Energy Research and Development Division

FINAL PROJECT REPORT

Validated and Transparent Energy Storage Valuation and Optimization Tool

Appendix D: StorageVET™ V1.0 User Guide

California Energy Commission
Edmund G. Brown Jr., Governor

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Appendix D

StorageVET™ V1.0 Software User Guide

User and Technical Documentation for the Storage Value Estimation Tool

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Principal Investigators
A. Cortes
G. Damato
B. Kaun

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This publication is a corporate document that should be cited in the literature in the following manner:

SOFTWARE DESCRIPTION

Software Description
This software is a publicly available, web hosted tool to help estimate the benefits and costs of energy storage in diverse use cases. The tool performs optimization and simulation of energy storage project dispatch for user-configured cases. The user has the ability to flexibly customize cases for different locations, project specifications, value objectives, and constraints. It is a price taker model which incorporates time-series loads, prices, and other information to run project simulations. The tool may utilize pre-configured data for reference scenarios or technologies, or the user may fully customize the case. It currently contains data customized for the California power market.

Benefits and Value
This simulation tool is publicly available, so it may be used by stakeholders to more clearly communicate the benefits and costs of energy storage in different instances. It is web-hosted, installed on a powerful, dedicated server, which avoids issues with minimum performance requirements. It enables the customization of energy storage projects for optimization, simulation, and financial analysis. This may help users to perform benchmarking of multiple project options. It may also support choice of energy storage project sizing and technology specifications, choose optimal location, and to maximize the operational value of existing energy storage projects through optimal

System Requirements
- Internet access
- Web browser – Google Chrome preferred
- Account setup is required – check www.storagevet.com for latest instructions.

Keywords
Cost-benefit analysis
Distributed energy resources
Energy storage
Integrated grid
Storage valuation
Storage modeling
EXECUTIVE SUMMARY

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StorageVET™ V1.0 Software User Guide: User and Technical Documentation for the Storage Value Estimation Tool

PRIMARY AUDIENCE: Energy storage project techno-economic analysts
SECONDARY AUDIENCE: Decision-makers for energy storage investment and operation

KEY RESEARCH QUESTION

Energy storage benefit-cost analysis has been historically challenging, due to the technology’s unique and diverse attributes, a limited field track record, and a rapidly developing policy and regulatory environment. This research seeks to develop and demonstrate analytical methods to produce credible estimates of energy storage project value for site-specific cases. It also seeks to provide an accessible, transparent, and validated platform for regulators, utilities, energy storage developers, and other stakeholders to engage in clear dialogue about the potential financial outcomes for energy storage projects and optimal operations.

RESEARCH OVERVIEW

A publicly available, web-hosted software model was developed to enable flexible characterization of energy storage projects of different characteristics, including size, location, and usage. This tool enables project lifecycle benefit-cost analysis and flexible, time-series simulation. It is a price-taker type of model, which means that it incorporates various constraints, both static and dynamic, and it optimizes energy storage dispatch based on the user-defined objectives, often referred to as services, on a rolling daily basis or other defined horizon. The tool provides the capability to investigate storage projects at all scales, from small residential systems to bulk-scale systems of tens of megawatts. The tool has certain limitations, depending on user objectives, that may be addressed by utilizing it in conjunction with other tool types, such as power flow models or production cost models. Initial incorporation of datasets supports valuation of energy storage in California and certain benchmark technologies. Research was supported by a grant from the California Energy Commission.

KEY FINDINGS

- Software is publicly available may be accessed, at no cost, by following instructions at www.storagevet.com (page ix)
- Software supports multiple energy storage analysis use cases including sizing, locating, and defining usage for energy storage projects (section 2)
- User interface provides option to interact with software via a web interface or through utilization of upload and download of MS Excel™ spreadsheet templates (section 4)
Technical information for modeling of energy storage value objectives and technologies is provided
Reference and test cases provide user support to get started (section 4)
A flexible model architecture supports resolution of diverse technological and grid-related constraints,
followed by energy storage scheduling optimization, dispatch, and financial analysis (section 7)

WHY THIS MATTERS
A robust and flexible tool is provided to enable communication of benefits and costs for energy storage
projects, to inform decision-makers and support optimized deployment of energy storage resources. A publicly
available, transparent model may serve as a touchstone to further advance and integrate a toolset for future
utility planning and operations processes which accurately consider energy storage.

