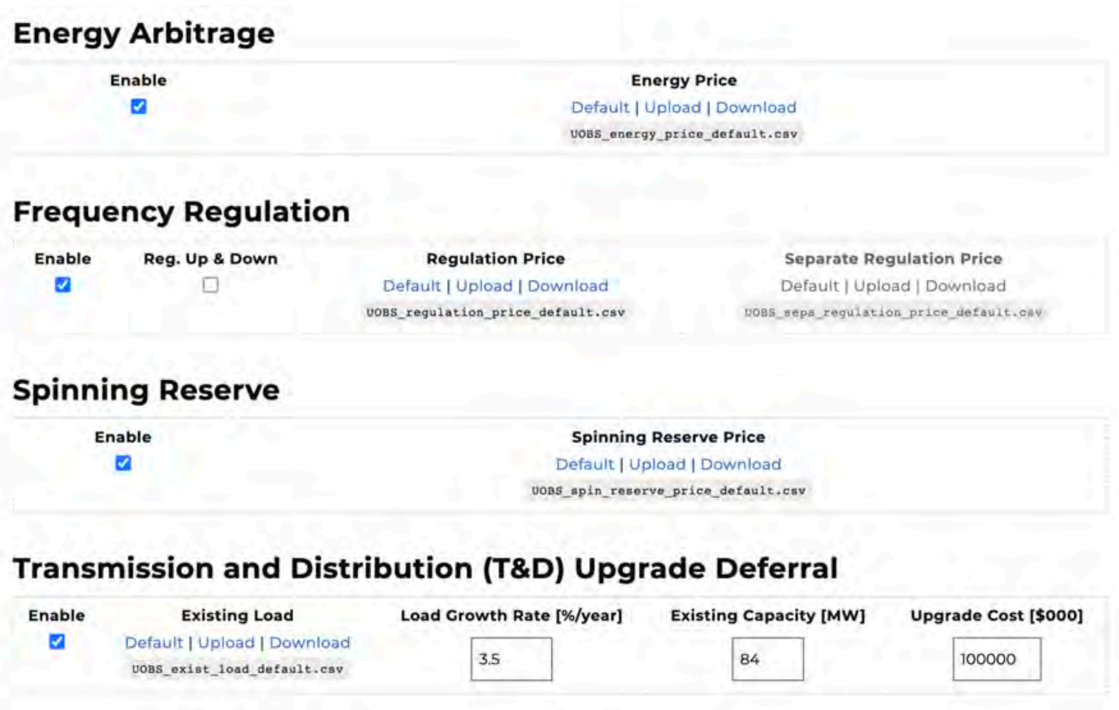


Figure 9: Simulation Input for Multiple Grid Services

Once the setup is completed, one can start the evaluation. BSET optimally schedules the battery operation using a model predictive control approach for grid services. At each hour, a look-ahead optimal dispatch is formulated based on information available at the scheduling stage. The length of the look-ahead window is set to be 24 hours. The optimal dispatch problem is solved to determine the base operating point and how the battery will be used for different services in each hour. The actual battery operation is then simulated with an appropriate time resolution based on additional information available in each operating hour, e.g., regulation signals. The same process repeats through a historical or representative year.

When the simulation is done, BSET reports the optimal dispatch and economic assessment results. The first output displays the present-value costs, benefits, and net benefits. Next, the annual benefits by service are provided. In this example, more than 75% of the benefits are tied to deferring the investment in the third transmission cable for 13 years. Another 11.9% of the benefits come from providing frequency regulation services. Furthermore, BSET plots the detailed ESS optimal operation, as shown in Figure 10.

Figure 10: Present Value Costs and Benefits

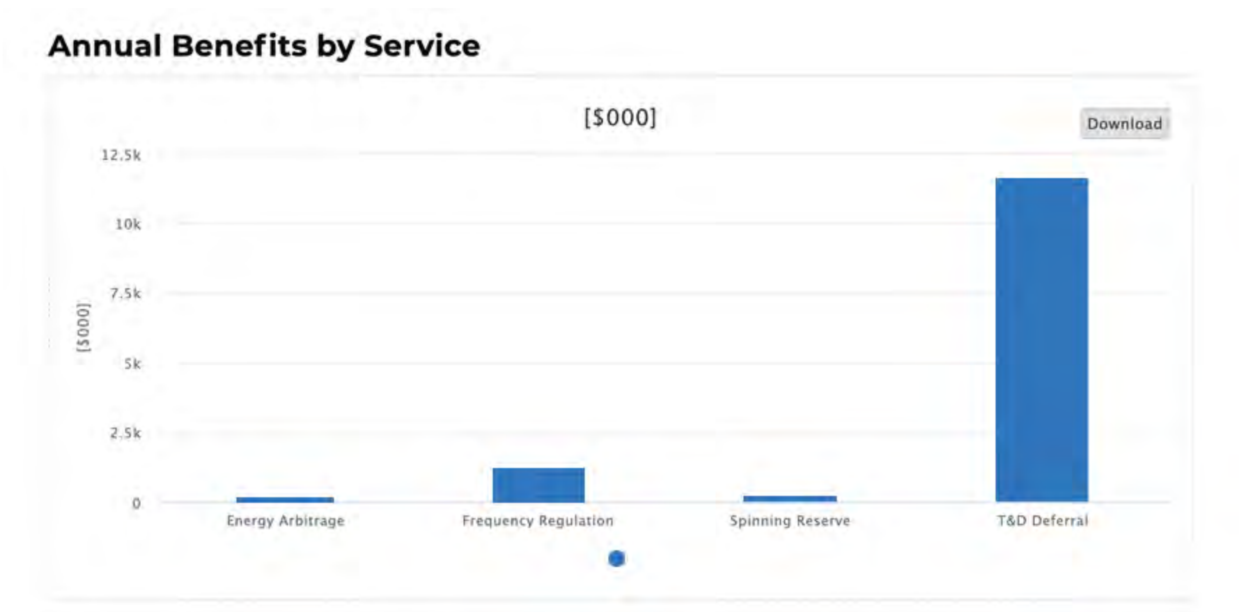


Figure 11: Annual Benefits by Service

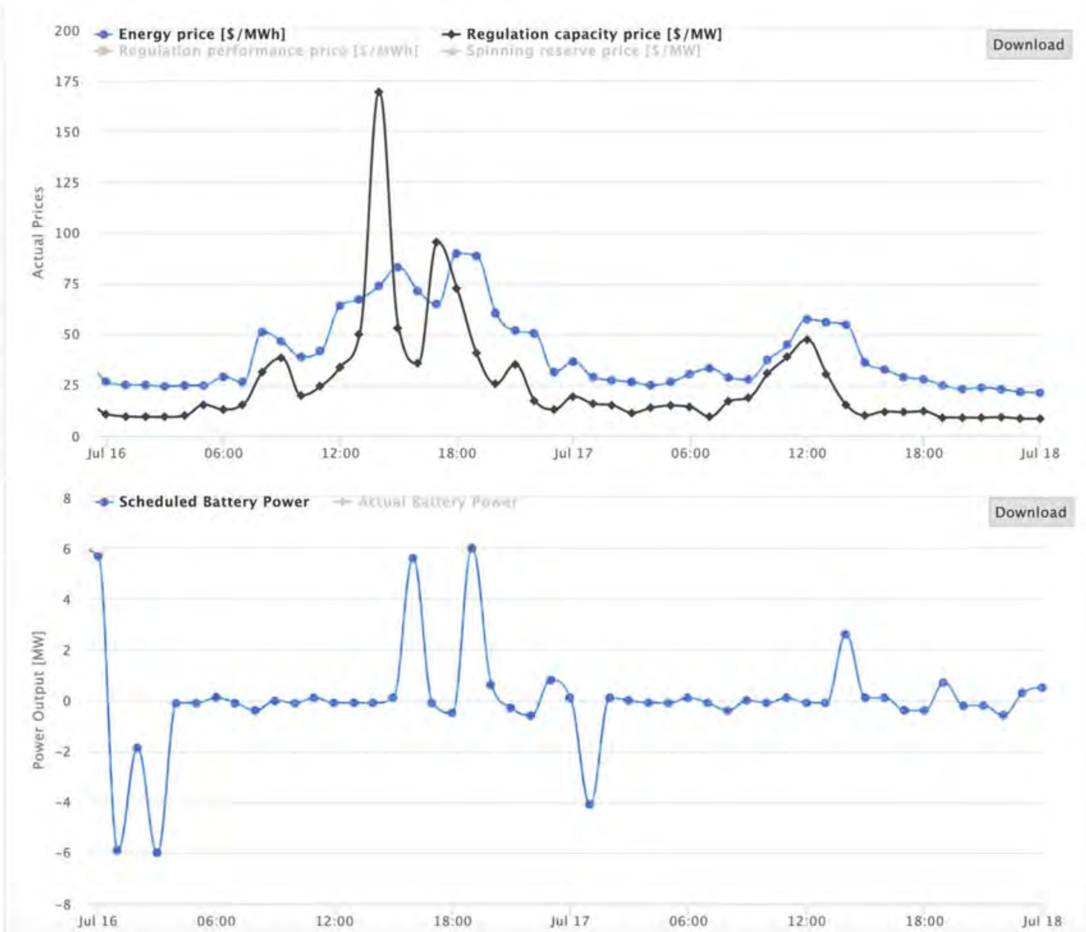


Figure 12: Optimally Scheduled Battery Power Output

Energy Storage for Microgrid Communities

Introduction

Resilience is the ability of a system to prepare for and adapt to changing conditions and to withstand and recover rapidly from deliberate attacks, accidents, or naturally occurring threats or incidents. Resilience has become a high priority for federal, state, and local governments, and is moving into the industrial and commercial sectors. With the development and advancement of renewable generation and energy storage, their deployment in distribution systems has increased considerably in recent years. These emerging DERs not only provide economic benefits, but also strengthen the resilience of distribution systems and reduce power interruptions of critical facilities. Increasing attention is being given to the use of distributed renewable generation and/or energy storage in addition to conventional distributed generators for cost-effective and resilient system operation.

A microgrid can be operated in grid-connected mode under normal conditions and island mode during an outage. In grid-connected mode, the existing and new DERs (except those restricted due to emission regulation) are optimally coordinated to provide end-user and/or grid services to maximize the economic benefits. During an outage, a microgrid is operated in island mode and all DERs are used to support the local load.

Specifications and Inputs

Herein, a community microgrid assessment in Northampton, Massachusetts, is adapted to illustrate how REopt™ can be used to evaluate ESS paired with other DERs for microgrid communities. The system consists of three Northampton facilities: Northampton Department of Public Works (DPW), Cooley Dickenson Hospital (CDH), and Smith Vocational Area High School (SVAHS). SVAHS is a 10-building school campus that serves approximately 600 people a day. The facility also acts as the regional Red Cross Emergency Shelter while providing emergency overflow services for CDH. The Northampton DPW supports several critical city functions, including emergency services radio communication, flood control, stormwater systems, and clean water processing and delivery. The CDH campus includes emergency services facilities, as well as a number of other patient care facilities, and serves approximately 2500 people each day under normal conditions and 1000 during an emergency. All three facilities are shown in Figure 13.

Figure 13: Satellite Google Earth Image of CDH, SVAHS, and Northampton DPW

The existing and planned power components of the Northampton microgrid project are shown in Figure 13. CDH is considering the addition of a 386 kW PV array, as well as a 441 kW/441 kWh BESS. Additionally, SVAHS currently has a 106 kW PV array installed and existing diesel generators at the three sites that include:

- 155 kW at SVAHS
- 40 kW at the DPW
- 2.4 MW at the CDH (three units at 800 kW each)

The on-site diesel storage tank has a capacity of 15,200 gallons.