HOW TO APPLY RESULTS
Interested users should visit www.storagevet.com to find most recent documentation and instructions for
access. The user guide provides instructions and test cases to support a user to get started with the tool.

LEARNING AND ENGAGEMENT OPPORTUNITIES
Access to the StorageVET subgroup of the Energy Storage Integration Council (ESIC) supports tool
and advancement and discussion of results. More info at www.epri.com/esic
Information pertaining to the latest project activities, training sessions, and new releases may be
tracked at www.storagevet.com

EPRI CONTACTS:
Ben Kaun, Senior Project Manager, bkaun@epri.com
Giovanni Damato, Technical Leader, gdamato@epri.com

PROGRAM: Energy Storage and Distributed Generation Program (Program 94)
STORAGENVET ACCESS

General Model Access Instructions
The user guide starts with key administrative instructions access to StorageVET™ online.

How to Use this Manual
☐ This user guide applies at the time of original release of StorageVET V1.0 in December 2016.
☐ The user guide is considered a living document.
☐ Instructions for accessing the latest user guide for all future releases of StorageVET can be found at www.storagevet.com.

Steps to Become a StorageVET User
The following diagram lays out the key steps to become a StorageVET user:

Request and Activate ESIC Collaboration Site Account at www.storagevet.com

Request Access to StorageVET at www.storagevet.com

Activate Analytica Cloud Player Account

Actively Participate in Using StorageVET

Figure SA–1
Key steps to become a StorageVET user

Activating your StorageVET Account
After processing a request for access to StorageVET at www.storagevet.com, an invitation email from auto@lumina.com will be sent to the user similar to the following:
From: Analytica Cloud Player <auto@lumina.com>
Sent: December 31, 2016
To: user@epri.com
Cc: storagevet@epri.com
Subject: Invitation to Analytica Cloud Player

Dear user@epri.com:

I invite you to be a Reviewer of the models in project 'StorageVET Live' online using the Analytica Cloud Player (ACP). Click this link below to access the project in ACP:

http://www.storagevet.com/login

LOGIN INFO

User name: user@epri.com
Password: randompassword
Group name: StorageVET

Thanks,
StorageVET Team
storagevet@epri.com

Figure SA–2
Sample email invitation from StorageVET

Follow the instructions contained in the invitation email to navigate to the StorageVET sever and activate the new account.

Logging into StorageVET Server

To access the StorageVET server online, navigate to www.storagevet.com/login in a web browser. To login for the first time, enter the user’s email account and temporary password assigned to the user in the invitation email:
Figure SA–3  
StorageVET sign in screen

First-time access StorageVET will take you to a password reset prompt. Follow the instructions on the screen to reset your temporary password on the next screen:

Figure SA–4  
Temporary password reset screen

After logging into StorageVET (and resetting the user password if applicable), the next screen will be a StorageVET Terms of Use splash screen similar to the following:
Figure SA–5
StorageVET Terms of Use splash screen

Review the Terms of Use and click the “Accept” button to proceed to the tool.

Opening a Model

Once the user is in the StorageVET tool, there is a project folder structure similar to Windows Explorer to navigate through project folders, StorageVET models, and import/export templates. The StorageVET project folder structure will look similar to this screen:
Click on one of the model hyperlinks in the folder to open a StorageVET model. In the example screen above, click on “StorageVET V1.0 User Guide.ana”. The model will take a few minutes to load and move onto the next screen that will look similar to the following:

From here, utilize the rest of this User Manual to navigate through the StorageVET model.

**System Requirements**

StorageVET resides on a server connect to the internet using Lumina Decision Systems’ Analytica Cloud Player platform. Therefore, system requirements are minimal:

- Web Browser (e.g. Chrome, Internet Explorer, Safari, or Firefox)
Internet Connection

Support

For the latest StorageVET support, go to www.storagevet.com, including troubleshooting requests.
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STORAGEVET SUMMARY

This section provides an initial overview of the objectives and capabilities of the StorageVET™ software.

Overview of StorageVET Objectives and Capabilities

StorageVET is a cost-benefit model for analysis of energy storage technologies and some types of aggregations of storage technologies with other energy resources. The tool can be used as a standalone model, or integrated with other power system models. StorageVET has the following key features:

- A highly detailed capability for energy storage project cost-benefit analysis
- Web-hosted tool, free to the public
- Open source tool availability
- Time-series dispatch optimization simulation
- Stacked services
- Ability to customize for location, sizing, use cases
- Ability to utilize hourly and subhourly data for California applications

Energy Storage Project-Specific Cost-Benefit Analysis

The fundamental use of StorageVET is to support understanding of energy storage project economics and operations. The tool is adaptable to many settings, including policy or regulatory analysis, commercial decisions (by a range of actors), infrastructure planning and research. With respect to costs, StorageVET incorporates realistic financial pro forma outputs which support analysis of project finance. With respect to benefits, it can calculate optimal market revenues or avoided costs associated with alternative infrastructure or resources. StorageVET can analyze many variations on storage services across a range of applications.

Web-Hosted Tool, Free to the Public

StorageVET is accessed online, and is freely available to the public.

EPRI provides user access via a log-in username and password combination, upon request by users. The StorageVET model is built on a third party software platform called Analytica™ by Lumina Decision Systems. Analytica™ is linked with a powerful optimization platform called Gurobi™. The model is then posted for usage on the Analytica Cloud Player (ACP). ACP allows a user to review and manipulate analysis inputs and outputs.

Figure 1-1 below illustrates the location and access of the StorageVET model.
A StorageVET user interacts with Analytica Cloud Player (ACP) on the server by configuring inputs to the StorageVET model and instructing it to provide specific outputs. The calculations to provide those outputs take place on the ACP server.

Users are provided with an account upon request and through registration in the Energy Storage Integration Council (ESIC). Latest access instructions can be found at www.storagevet.com.

StorageVET is hosted on a high performance computing server.

The architecture chosen provides accessibility and feasibility to host models online and to provide updates and bug fixes to the model in a centralized location. This also allows users to save cases to a server-hosted project folder and use default model configurations. This is expected to facilitate collaboration and discussion related to the benefits and costs of energy storage and approaches to modeling.

StorageVET may experience solution problems which result from loss of internet connection, server error, ACP-related error, StorageVET model issues, or user input errors. At the same time, the user computer serves only as an interface for providing inputs and outputs to the tool, so the user computer capabilities should not impact the performance of StorageVET runs.

Future Open Source Release

EPRI intends to release StorageVET as an open source tool, posted to Github (www.github.com) or similar site. The objective is to refine and release “desktop version” of the Analytica file so that the user community may revise the model code and create derivative works, with encouragement to offer the code back to EPRI to improve the version posted on ACP. Additionally, users may choose to use proprietary data in the model without concerns about utilizing a shared, external server. It should be noted that use of a local version of StorageVET will require purchase of an appropriate license of Analytica Power Player™ with Optimizer or Analytica Optimizer™, depending on whether the user would like to run the model or revise the
model, respectively. More information on minimum requirements for running or editing StorageVET will be provided upon release of the open source code.

**Time-Series Dispatch Optimization Simulation**

StorageVET is designed to calculate optimal dispatch of energy storage projects, within a default or user-specified environment. Therefore, it incorporates time-series data on loads and prices of interest to the use case for energy storage. These data can be either on an hourly or 15-minute basis, depending on the application. In addition to many static technology parameters, it also incorporates certain energy storage time-dependent variables, notably tracking of state of charge.

Due to the large number of expected users, and potentially a number of simultaneous users, the developer sought to maintain linear optimization wherever possible for optimal scheduling of storage dispatch. That is, StorageVET was developed to avoid mixed integer programming (MIP) and nonlinear optimization where possible to reduce computing intensity and support higher levels of usership. However, StorageVET has the capability to run MIP and nonlinear optimizations which may be configured and released in a future open source release.