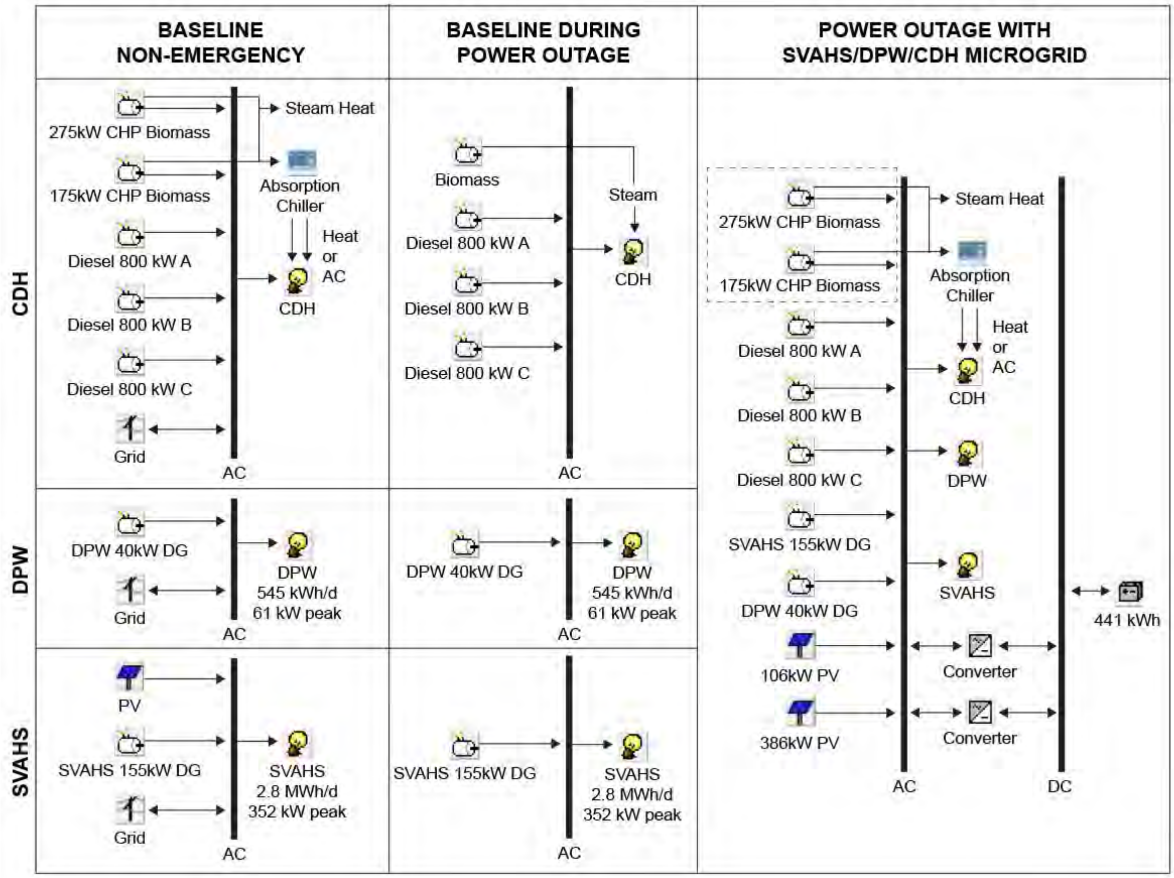


Figure 14: Existing and Planned Power Components of the Northampton Microgrid

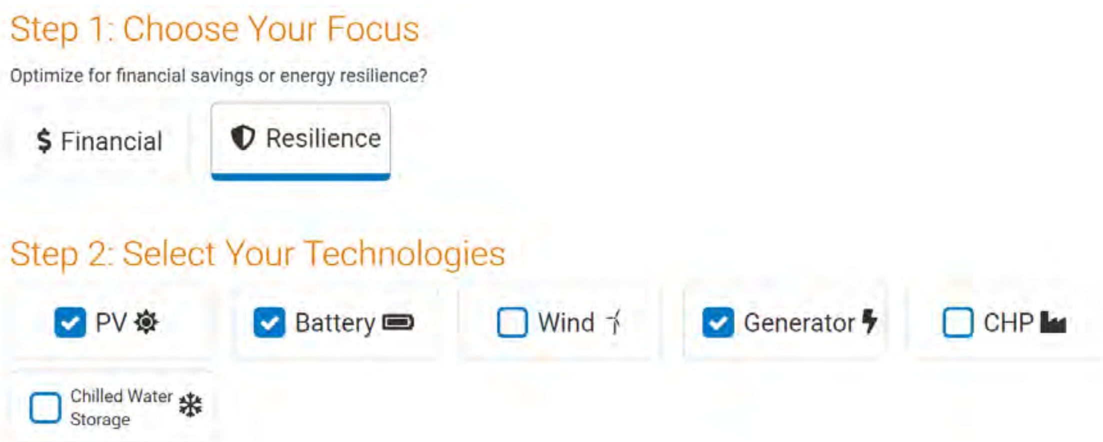
In grid-connected mode, all assets except the diesel engines must be operated. The potential benefits of the investment come from energy and demand charge reduction. The utility rate tariff structure considered for the microgrid is “Massachusetts Electric Co - G-3 Time of Use WCMA Load Zone,” which is available in the OpenEI utility rate database. In island mode during an outage, all assets can be operated to serve the critical load, which is assumed to be 50% of the total load.

The applications considered in this example include the following.

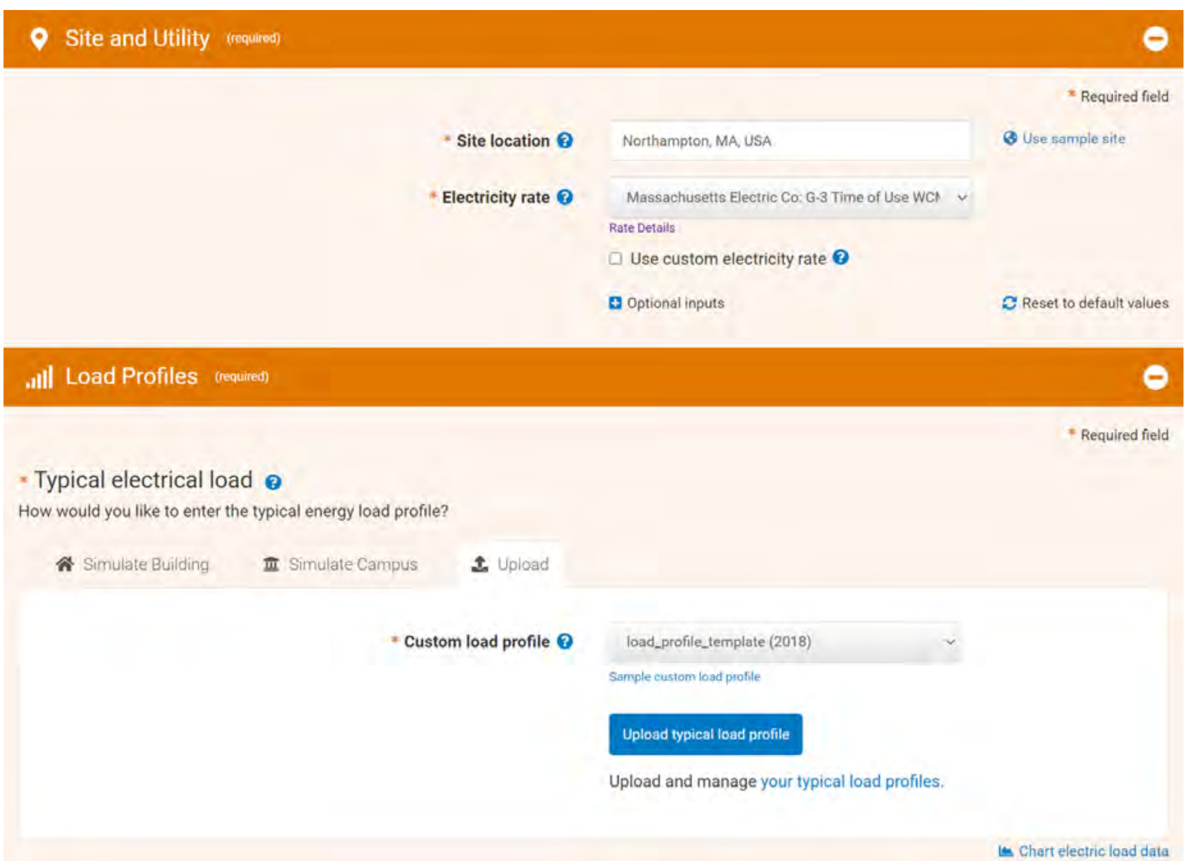
- Energy purchase reduction: The microgrid purchases energy from a distribution utility (National Grid) at TOU rates. The BESS can help reduce the energy charge by 1) shifting energy purchases from hours with high rates to those with low rates and 2) storing excess PV generation to avoid curtailment.
- Demand charge reduction: Every month, the microgrid faces a demand charge of $5.76/kW on its energy bill, which is correlated to the single highest 15-minute load between the hours of 8 a.m. and 9 p.m., Monday through Friday. The BESS can help reduce the demand charge.
- Outage mitigation: In the event of an outage, the ESS can be coordinated with other resources to serve the critical load. This operation would be monetized in terms of the value of lost load.

Analysis of the Use Case in REoptTM

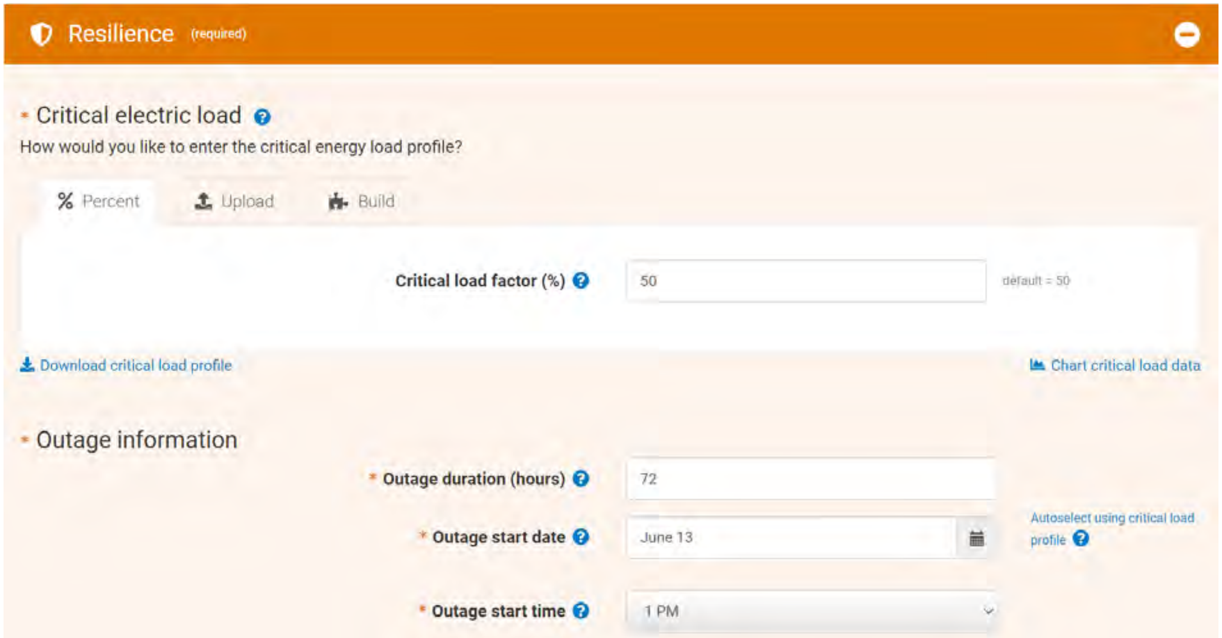
The evaluation of this example using REopt™ is detailed as follows. First, select "resilience" as the analysis type and then select the types of resources to be considered.



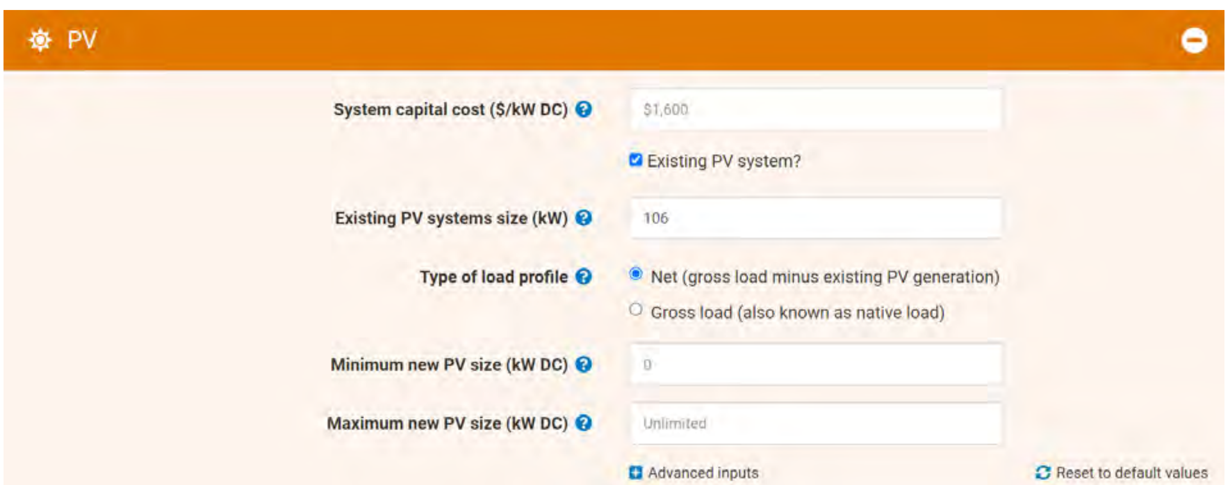
Select utility rate structure from the database and upload load profile



Specify critical load percentage, outage duration, and start time.



Input parameters for the existing and proposed PV arrays, including existing PV size, the range of new PV size, and the per kW capital cost.



The new BESS and the existing DG can be added similarly.

Once all inputs are provided, we can start the evaluation. Results are returned and displayed when the evaluation is completed. The recommended sizes for the new PV array and BESS are 1327 kW and 468 kW/2225 kWh, respectively.