**Calculation of Joint or Stacked Services**

Energy storage technologies can be connected in three domains: the transmission system, the distribution system, and customer-sited. Depending on the location, and applicable regulatory or market rules, energy storage technologies are typically capable of offering a wide range of services, include those related to the wholesale market, distribution planning and operations, and customer-sited uses. When storage can provide these services jointly, the resulting values from each service are “stacked” on each other to achieve the total value. In these calculations, it is critical not to “double-count” the uses of the storage project. When the user selects services for analysis, StorageVET evaluates compatibility and prioritization of different services when developing the stacked valuation. Compatibility and prioritization have a few key dimensions to consider, including:

- **Location-Related**
  Certain services are only accessible at certain locations. For example, customer bill savings related services require a location behind the customer meter. Distribution or customer connected systems may be able to sell wholesale services but only after reservation of storage capacity needed for distribution services. StorageVET respects all such limitations, but can also be used to evaluate combinations of applications which may be physically feasible but not allowed under current market or regulatory rules.

- **Time-Related**
  Due to the potential for multiple services, some of which require concurrent operations and others which do not, StorageVET can disaggregate constraints and compile them into power and energy reservations or constraints at the energy storage point of interconnection. These reservations and constraints need to be applied during the time periods when the storage device is allowed to operate and ensure that the device does not operate beyond allowed limits in other time periods.

- **Prioritization in Selection Among Applications**
  In many applications, the storage device will provide certain services or uses which have a priority over other services. For example, the system operator may want to ensure that the
device is available for discharging during peak load periods (as a resource adequacy capacity resource) regardless of what energy market prices are in those periods. Similarly, for a device providing distribution deferral or customer retail rate management, there may be residual opportunities for providing wholesale services which cannot violate the primary uses. There are many such possibilities. StorageVET prioritizes among services when optimizing storage operations.

**Customizable for Location, Sizing, Use Cases**

StorageVET allows the user to conduct sensitivities on location, size, and use-cases until an optimal set of these attributes is identified. While the tool does not endogenously calculate optimal size, it can be used iteratively to identify an optimal size given the inputs.

**Data Options**

StorageVET includes certain pre-loaded data and users can upload their own data, as long as it is compatible with the time-series definitions. While the model has been developed for California applications, it can also evaluate similar services in other regions. The pre-loaded California data includes several years of hourly and subhourly wholesale historical and forecast market prices at a zonal level and load information sourced from the California Independent System Operator (CAISO). It also includes tariff structures for certain groups of California retail customers which have the potential to benefit from energy storage, particularly those with significant demand charges or time-of-use (TOU) energy rates. The data sets include illustrative load shapes for customers and distribution loads.

The pre-loaded data is accurate and useful for illustrative purposes, but generally is not sufficient to evaluate projects located at one of the over 3000 CAISO energy pricing nodes or specific distribution level applications. Finally, cost and performance information is provided by EPRI from recent cost studies to provide default characteristics (EPRI 3002008877). ESIC provides templates for supporting the collection of data related to energy storage cost and specification. Latest versions can be found at www.epri.com/esic.

**Compatibility with Other Tools**

StorageVET can interface with other tools that complement its capabilities and offer a more complete picture of energy storage benefits, costs, objectives, and constraints. It is currently being used for research that interfaces the tool with distribution-level power flow modeling and production cost modeling tools. In general, a modeling framework which utilizes StorageVET in tandem with these other types of tools, will use the power system model to calculate prices or operational constraints for use within StorageVET, while StorageVET will be used to determine feasible storage operational schedules which can be used in the power system model.

When interfacing with distribution power flow modeling tools, the specific analytical process could be:

1. The power flow model is used to characterize locational and time-varying constraints on the distribution feeder relevant to storage operations,
2. Those constraints are incorporated into StorageVET optimization of storage project operations,
3. The resulting storage dispatch from StorageVET is incorporated back into the power flow hosting model to validate the storage solution abides by all constraints applied and that there are no second-order violations. Also, this may enable the refinements of understanding for asset loading and distribution-related energy losses.

When interfacing with production cost modeling tools, there are several variations. First, production cost models are typically used to determine system operations, emissions, aggregate production costs and hourly marginal prices for certain market services in future scenarios. The resulting hourly prices can then be used in StorageVET to calculate future storage value across a range of applications. Second, the production cost model may have certain modeling limitations which can be partially addressed by using StorageVET and possibly other tools. For example, these models typically do not represent distribution level networks or customer-sited uses of storage, and hence cannot be used to determine constraints on storage operations resulting from those applications. Another example is that they typically have an internal storage technology representation which does not incorporate as many constraints as StorageVET. In these types of uses, StorageVET could similarly be used to clarify the likely dispatch by the storage device, and returned to the production cost model.