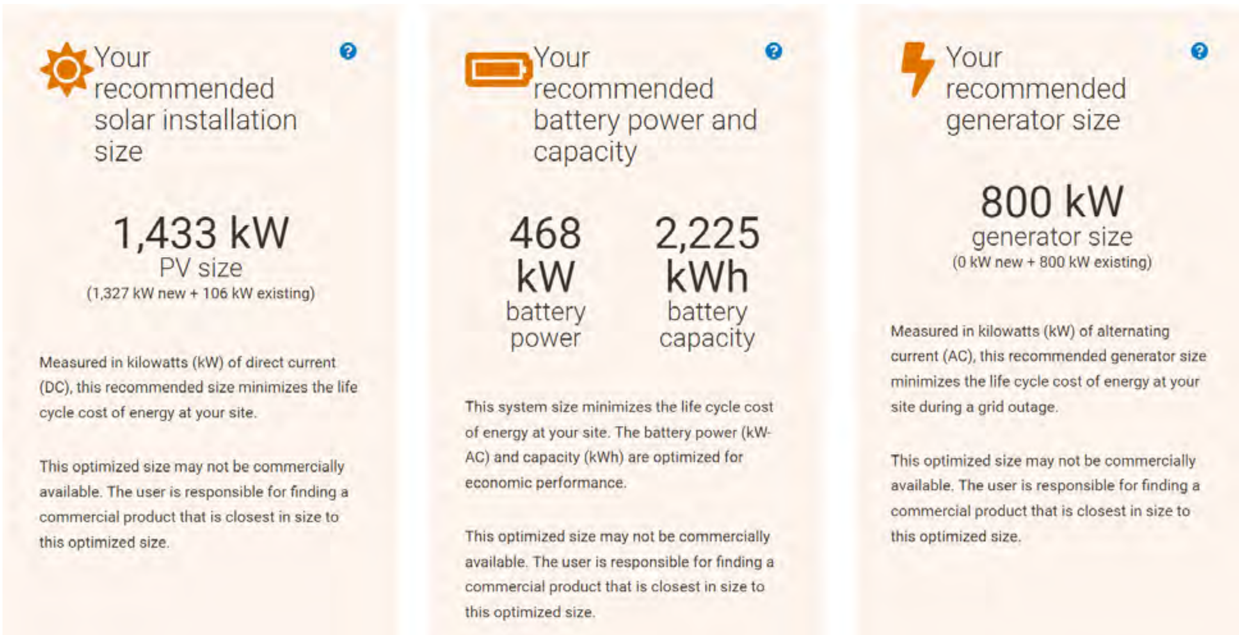


Figure 15: REopt™ Recommendation

The assets are sized to minimize the life cycle cost of the system while ensuring the critical load can be served during the specified outage. The DER operation during the outage is also provided, as shown in Figure 16.

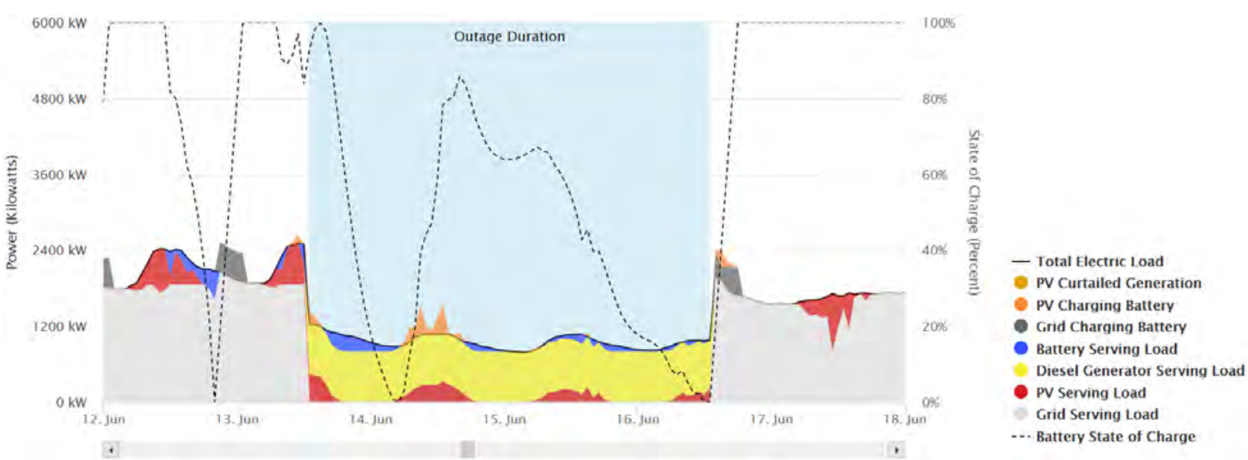


Figure 16: Operation of Assets during the Specified Outage

Net present value is calculated, including benefits from normal operation, microgrid upgrade cost, and avoided outage costs, as shown in the waterfall plot in Figure 17.

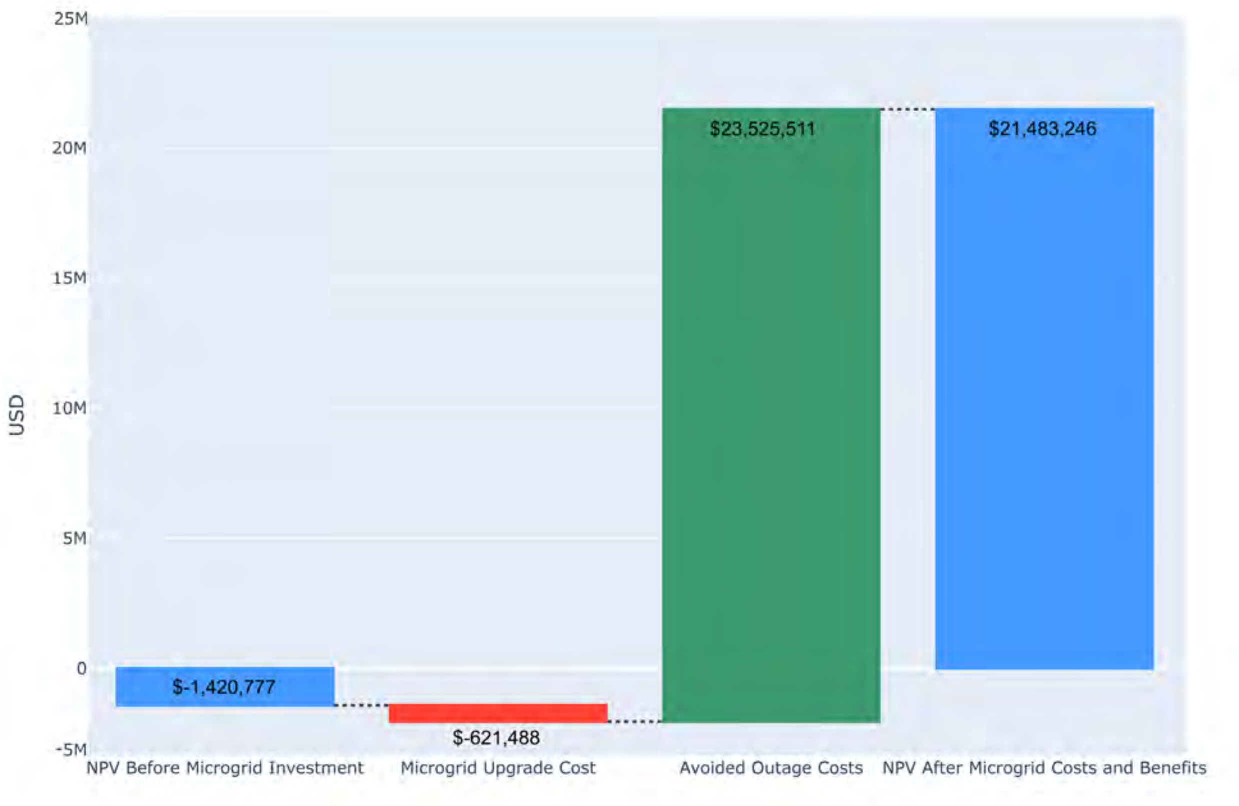


Figure 17: Present Value of Benefits and Costs

Energy Storage for Residential Buildings

Introduction

To work through the process of how a stakeholder would use a valuation tool from beginning to end, this report presents a detailed example of the Facility, Flexibility, Efficiency and Value Enhancement for Commercial or Residential Buildings Use Case. In the ESGC draft roadmap,[5] this use case is characterized using the following information:

[5] DOE Draft ESGC Roadmap, https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf

Use Case	Flexibility for Commercial and Residential Buildings
Scope	• Commercial and residential buildings
Major Drivers	• Enhance the overall facility value to the owner, operator, and the occupant • Promote distributed renewable generation use in buildings • Assist in reducing peak demand and high price electricity use when the grid has constrained capacity • Resilience of building operations • Local codes and regulations
Success Criteria	• Behind the meter storage and flexibility solutions that deliver net benefits including energy expenditures, comfort, and functionality • Market penetration of flexible building technologies and energy storage
Beneficiaries	• Commercial and residential building owners, operators, and occupants • Utility and grid operators seeking means to avoid costly grid upgrades • Government agencies wishing to promote reduced carbon emissions, increased renewable energy generation, improve resiliency • Businesses that are experiencing load growth • Lower operating costs for building owners and occupants • Improved productivity and comfort for building occupants • Increased asset value for building owners

Figure 18: Flexibility for Commercial and Residential Buildings

This use case uses example parameters sourced from publicly available data sets and derived assumptions. The considerations and derived parameters for this specific use case that will be looked at include:

- Locational characteristics
- Building specifications
- ESS specifications
- Electrical load data
- Electricity rate structure
- Incentives

Analysis Parameters

Locational Characteristics

For this use case, the example residential facility will be in New York City due in part to easily obtainable public data that will inform the following sections. Location directly influences how buildings operate, how they are built, and their electricity usage patterns. DOE's Building Technologies Office (BTO) has segmented the United States into different regions based on historical temperature data to broadly characterize the climates for every location. New York City falls into the mixed-humid region[6]; this classification will inform both model load data and building specifications, both provided by BTO, that would be typical in this climate.

[6] BTO Climate Regions: https://www.energy.gov/eere/buildings/building-america-climate-specific-guidance

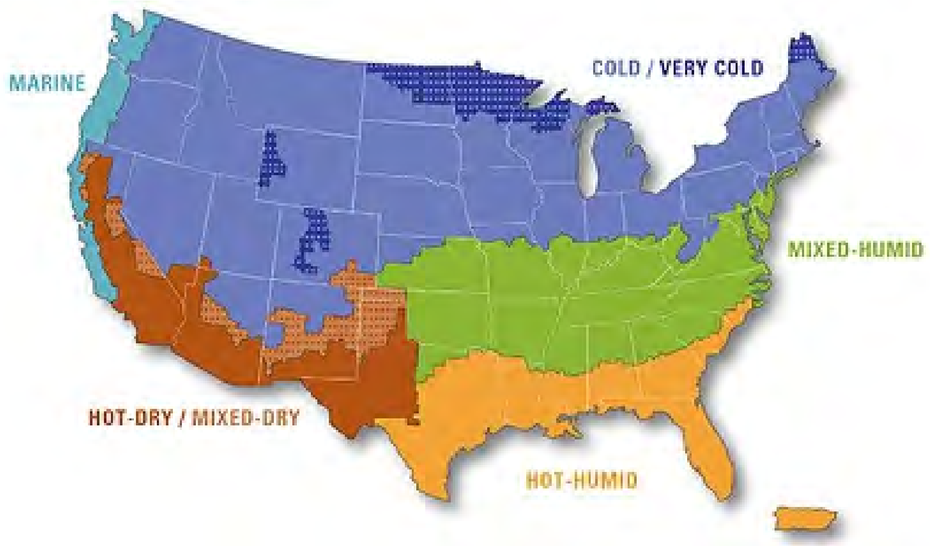


Figure 19: BTO Climate Regions

Building Specifications

BTO also provides typical characteristics of a building located in the respective climate.[7] These building characteristics differ based on high, base, low load model features that, among other factors, are based on how large the unit is. Since the example use case is examining an urban residential facility (mid- to high-rise apartment building), the low load model characteristics will represent the typical unit that the apartment consists of. The characteristics of the low load mode are given in Figure 20.

Location Climate	Mixed-Humid
Heating Set Point (degrees)	66
Cooling Set Point (degrees)	78
Water Flow Rate (Showers / Sinks)	Low Flow
Natural Ventilation	B10 Benchmark
Wall Insulatation Type	R21 Foam
Unifinshed Attic Insulation Type	R38
Finshed Basement Wall Insulation	N/A
Exposed Floor (%)	20
Infiltration	Tight
Refrigerator	Energy Star Top Mount
Cooking Range	Gas Conventional
Dishwasher	Energy Star
Clothes Washer	Energy Star
Clothes Dryer	None (Clothes Line)
Lighting	100% Fluor.
Air Conditiong Unit Type	SEER 16
Water Heater	Electric Premium
Furnace	Gas, AFUE 92.5%

Space Heating	Natural Gas
Air Conditioning	Yes
Water Heating	Electric
Total Size (Sq. Ft.)	1273
Urban and Rural	Urban
Metropolitan and Micropolitan	Metro
Number of Stories/Levels	1 Story
Major Outside Wall Construction	Siding (Aluminum, Vinyl, Steel)
Major Roofing Matieral	Ceramic or Clay Tiles
Foundation/Basement of Single Family	Slab
Bedrooms	2
Full Bathrooms	1
Half Bathrooms	0
Basement Single-Family Homes	No
Finished Basement	No
Type of Glass In Windows	Double-Pane Glass

Figure 20: Low Load Model Unit Characteristics

[7] Model Building Characteristics: https://openei.org/doe-opendata/dataset/eadfbd10-67a2-4f64-a394-3176c7b686c1/resource/cd6704ba-3f53-4632-8d08-c9597842fde3/download/buildingcharacteristicsforresidentialhourlyloaddata.pdf

To estimate if this would accurately reflect a typical unit and how many of these units would be in a typical New York City apartment building, data from the city on ongoing construction projects are examined to obtain an average number of square feet per unit and units per apartment building.[8]