In addition, StorageVET could interface with many other types of models or tools. In all these joint model applications, the uses of StorageVET will evolve over time. EPRI will make available additional methodological details as they are available.
2

STORAGEVET USE CASES

Introduction

This section provides an overview of the StorageVET model and its intended uses. The section is organized around two ways to deploy StorageVET: (1) as a standalone model, or (2) integrated with other models, notably production cost models and power flow models commonly used for power system analysis. The section also explains certain strengths and limitations of StorageVET in both these approaches.

Within each category, the tool has a number of different uses. As a standalone model, the section reviews four types of uses: estimation of project benefits and costs; comparison of project options, optimization of project specifications; and optimization of project operations. When integrated with other models, and utilized iteratively, the tool could still be used in these prior types of uses, but can also be deployed to examine planning functions, including hosting capacity analysis and long-term resource and transmission planning, including economic valuation.

At the end of this section, there is a set of annotated references which the user can refer to for illustrations of uses of models like StorageVET and the interface between such models and other power system models. We do not necessarily endorse the findings in these papers, but they can be referred to for methodological purposes.

Goals and General Uses of StorageVET as a Standalone Model

We define StorageVET used as a standalone model as any use in which the user utilizes a set of fixed inputs in the model, and does not have to consider how the resulting operations of the storage technology will impact the power system or electricity markets. The fixed inputs could come from historical data or forecast data.

Use #1: Estimate Project Benefits and Costs

A user desires to determine the potential benefits and costs of an energy storage project given its location, size, and services available. This functionality may be useful for various potential investors of energy storage, including utilities, project developers/independent power producers, and electricity end-use customers. It may also be valuable for regulators reviewing investment decisions.

The steps a user follows to perform this use case are:

☐ Step 1: Provide StorageVET own data, and/or utilizes default data captured within the software, including energy storage project cost and performance, services and value streams addressed, and other location-specific and financial information.

☐ Step 2: Run simulation to determine optimized project operations under user-defined configuration for services, priorities, and time

☐ Results: Review financial results including net present value (NPV), benefit-to-cost ratio, optimized storage operation schedule, and other financial and technical outputs
Use #2: Compare Project Options

A user desires to compare multiple potential projects on a consistent basis. Differences between projects may be the project specification, location, or services addressed. This may be valuable to investors or regulators which desire to benchmark multiple project options while using an equivalent set of assumptions and modeling methodologies.

The steps a user follows to perform this use case are:

- Step 1: Provide StorageVET with own data for multiple project sites using StorageVET Case Definition Spreadsheet (a Microsoft Excel®-based spreadsheet tool to fully define a case for modeling)
- Step 2: Run batch of simulations to determine optimized project operations under user-defined configuration for services, priorities, and time
- Results: Review financial results including net present value (NPV), benefit-to-cost ratio, optimized storage operation schedule, and other financial and technical outputs. StorageVET will also rank and evaluate project options by output metrics of interest to user or decision-maker

Use #3: Optimize Project Specification

A user desires to determine the optimal characteristics for specifying a project specification, location, or services addressed. This may be valuable to investors choosing from a group of potential projects, or to an energy storage project or technology developer, attempting to design product options with the greatest potential.

The steps a user follows to perform this use case are:

- Step 1: Provide StorageVET with own data for a base case that represents the user’s guess for an appropriately configured and sited project
- Step 2: Develop hypothesis for an improved energy storage project specification, location, or services and provide data for a second case, which alters one variable or batch of variables
- Step 3: Run simulation
- Results: Review results of interest
- Step 4: Choose case result with more desirable results
- Step 5: Develop a new hypothesis, input data, run, review results
- Step 6: Repeat until optimal or user acceptable result is reached

Use #4: Optimize Project Operations

StorageVET uses actual or forecasted pricing and load data to simulate real operating conditions, and advanced optimization techniques are used to generate optimal dispatch. The optimization framework implemented in StorageVET allows modeling operating constraints inherent to the storage system, such as interconnection constraints, as well as those related to the operating specifications, such as control actor, interaction with solar PV, energy exchange with the grid, and reliability service reservations.