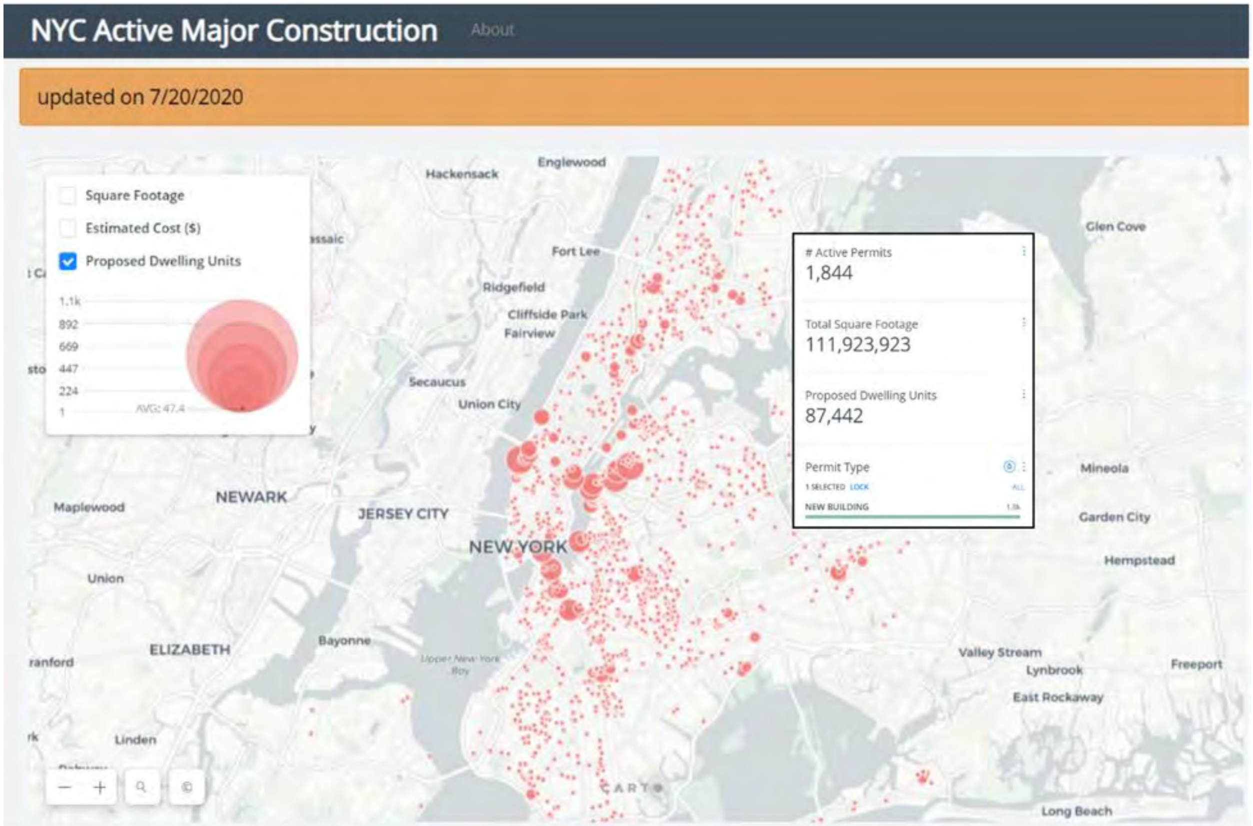


Figure 21: New York City Apartment Construction

Based on these data, the average apartment building being built would have 47 units per building and each unit would have approximately 1280 square feet per unit, which matches closely to the BTO low load model for this region. These numbers are used to inform what the building load will look like for this example; in reality, the input load data would be based on actual meter data, which would eliminate the need for these approximations. These load approximations can also be useful for analysis of future projects that aim to estimate what a typical load may look like in a specific location of interest.

Electrical Load Data

The locational and building characteristics described in the previous sections are directly related to the example electricity load data used. The BTO database provides an entire year of hour-by-hour electricity usage for a variety of locations in each climate region, with options for low, base, and high building models.[9] The load data file used in this use case is the Low Model based on Central Park Temperature

[8] NYC Building Data https://www1.nyc.gov/assets/buildings/html/nyc-active-major-construction.html

[9] BTO Load Datasets https://openei.org/datasets/files/961/pub/

Data; the file shows hourly kW usage for both gas and electricity. The subcategories that make up the total facility electricity usage number are:

- Heating (only if provided by electricity, based on building specs)
- Cooling
- Water heater (only if provided by electricity, based on building specs)
- HVAC
- Interior lights
- Exterior lights
- Appliance interior equipment
- Misc. interior equipment

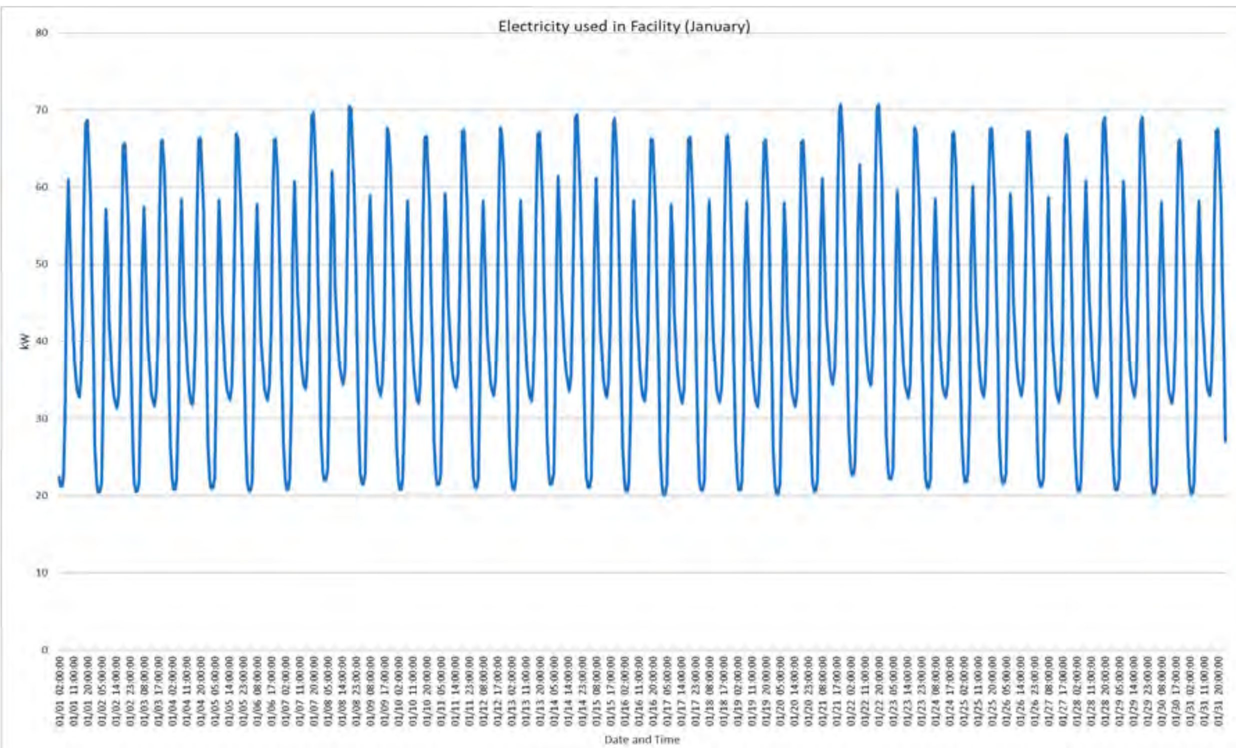


Figure 22: Facility Load Data in Month of January

Electricity Rate Structure

The utility that would service a building in this territory is Consolidated Edison (Con Edison), which serves 10 million customers in New York City and Westchester County, NY.[10] Con Edison has a variety of rate structures based on factors such as building classification, interconnection requirements, and peak demand.[11] Apartment buildings fall into Service Classification (SC) 8, which is intended for multi

[10] Con Edison Company Info: https://www.coned.com/en/about-us/company-information

[11] Con Edison Energy Storage Guide: https://www.coned.com/-/media/files/coned/documents/save-energy-money/using-private-generation/specs-and-tariffs/energy-storage-guide.pdf?la=en

dwelling housing buildings. SC-8 charges are master metered and include energy usage charges ($/kWh) and a variable demand charge ($/kW) adjusted monthly based on the highest 30 minutes of demand.[9] There are also different rates for low tension vs. high tension conditions, which refers to the needed interconnection voltage; high tension typically involves DERs sized from 5 to 20 MW,[12] so low tension will be assumed in this case. There are two SC-8 rate options that could be applicable to this example use case. the first one is "SC-8 Multiple Dwellings Redistribution Low Tension Service (Delivery w/Standard Offer)," which is applicable for a minimum 10 kW and maximum 1500 kW demand.[13] The electricity bill is calculated based on the following:

- Flat monthly charge of $319
- Energy charge of $.0176/kWh plus $0.008745/kWh in adjustments
- No TOU or time of day (TOD) charges
- Demand charge schedule based on the following:

Period	Tier	Max kW Usage	Rate $/kW	Adjustments $/kW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	10	12.83	-1.2												
	2		38.93	-1.2	•	•	•	•	•					•	•	•
2	1	10	12.83	-1.2												
	2		46.73	-1.2						•	•	•	•			

Figure 23: SC-8 Redistribution Low Tension Demand Schedule and Rates

- Here is an example monthly charge calculation assuming a peak demand rate of 70 kW, total energy of 30,000 kWh, and time and date of peak demand on July 5 at 5 p.m.

$$Total\ Monthly\ Charge\ (\$) = Energy\ Charge + Flat\ Monthly\ Cost + Demand\ Charge$$

$$Energy\ Charge\ (\$) = (.0176 + .008745)\ \frac{\$}{kWh} \cdot 30{,}000\ kWh = \ \$790.35$$

$$Demand\ Charge\ (\$) = (12.83 - 1.2)\ \frac{\$}{kW} \cdot 10\ kW + (46.73 - 1.2)\ \frac{\$}{kW} \cdot (70 - 10)\ kW = \ \$2{,}848.10$$

$$Total\ Monthly\ Charge\ (\$) = \$790.35 + \$319 + \ \$2{,}848.10 = \$\mathbf{3957.45}$$

The other applicable rate is "SC-8 Multiple Dwellings Redistribution Voluntary TOD Service (Delivery w/Standard Offer)," which requires a minimum load of 10 kW.[14] The electricity bill is calculated based on the following:

- Flat monthly charge of $11
- Energy charge of $.0079/kWh plus $0.008745/kWh in adjustments
- TOD charges based on the following (only on weekdays):

---

[12] High Tension Service for Con Edison https://www.coned.com/-/media/files/coned/documents/save-energy-money/using-private-generation/specs-and-tariffs/high-tension-service-welcome-kit.pdf?la=en

[13] SC-8 Redistribution Low Tension Service Rate https://openei.org/apps/USURDB/rate/view/5cd1ec805457a3192454e9d1#2__Demand

[14] SC-8 Multiple Dwellings Redistribution Voluntary TOD Service https://openei.org/apps/USURDB/rate/view/5cd1f6505457a3f73d54e9d1

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Feb	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Mar	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Apr	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
May	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Jun	1	1	1	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4	3	3	3	3	1	1
Jul	1	1	1	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4	3	3	3	3	1	1
Aug	1	1	1	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4	3	3	3	3	1	1
Sep	1	1	1	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4	3	3	3	3	1	1
Oct	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Nov	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Dec	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1

Period	Tier	Max kW Usage ?	Rate $/kW ?	Adjustments $/kW ?
1	1		0	
2	1		15.9	13.95
3	1		21.52	
4	1		30.54	13.95

Figure 24: SC-8 TOD Schedule and Rates

- Demand charge schedule based on the following:

Period	Tier	Max kW Usage ?	Rate $/kW ?	Adjustments $/kW ?	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1		6.31	-1.2	•	•	•	•	•					•	•	•
2	1		19.82	-1.2						•	•	•	•			

Figure 25: SC-8 Demand Schedule and Rates

- Here is an example monthly charge calculation assuming a peak demand rate of 70 kW, total energy issue of 30,000 kWh, and time and date of peak demand on July 5 at 5 p.m.; the peak demand between the hours of 6 p.m. to 9 p.m. is 65 kW for the month of July

$$Total\ Monthly\ Charge\ (\$) = Energy\ Charge + Flat\ Monthly\ Cost + Demand\ Charge$$

$$Energy\ Charge\ (\$) = (.0079 + .008745)\ \frac{\$}{kWh} \cdot 30{,}000\ kWh = \ \$262.36$$

$$Demand\ Charge\ (\$)^{15} = \left((19.82 - 1.2)\ + (30.54\ +\ 13.95)\right)\frac{\$}{kW} \cdot\ 70\ \text{kW} + \left(21.52\ \frac{\$}{kW} \cdot 65\ \text{kW}\right) = \$5815.80$$

$$Total\ Monthly\ Charge\ (\$) = \$262.36 + \$11 + \$5{,}815.80 = \$\mathbf{6{,}089.16}$$

[15] Demand Charge Calculation Explanation https://www.renewableenergyworld.com/2017/06/06/making-sense-of-demand-charges-what-are-they-and-how-do-they-work/#gref

A Con Edison customer under this service classification would have the option to choose between these two rates, thus making it of interest to examine which rate structure would be more financially appealing when using a storage system. In this analysis, we will assume that the utility rate with the TOD charges would create more favorable incentives to justify an ESS and therefore would be the rate that the building owner is under.