The user will perform the following steps for this use case:
Step 1: Provide StorageVET with project-specific data, including locations, technology specification, and contracted or desired services.

Step 2: Run a simulation to determine the optimized project operations, more specifically, what services the project should provide at any given time.

Results: The use case produces the optimized storage operation schedule, and related financial and technical outputs.

**StorageVET Limitations as Standalone Tool**

**Price Taker**

StorageVET is a price taker model, in that it uses already determined market prices (or costs) as an input but does not determine how the resulting storage dispatch might affect those prices. These prices could be historical prices from the wholesale market, or forecast prices.

An interpretation of this approach is that the storage device is a very small or “marginal” resource and hence has a small, non-measurable impact on the market or power system.

StorageVET can also be used in tandem with models of the power system to develop inputs into those models, or to calculate the benefits of a marginal storage resource in different power system scenarios. In these applications, StorageVET is still a “price-taker”, but can iterate with another model which can determine impacts of the storage resources on the market or system operations (see discussion below).

**Static Time-Series Load Simulation**

For the same reason that it doesn’t model impacts on market prices, StorageVET also does not model effects of the storage system on exogenous loads, or other elements within a transmission/distribution system, such as power flow or voltage control. Load effects, and interaction with transmission/distribution circuits are modeled as data time-series that are included as requirements for the storage system operation.

StorageVET does not model or simulate transient behavior at circuit level, such as frequency/voltage stability. The tool only models power and energy balances over time.

**No Direct Measurement of Societal Benefits**

**Emissions Benefits/Costs**

Storage resources will affect greenhouse gas emissions by altering the operations of conventional, fossil generation. However, because it doesn’t model the impacts of the storage resource on other generators, StorageVET does not calculate the costs and benefits of the project in terms of increased or decreased emissions. These benefits would be derived from power system models.

**System Production Cost Portfolio Impacts**

Storage resources will also affect non-market priced aspects of power system operations and markets, such as improving the efficiency of generation commitment and dispatch. The resulting avoided costs, such as generator start-up costs or minimum load costs, could be significant in some scenarios. These benefits would be derived from power system models.
Others

StorageVET does not perform storage sizing endogenously within the model. To perform this calculation, the user would run sensitivity analysis over varying parameters that might allow for optimal sizing by evaluating a set of alternatives and providing information on their value.

Using StorageVET with Other Tools

The use of StorageVET with other power system modeling tools opens a further range of potential uses, particularly in resource planning processes in distribution and transmission systems. Two commonly used power system tools in storage integration studies are production cost models and power flow models. These model types are discussed in this section.

Using StorageVET with Production Cost Modeling

Power system economic and operational models require consideration of supply, demand, storage and transmission at various levels of spatial and temporal resolution, along with simplification of actual constraints (most commonly, linearization of non-linear constraints), with the capability to track generation and non-generation resource operations over time to ensure steady-state operational feasibility and measure operational costs and revenues. A particular class of these models used to evaluate resource or portfolio operations and economics is called “production cost models” (PCM). PCM are used to simulate a period of operation (typically a year) and focus on the commitment and dispatch of all resources on the system at some temporal granularity (typically hourly) to meet the load at least cost while obeying numerous generation, operating reserve, and transmission network constraints. The results of these tools represent anticipated energy usage throughout the period as well as system and individual technology or portfolio costs and revenues/profits. The results can be extremely useful for energy storage valuation as costs and both energy and ancillary service revenues can be captured.

These types of models have been available for decades, but have undergone additional refinements to accommodate more services and improve both short-term and longer-term market and operational forecasting. In addition, some software packages include market bid curves using ISO-released data, and hence can be used for near-term market price forecasts. Historically, these models were primarily deterministic, in that they evaluated a single load forecast and assumed perfect foresight over the time-horizon for generator operations. More recently, additional stochastic elements have been introduced, both in determining the inputs to the models and in adding types of uncertainty to the sequence of commitment and dispatch operations.

There are many recent examples of storage studies using production cost models, including [1], [2], [3], [4]. Some of these are discussed further below.

Flow Chart Conceptual Methodology

Figure 2–1 illustrates the interface between production cost models and StorageVET or similar tools. On the left hand side, the production cost model is used to generate inputs for use in StorageVET, which can further refine the storage value calculation. StorageVET could be used to develop production profiles which capture constraints not in the production cost model (such as distribution deferral constraints) before the storage system is modeled in the production cost model. These functions are described further below.
Figure 2–1
Conceptual framework for StorageVET usage with production cost modeling

Use PCM to Generate Time-Series Price Data for StorageVET to Use

Production cost models are one method to calculate future aggregate production costs and marginal prices in each time interval being modeled on the power system, under different scenarios for fuel costs, resource mix, market scope and other factors. As StorageVET, does not model power systems, it must rely on other models to generate price forecasts which can be used to estimate future value of storage.

StorageVET includes some representative future energy prices calculated using production cost models.

Using StorageVET Outputs to Configure Production Cost Modeling Runs

In these uses, StorageVET would be used to adjust storage capacity (MW) available for dispatch to reflect storage operational or economic constraints not captured in the production cost model, or to represent market rules which could result in different types of market operations for different storage technologies (e.g., limited energy vs. longer duration). There could be a number of these types of uses, of which we mention a few here.

Generally, production cost models adapt their existing pumped storage model representations to evaluate other types of storage at the bulk level. The pumped storage representations typically do not include certain types of storage technology constraints which might apply to other technologies, such as effect on project life of the number of cycles when providing certain services or other constraints. StorageVET could be used to adjust the value of the storage device resulting from the production cost model *ex post* to reflect these additional constraints.

In other cases, the decision about storage applications in the production cost model may depend on market rules which can be better assessed initially with StorageVET. For example, in the
CAISO, while there is one frequency regulation control signal, there are several participation models for providing Regulation, with different methods for determining the quantity of eligible Regulation capacity (see EPRI, *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model*, [5], chapters 6 and 9) submitted into the day-ahead market. StorageVET could be used either to help determine the capacity of the storage resource assumed to be available in the production cost model, or to help check the allocation of the storage resource’s capacity to Regulation resulting in the production cost solution.

Another use is to determine operational constraints for storage technologies providing multiple-use applications. For example, for a device providing distribution upgrade deferral and wholesale services, production cost models would need inputs on hourly constraints on storage operations due to these sub-transmission operating constraints.

**Using StorageVET with Power Flow Modeling**

StorageVET can leverage the results of power flow modeling and analysis tools. It is done via an iterative process in which the power flow modeling tool can generate operational constraints that the StorageVET project must follow. The process is subject to iterative redesign of the constraints that are input, to force the operation to satisfy the operational requirements.

![Conceptual framework for StorageVET usage with power flow modeling](image)

Figure 2–2  
Conceptual framework for StorageVET usage with power flow modeling

StorageVET has functionality to import time-series of constraints on the power/energy variables of the storage system, as well as the ability to export the calculated dispatch variables. This enables the two-way communication required to perform the iterative operation design.
Additional References

The following additional references can be used for further information on energy storage modeling available in StorageVET on both a stand-alone basis and through integration with other tools. Full references and links can be found in the reference section at the end of the document.

Electric Power Research Institute (EPRI), Integrated Grid: Cost-Benefit Framework [6] – although not developed specifically for StorageVET, this publicly available EPRI report provides a comprehensive analytical framework for valuation of resources at all levels of connection on the electric power system.

Energy Storage Integration Council (ESIC), Cost-Benefit Analysis of Distribution-Connected Storage Projects: Analytical Frameworks, Models and Tools – a detailed forthcoming guide to the selection of storage modeling tools, by type of model, as well as to the interpretation of model results; this includes extensive discussion of optimization models for analyzing storage technology operations and economic benefits such as StorageVET.

The following references are all studies of California:


DNV-GL, Energy Storage Cost-effectiveness Methodology and Results, August 2013 [8] – analysis of several energy storage applications in California using both production cost models and subhourly operational models to evaluate costs and benefits.


The following references have useful methodological review:


3

USER INTERFACE

Getting Started
The StorageVET user interface (UI) consists of a web interface on Analytica Cloud Player (ACP) and various Microsoft Excel-based import/export templates.

ACP has a login page and project folder structure for each user. The StorageVET model and shared reference cases are the same for all users. Each user also has access to a private folder to store StorageVET model snapshots and saved import/export Excel files.