Energy Storage System Specifications

For this use case example, it is assumed the building owner has a specific ESS in mind and they would like to know the value proposition for their building. The assumed ESS is the Tesla Powerpack, which is a popular storage solution for commercial consumers and lists their system specifications publicly. Below are the details for the system that will be used in the valuation model:

Overall System Specs

AC Voltage	380 to 480V, 3 phases	**Energy Capacity**	Up to 232 kWh (AC) per Powerpack
Communications	Modbus TCP/IP; DNP3; Rest API	**Operating Temperature**	-30°C to 50°C / -22°F to 122°F
Power	Up to 130 kW (AC) per Powerpack	**Enclosures**	Pods: IP67 Powerpack: IP35/NEMA 3R Inverter: IP66/NEMA 4
Scalable Inverter Power	From 70kVA to 700kVA (at 480V)		
Depth of Discharge	100%	**System Efficiency (AC)** *	88% round-trip (2 hour system) 89.5% round-trip (4 hour system)
Dimensions	**Powerpack Unit** Length: 1,317 mm (50.9 in) Width: 968 mm (38.1 in) Height: 2,187 mm (86.1 in) Weight: 2,199 kg (4,847 lbs) **Powerpack Inverter** Length: 1,044 mm (41.1 in) Width: 1,394 mm (54.9 in) Height: 2,191 mm (86.2 in) Weight (max): 1,120 kg (2,470 lbs)	**Certifications**	Nationally accredited certifications to international safety, EMC, utility and environmental legislation.

* Net Energy delivered at 25°C (77°F) ambient temperature including thermal control

Figure 26: Tesla Powerpack Specifications[16]

[16] Powerpack - Commercial & Utility Energy Storage Solutions | Tesla

Incentives

Both federal and state incentives are available for ESSs that may increase a project's financial viability. The Federal Investment Tax Credit (ITC) and Modified Accelerated Cost Recovery System (MACRS) depreciation deduction are two federal tax incentives available to ESS owners. The main distinction between these incentives is based on how much of the energy used to charge the battery comes from renewables; the incentive structure is as follows[17]:

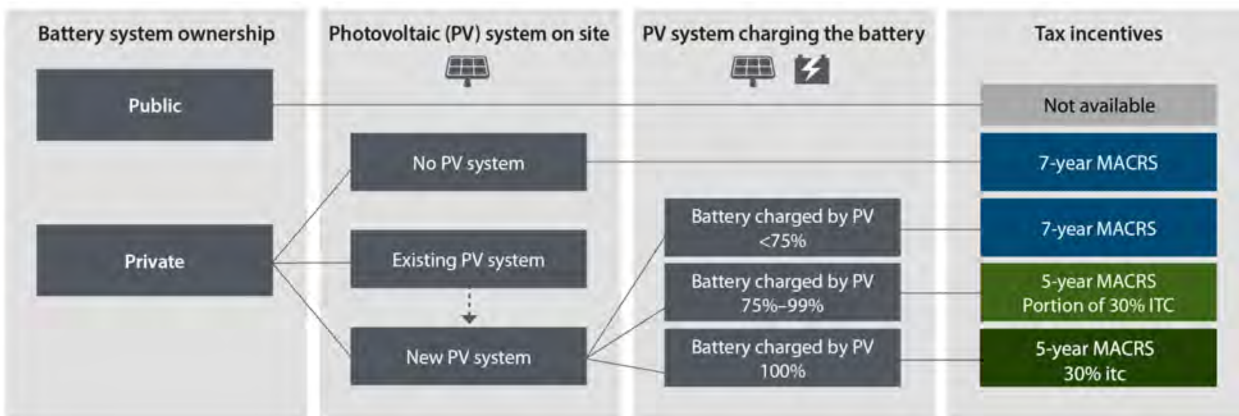


Figure 27: Storage Incentive Structure

For ESS coupled with PV or other renewable generation, the ITC will be the more lucrative incentive as the credit is calculated by the current ITC percent (26% until the end of 2020) multiplied by the proportion of renewable energy used to charge the system. The 7-year MACRS schedule equates to a reduction in capital costs of about 20% while the 5-year schedule equals about 21%. New York State also offers incentives through the New York State Energy Research and Development Authority (NYSERDA), which provides a credit of $240/kWh to the project contractor installing the system.[18] One tool to find other incentives is the Database of State Incentives for Renewables and Efficiency (DSIRE) website created by North Carolina State University's Clean Energy Technology Center.

In addition, an ESS in this location may be able to take advantage of utility value stack credits that compensate system owners for exporting excess energy back to the grid based on time and location.[19]

[17] NREL Federal Incentive Description https://www.nrel.gov/docs/fy18osti/70384.pdf

[18] NYSERDA Storage Incentive Program, https://www.nyserda.ny.gov/All-Programs/Programs/Energy-Storage/Developers-Contractors-and-Vendors/Retail-Incentive-Offer/Incentive-Dashboard#nygov-header

[19] Con Edison Energy Storage Guide, https://www.coned.com/-/media/files/coned/documents/save-energy-money/using-private-generation/specs-and-tariffs/energy-storage-guide.pdf?la=en

Analysis of the Use Case in the Model

For this use case, we use the QuEST tool to assess the value of energy storage based on the parameters and conditions described in the above sections. The tool's BTM function will estimate the value that storage will provide in a typical year based on the rate savings that the owner would receive through optimal operation of a system during this time.

The first step in this analysis is to ensure that the correct utility rate and building load profile is loaded into the software. These both can be downloaded by selecting the "QuESt Data Manager" option and downloading the files through the "Utility Rate Structure" and "Commercial/Residential Building Load Profiles." Other load profiles and utility rates that are not found by the data manager can be added by placing them in the QuESt file directory that is created when downloading the software.

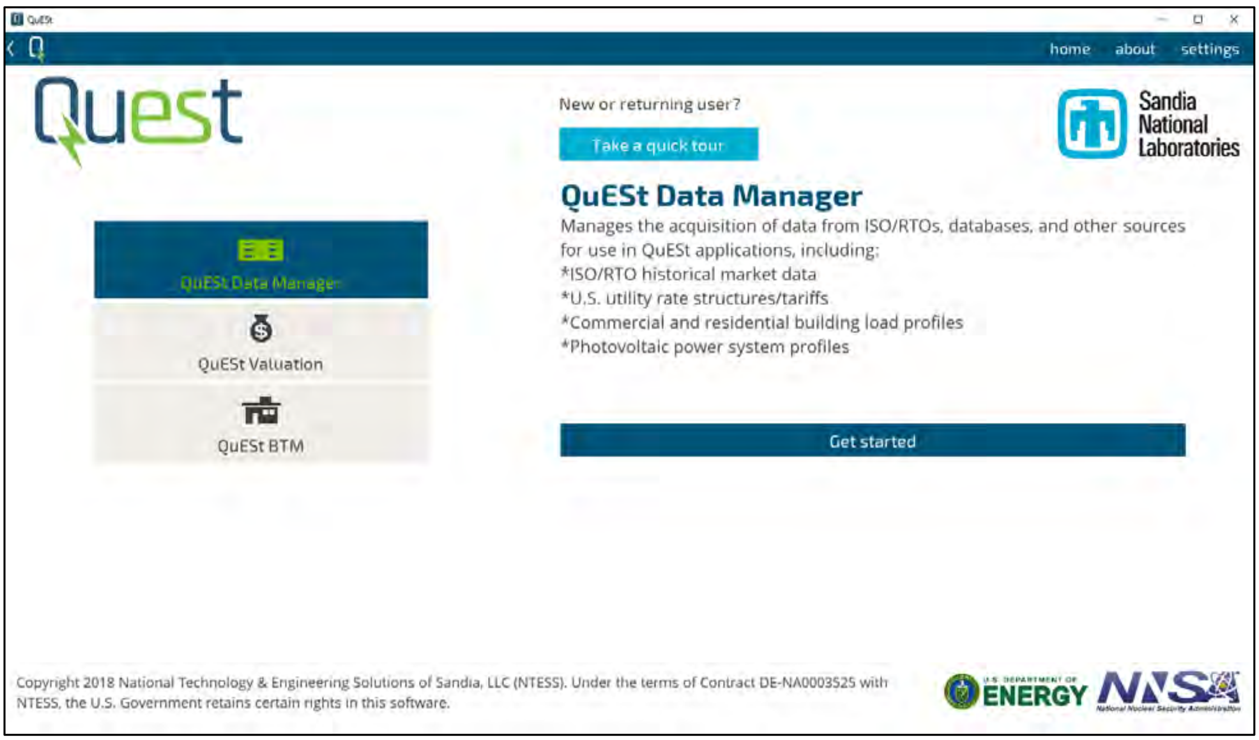


Figure 28: QuESt Startup Screen

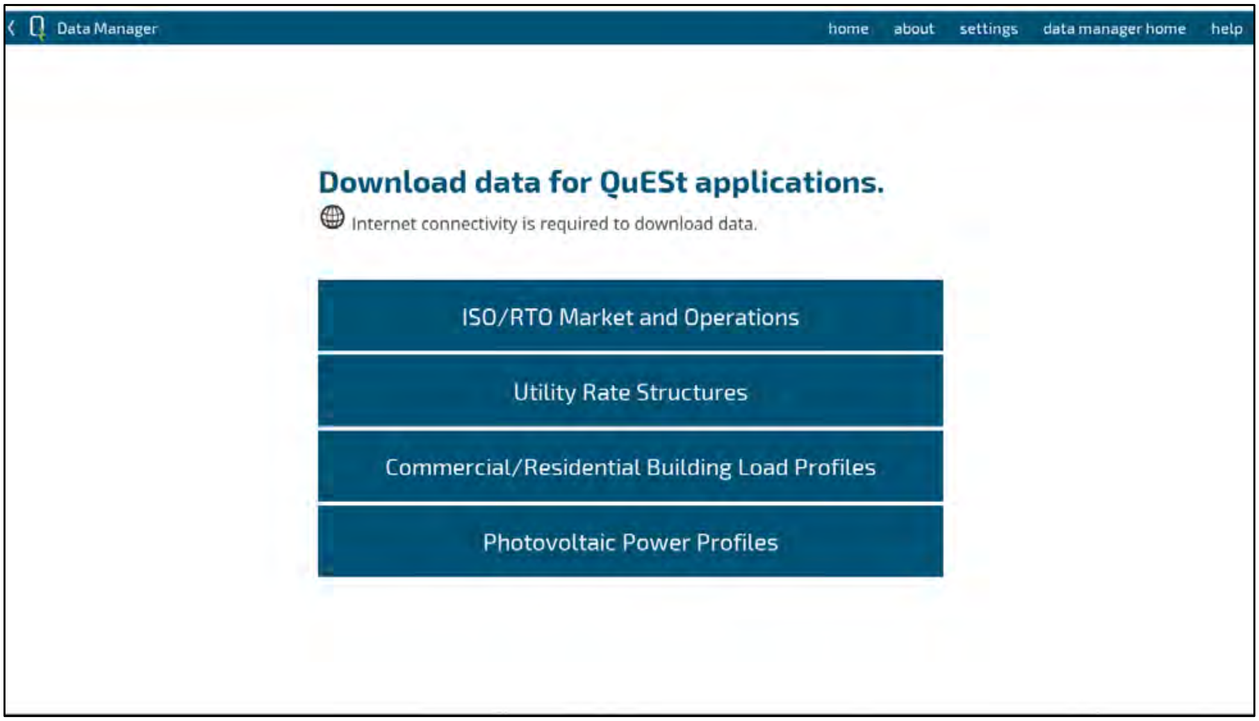


Figure 29: QuESt Data Manager Options

After the utility rate structure and load profile data have been downloaded, the “Time -of-Use Cost Savings” simulation is selected after clicking the “QuESt BTM” option on the main menu.

Figure 30: Behind-the-Meter Analysis Options

The next screen shows a panel on the left with any downloaded utility rate structures, where the Con Edison rate titled "NYC TOU SC-8 (Standard Delivery)" is selected and the energy, demand, and TOU prices are loaded into the simulation.

Figure 31: QuESt Utility Rate Selection and Information

After confirming the rate details, the load profile is selected.

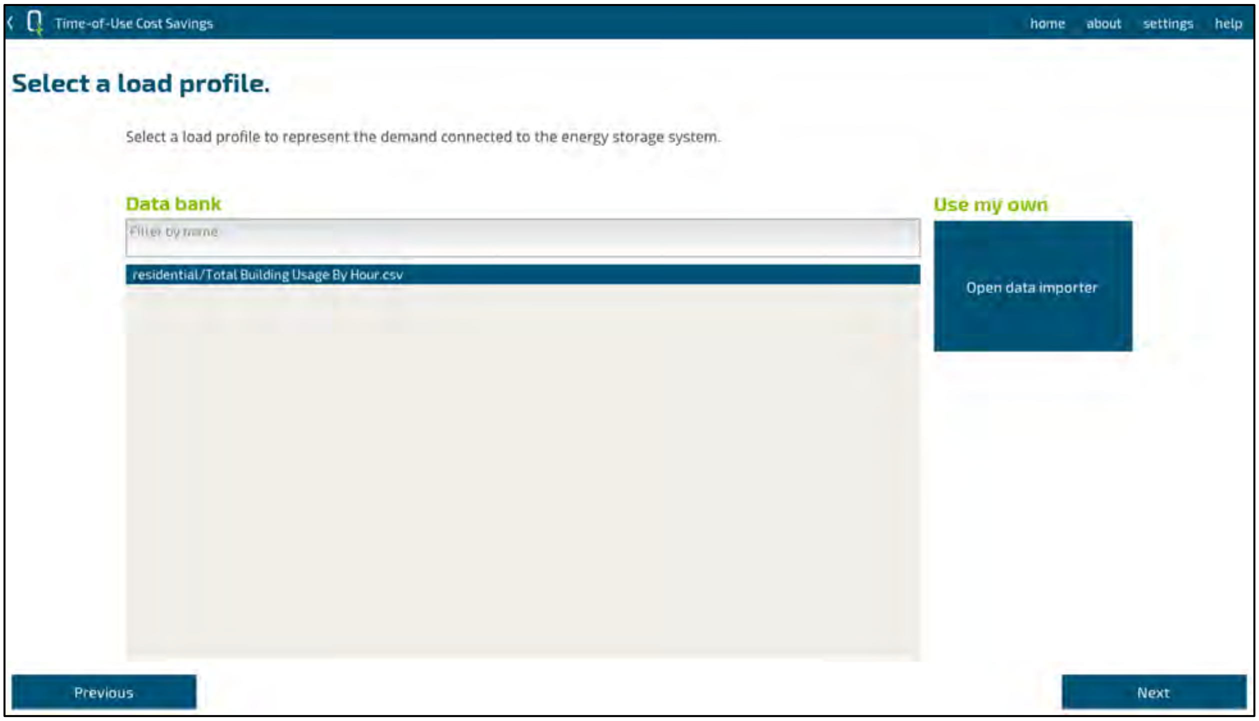


Figure 32: QuESt Select Load Profile

Here, the tool asks for the ESS parameters; the list of specifications in the previous section gives the values for energy capacity, power rating, and round-trip efficiency. The rest of the values we will keep the defaults.

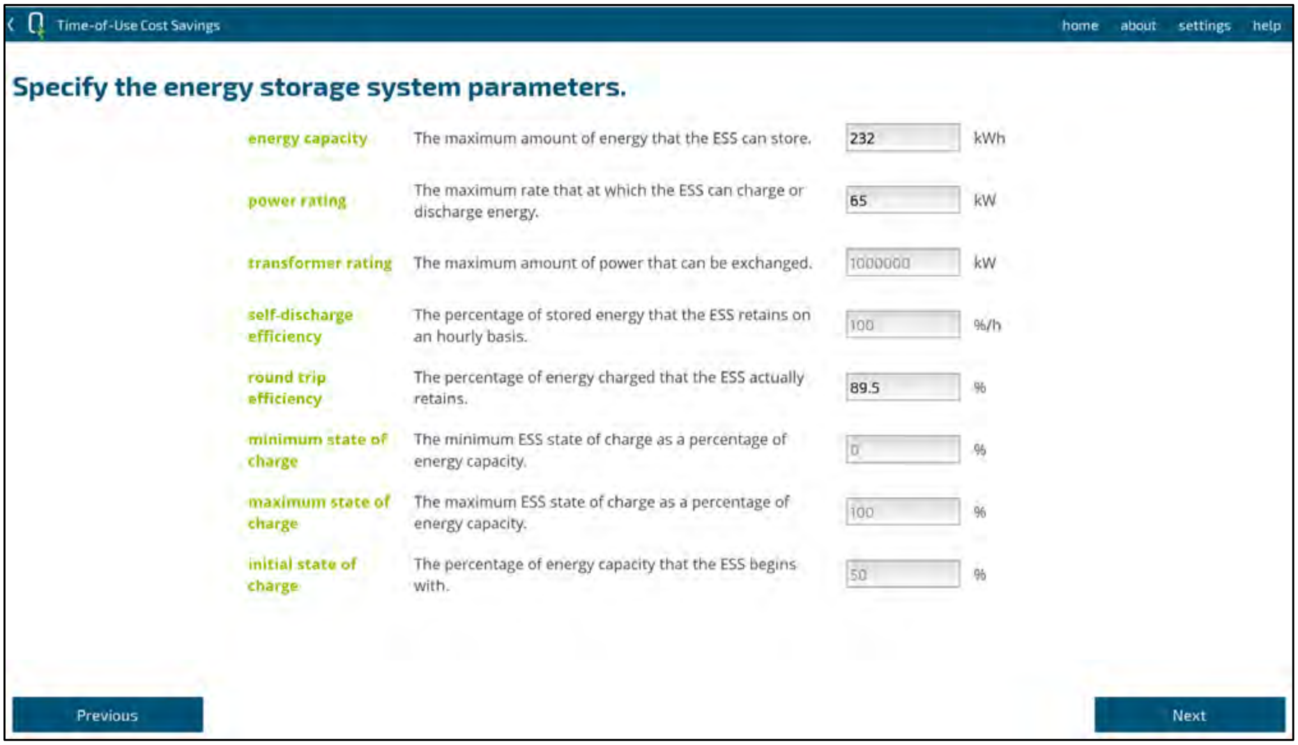


Figure 33: QuESt Battery Parameters

All the information now has been entered and the tool will calculate the electricity bill savings that the system provides, broken down by each month of the year that is being analyzed. The first figure shows how much the owner pays each month, while the second figure compares the expected bill with the ESS to the bill without the ESS. It notes that in this case the ESS would save the owner more than $13,000 through reducing the demand changes in each month, which can be seen in Figure 36.

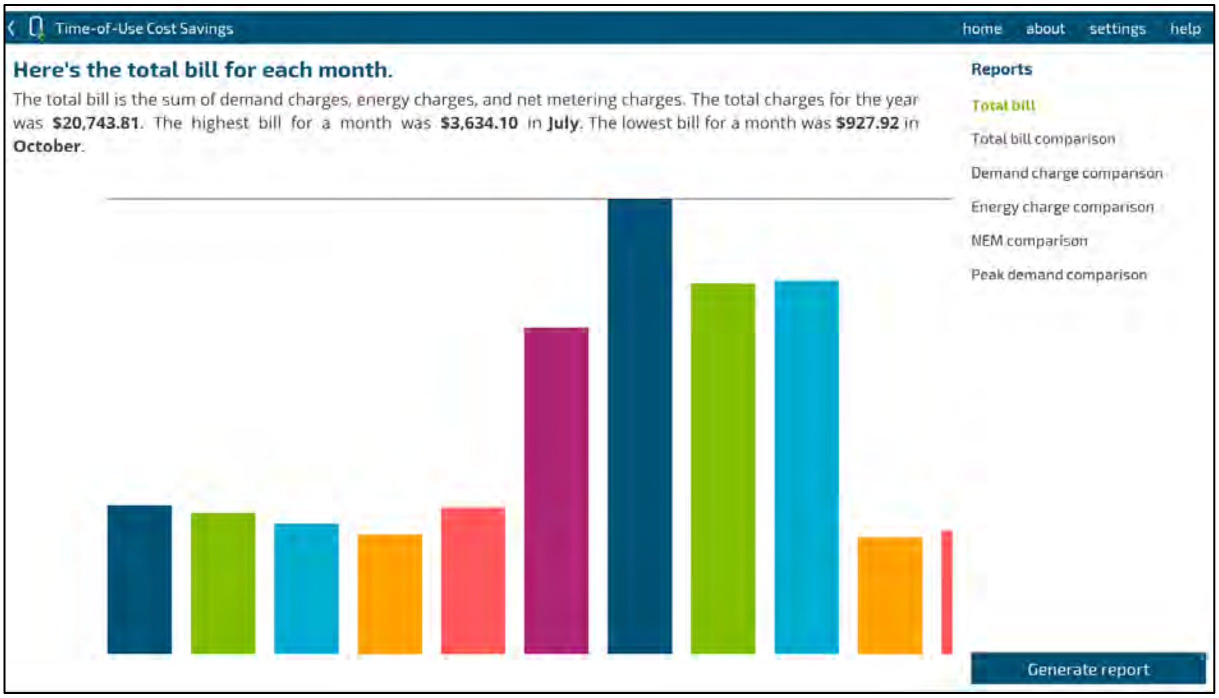


Figure 34: QuESt Total Electricity Bill

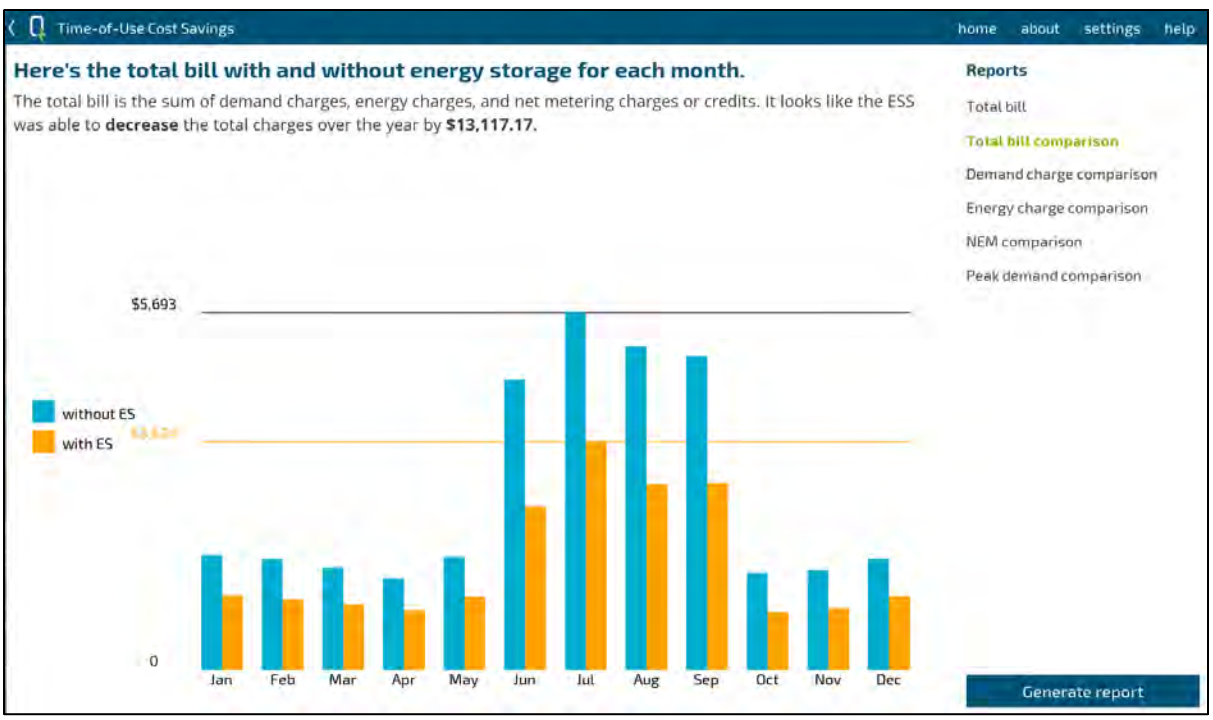


Figure 35: QuESt Bill Comparison

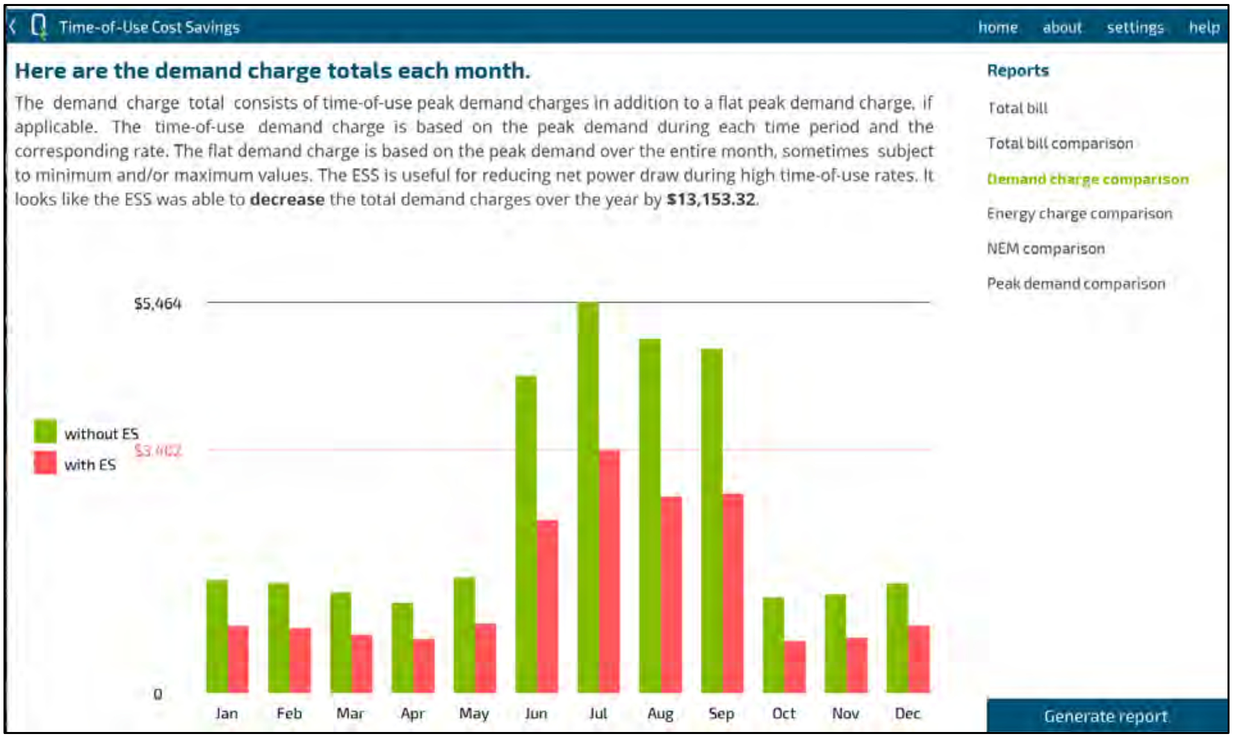


Figure 36: QuESt Demand Charge Savings

Model Selection Platform

Introduction

The DOE energy storage valuation tools are valuable for industry, regulators, and other stakeholders to model, optimize, and evaluate different ESSs in a variety of use cases. There are numerous similarities and differences among these tools. It is not easy for general users to differentiate these tools and select the most appropriate tools to meet their specific needs. To address this challenge, an MSP was developed at PNNL to review and compare a list of publicly available storage valuation tools and suggest the best-suited tools based on user needs and requirements. The MSP tool guides users through a series of steps and questions. At each step, the tool starts with a single question and follows down a singular path based on the response. Each path branches until the next step is reached, where the user is asked subsequent questions to eventually lead them toward conclusions.

The core of the platform is based on 1) a specification discovery procedure and 2) an engine that dynamically calculates scores for different tools as users are guided through the selection process. Key attributes that are important to characterize these DOE tools are identified and used to develop the specification discovery process and scoring engine, including:

- Available ESS technologies
- Other resources that are often considered together with ESS, such as solar PV, wind, and distributed generators
- Available grid and end-user services
- Types of analyses, such as evaluation, sizing, and siting
- Software distribution and other features/capabilities, such as available platform and built-in library.

Based on these attributes, a hierarchical specification discovery procedure has been developed. The core of specification discovery is a flowchart governing information flows and inputs/outputs adaptively. By collecting answers to a set of deliberately designed questions regarding the valuation analyses to be performed, the desired capabilities and needs are discovered and recorded. Some inputs and specifications may trigger additional questions and answers regarding certain aspects in detail. User responses are organized into a specification tree.

Inside the scoring engine, a binary matrix is constructed offline to record whether individual tools have the identified attributes. In addition, weights are assigned to each group of attributes based on our experiences in various ESS assessment projects. A vector of weights for individual attributes is generated to reflect user needs. Based on the vector of weights and attribute matrix, scores are calculated and the tools are ranked dynamically as users respond to questions. Once users complete all steps and questions, MSP provides final scores and recommendations together with key factors that affect the scores.

MSP has been implemented as a publicly accessible web-based tool: https://msp.pnnl.gov/. It runs from a host server, eliminating the need for download, installation, and updates on local machines, and can be used across a variety of platforms and devices. Both the specification discovery and scoring engine are based on a modular design. Different modules and components are implemented in a separated and isolated manner, which facilitates the maintenance and extension of the platform to include additional attributes and tools.

Specification Discovery

The proposed hierarchical design for specification discovery is illustrated in Figure 37. Each block in the diagram represents a key aspect to be discovered for the analyses to be performed, and all blocks are organized in a tree structure. Beginning from the "Start" node, MSP traverses all the blocks in a depth-first manner and thereby collects user needs and translates them into specifications. Some inputs and selections may trigger additional questions about details of certain aspects. In that case, the tool automatically guides users to explore deeper layers of the tree as needed. For instance, when users select batteries as the ESS technology to be modeled, additional questions and options are provided to gather user preferences and needs in BESS modeling, such as 1) system-level vs. component-level modeling and 2) constant-efficiency with static operating range vs. varying efficiency with dynamic operating range. In this way, different storage valuation tools can be better differentiated.

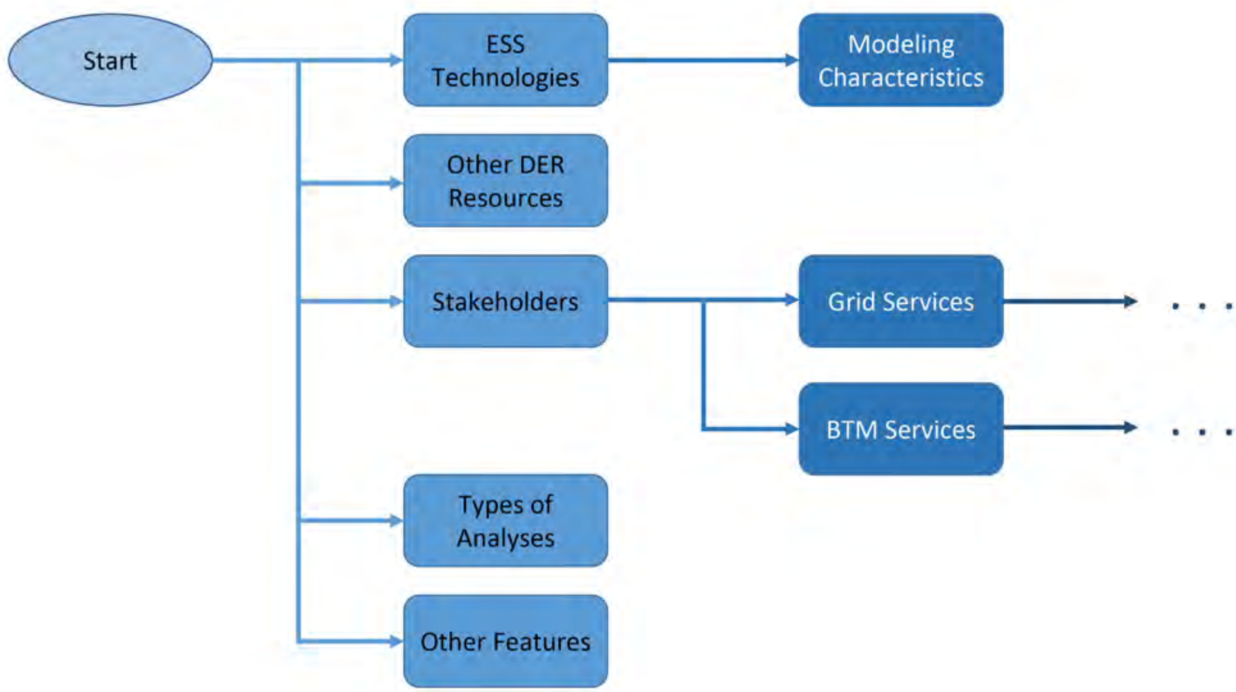


Figure 37: Illustration of the Proposed Hierarchical Design for Specification Discovery

Each of the key aspects to be discovered is briefly described as follows.

- **ESS Technologies**

  Energy storage includes a broad range of technologies that fall into two basic categories: potential energy and kinetic energy. Potential energy is stored energy and the energy of position, and includes chemical, mechanical, and gravitational energy. Kinetic energy is the motion of waves, electrons, atoms, molecules, substances, and objects, and includes thermal, motion, and electrical energy. The DOE ESGC groups storage technologies into three categories: bidirectional electrical storage, chemical and thermal storage, and flexible generation and controllable loads. Detailed information on various energy storage technologies can be found in the ESGC roadmap report. Key energy storage technologies that are modeled in DOE's storage valuation tools include batteries, hydrogen, pumped hydro, compressed air, and flywheels. In the current design, the MSP enables users to directly select one or multiple items from the five ESS technologies. As the list of storage valuation tools reviewed in the MSP expands in the future, additional ESS technologies may be included and grouped by category.

  Battery energy storage is commonly modeled in all DOE's storage valuation tools. Technical characteristics and physical capability need to be appropriately modeled when scheduling, evaluating, or sizing a BESS for grid applications. For example, the rated power capacity of a BESS limits its ability to interact instantaneously with the grid. The energy capacity limits its capability to shift energy over time. The charging and discharging profiles have a direct impact on loss of life and degradation in performance, affecting strategies of using a BESS for grid services over its service life. Constant-efficiency models with a static operating range are easy to use and are often employed in BESS techno-economic analysis. Advanced operation and degradation models can more accurately represent the physical characteristics and operational flexibility of BESS. Users are also enabled to provide their preferences and needs when modeling BESS.

- **Other DER Resources**

  Users may need to model ESS paired with some other resources, such as solar PV, wind, biomass generation, and diesel engines, in a valuation study. The selection of other resources may affect the score and recommendation of the DOE valuation tools that have different capabilities in modeling the integrated systems.

- **Stakeholders and Use Cases**

  ESS can provide a variety of grid and end-user services in different use cases that users are not familiar with. The potential use cases and applications of energy storage vary with stakeholders and typically require different modeling and solution methods. Therefore, based on stakeholder information users provide, the tool displays applicable use cases and applications for users to select. In the current design, four types of stakeholders are considered: vertically integrated utilities, market participants, distribution utilities, and electricity end-users.

- A vertically integrated utility handles all functions of generation, transmission, and distribution within a certain geographical area. Energy storage can be used by a vertically integrated utility to reduce operational costs and avoid or defer investment in generation, transmission, and distribution.
- Energy storage can participate in wholesale energy, ancillary, and capacity markets to generate revenue for storage owners. It can also be used by load serving entities for load management and thereby reduce the cost for procuring electricity and various capacity reservations in power markets.
- Many small distribution utilities, including municipally-owned electric utilities and electric cooperatives, own no or little generation and purchase power from other utilities under purchase agreements. Energy storage can be used for load management and thereby reduce power purchasing costs.
- Electricity end-users, including residential, industrial, and commercial customers, can use energy storage for electricity bill management and DR.

Depending on stakeholders selected, options of grid and/or BTM services are provided. Grid services include energy arbitrage, frequency regulation, spin/non-spin reserve, peaking capacity, critical infrastructure upgrade deferral, and resilience. BTM services include energy and demand charge reduction, DR, and resilience.

- **Types of Analysis**

  The required modeling capabilities also depend on the type of analysis, including evaluation, sizing, and siting.

  - **Evaluation:** to define technically achievable economic and/or resilience benefits through advanced modeling and optimization for a given ESS.
  - **Sizing:** to determine the optimal size or capacity of ESSs and other optional energy sources with an objective to maximize the net benefits or minimize the investment or net cost to meet a resilience requirement.
  - **Siting:** to identify the optimal location to place ESSs to maximize net benefits or cost-effectiveness.

- **Other Features and Capabilities**

  All of DOE's storage valuation tools compared in the current version of MSP are publicly accessible and free to use. They are designed to be easy to use without requiring knowledge of the modeling, optimization, and solution process behind them. Most of these tools can be used across a variety of platforms and devices. Some of them are web-based and run from a host server, eliminating the need for download, installation, and updates on local machines. Currently, a couple of them are open source. An electricity market data manager and building library are also available in some of these tools to save user efforts in preparing inputs for a valuation study. Users can select one or multiple features and capabilities they will need for their analyses.

Scoring Engine

Designing a scoring engine is challenging. First, it is difficult to directly score individual tools by attribute. The same goal may be achieved using slightly different models, parameters, and procedures. It is hard to develop commonly accepted metrics and methods to quantify tools by attribute as scores. More importantly, determining the most appropriate tool for a certain type of valuation analyses generally involves multiple required and preferred attributes. Individual attribute scores cannot be easily converted to total scores that capture both user preferences and capabilities of individual tools. To address this challenge, a scoring engine is proposed based on 1) whether a tool has certain attributes, 2) desired and preferred attributes, and 3) weights assigned to different aspects. The proposed scoring engine consists of two parts: offline setup and online scoring, which are briefly described as follows.

Offline Setup

During the offline setup, a binary matrix is generated to describe the capabilities of individual tools with respect to the identified key attributes. The matrix is static and independent of user inputs. Based on our experience in various ESS assessment projects, weights are assigned to different aspects that correspond to different groups of attributes. The weights represent the relative importance of different aspects, such as ESS technologies, grid and end-user services, and functionalities. For example, “ESS Technologies” is assigned a weight of 30, while “Other Resources” gets 20 in the current platform. While the empirical weights are somewhat subjective, they can be easily adjusted to better reflect user perspectives. Future releases will enable advanced users to customize these weights.

Online Score Calculation

Assuming there are N key attributes, an N by 1 weight vector $\boldsymbol{W}$ is generated and updated dynamically. As the platform collects specifications from users, the scoring engine equally distributes the weights at the group level to individual discovered specifications. The attributes that are irrelevant to user needs get zero weights. In this way, the vector $\boldsymbol{W}$ updates dynamically.

The dimension of the binary matrix $\boldsymbol{A}$ is M by N, where M is the number of tools. The vector of scores can be calculated as

$$\boldsymbol{S} = \boldsymbol{A}\,\boldsymbol{W}$$

which is also updated dynamically.

Use of MSP

In the current design, the landing page lists the five DOE storage valuation tools with a link and brief description for each of them, as shown in Figure 38.

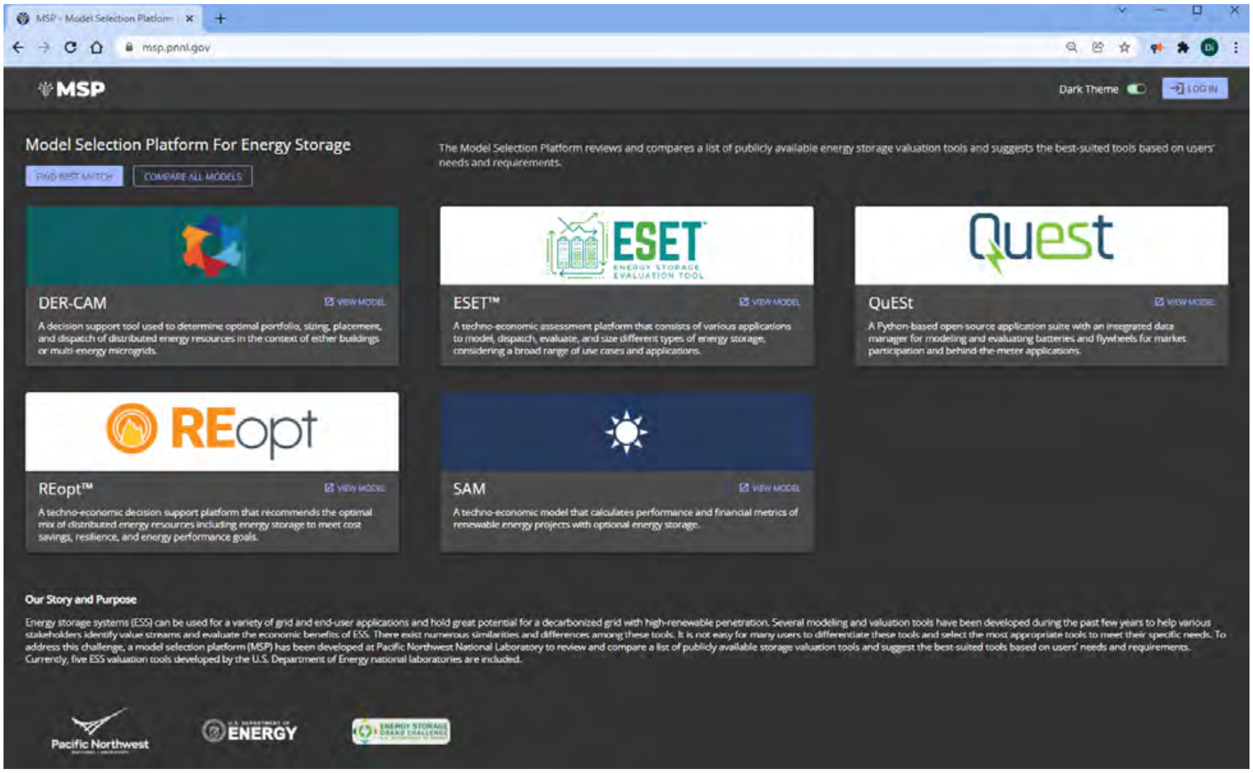


Figure 38: MSP Landing Page

The platform currently consists of two modules: Model Comparator and Tool Finder.

Model Comparator

Model Comparator enables users to select tools for comparison and generate an attribute table for the selected tools, as shown in Figure 39. The comparison table provides an easy way for users to quickly browse and compare the features and capabilities of different tools. All the attributes listed in the table are consistent with the scoring engine and recommendation system in Tool Finder.

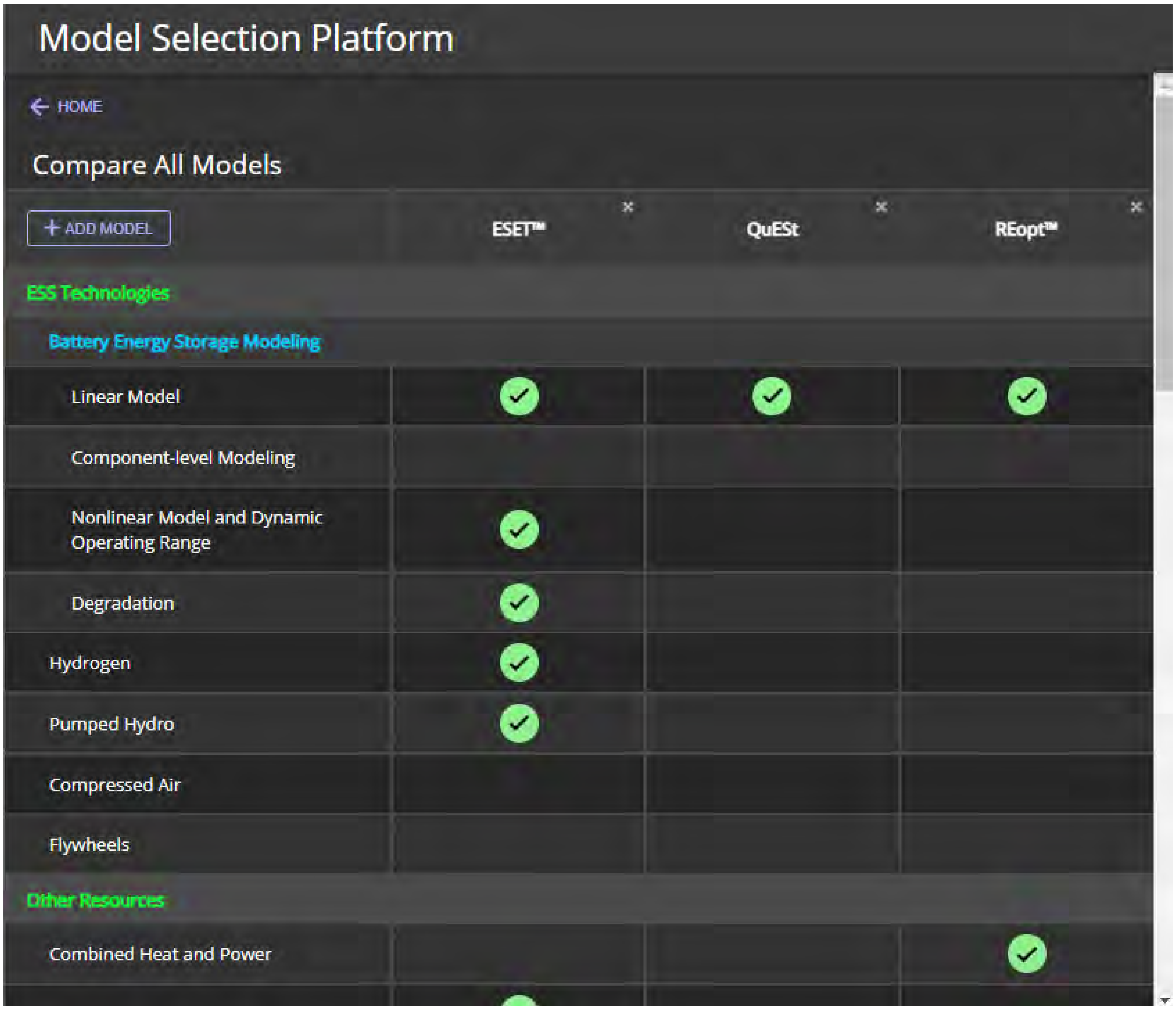


Figure 39: Model Comparator

Tool Finder

Tool Finder guides users through a series of steps and questions to collects their needs and preferences and suggests the best-suited tools accordingly. An example page is provided in Figure 40.

- The navigation panel on the left shows all the steps and updates automatically based on user selection. The current step is highlighted and users can navigate to previous steps by clicking the corresponding labels.
- The Q&A panel in the middle displays questions and options as well as useful information to help users make selections. Users can check one or multiple items and reset the selection.

- The ranking panel on the right displays the scores of different tools that are ranked from high to low. Both the scores and ranks are dynamically updated as users proceed. When the user clicks the ⓘ icon for an option in the Q&A panel, a glossary block appears at the bottom of the ranking panel to provide tips and useful information.

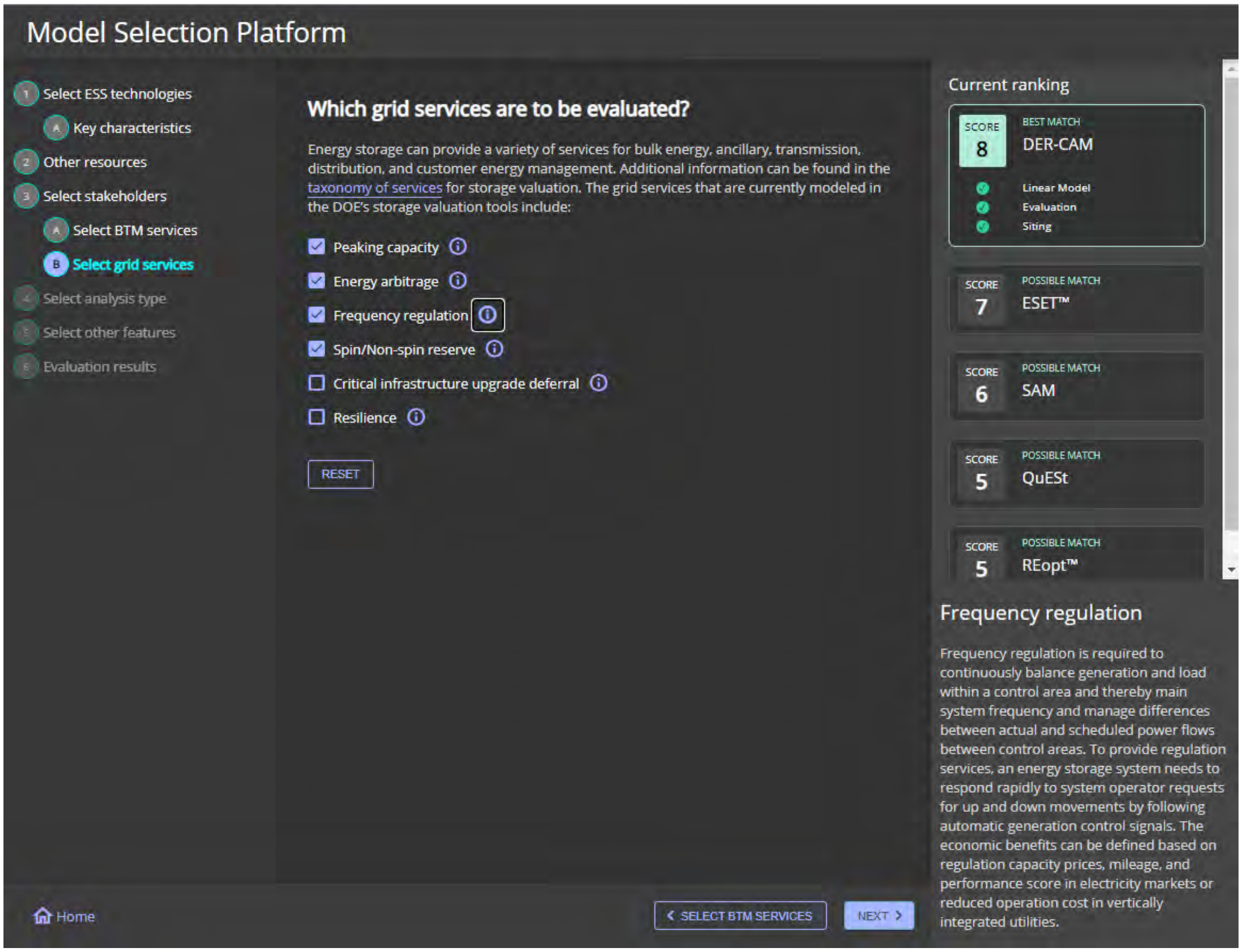


Figure 40: MSP Scoring Example Page

Once users complete all steps and questions, the final scores and recommendations are provided on the result page, as shown in Figure 41. The two most suitable tools together with the three attributes that contribute to the scores are mostly displayed on the top of the page. In addition, a summary table is provided to highlight the capabilities and features that are relevant to user needs and preferences. In contrast to the comprehensive table generated by Model Comparator, this one excludes the irrelevant rows.

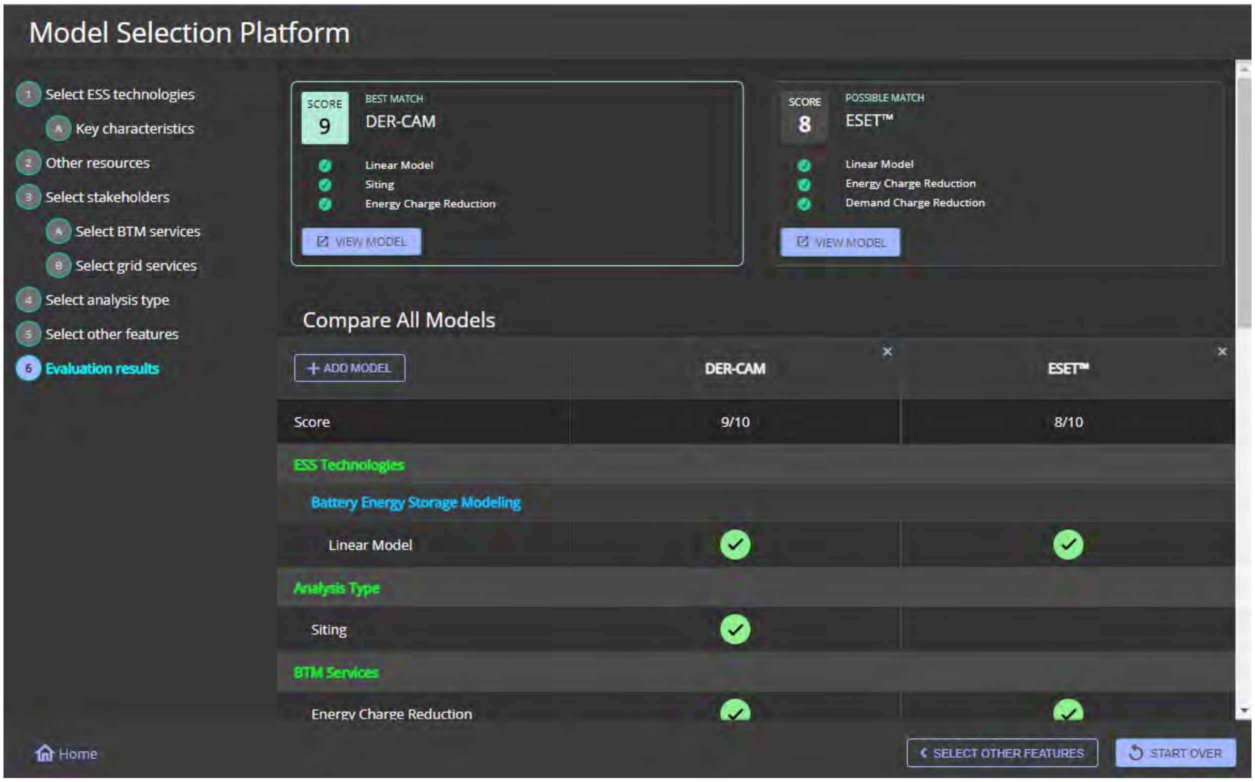


Figure 41: MSP Final Recommendation