The Excel-based templates assist the user with collecting and uploading the various scalar and time series data items beyond the reference data pre-loaded in the StorageVET model. The Excel templates also enable an efficient way to export model results, including a snapshot of the model input settings associated with the results.

Overview
The ACP UI contains certain features with which a user should be familiarized prior to using StorageVET. This section provides a snapshot of the StorageVET UI, which highlights the following elements:

- Major tab
- Subtab
- Mouseover description
- Input data table
- View data button
- Drop-down data selection

These elements of the StorageVET UI are highlighted in Figure 3-1 below.
Major Tab

Major tabs reside on the top row of the ACP UI for StorageVET. These contain the major categories for user inputs and outputs to the model. Typically, the user should start on the left tab and sequentially move right through model configuration and results.

Subtab

Subtabs provide navigation to more granular categories of inputs and outputs in the model. They are nested within the major tabs.

Mouseover Description

Mouseover descriptions are value information for the user to understand the purpose of different major tabs, subtabs, and user input and output fields. The user may simply hover the mouse over a word. If there is a description, a window will pop up with further information to support clarity.

Input Data Table (’Edit Table’)

In certain cases, a particular input field may have a table underlying it. If a button says “Edit Table”, a user click will cause a new table to appear in the white space to the right side of user inputs. Depending on the nature of the input, the user may access selection check boxes or have the ability to enter numerical parameters.

View Data Button (’Calc’)

The ‘Calc’ button works similar to the ‘Edit Table’ button, in that it causes data to pop up on the right side of the UI screen. The difference is that a ‘Calc’ button will cause data to display for the
user to understand more about the current selection. This is useful for a user who wants to double-check that they have appropriately configured the model before doing a run.

**Drop-Down Data Selection**

The user interface provides multiple drop-down lists to allow for the user to select pre-loaded data sets or to select options from a multiple choice list provided by the model developers. This is important for data selections which are not continuously variable.

**User Interface Category Overview**

There are nine major tabs in the UI:

- **Help** contains instructions for interacting with model in the ACP environment.
- **Quick Start** enables users to select from a collection of pre-loaded reference cases or previous user-saved cases that have a full set of input values and settings to run the model and review results quickly. The user can then go through the model tabs and make individual input value changes to modify the case to produce additional, refined results.
- **Service Selection** facilitates the selection of grid services. Grid service choices are available based on grid location and control actor.
- **Transmission, Distribution, and Customer Service Configurations** allow the user to define grid services, reservations, and constraints for each of the three categories. This includes but is not limited to service prices, loads, and service reservation definitions.
- **Project Specification** includes technology type selection, technical parameters, costs, and constraints for a project. This is also the location of specification for PV located at the project site.
- **Financial Inputs** organizes inputs for ownership structures, financing and tax assumptions, incentives, and cost test parameters.
- **Results** houses the technical and financial outputs of the model. Technical outputs are generally organized as time series reservations, dispatch, state of charge evolution, net load, and revenue. The financial results contain summary cost-benefit analysis, cost test results from various perspectives, and pro forma cash flow statements.
- **Data & Scenarios** contains the model infrastructure for generating the Excel-based templates for user data collection and upload. This is also the location to download model results in Excel format. Users can construct scenarios for side-by-side scenario comparison and sensitivity analysis.
- **StorageVET MS Excel Input Spreadsheets** In addition to the web user interface, spreadsheet templates have been developed to facilitate the data gathering and post-processing of data online, utilizing the same general tabs and structure as the web user interface.
The key import/export spreadsheet interface is the Case Definition Spreadsheet feature. To navigate to the Case Definition Spreadsheet functionality, go to Data/Scenarios → Case Definition Import/Export here: Three separate templates may be used with StorageVET.

The first spreadsheet is required for the entry of time-series data.

**Spreadsheet #1–Time-Series Data**

Time-series data for loads, prices, and other information is very important for scenario customization. One spreadsheet template is specifically developed to support upload of this data, typically in hourly or 15 minute time steps. After upload, the time-series data becomes accessible in the associated drop-down menus.

**Spreadsheet #2–All Other Scenario Data**

A second spreadsheet contains similar data input fields as provided in the web user interface.

**StorageVET MS Excel Output Spreadsheet**

A third spreadsheet enables download of certain technical and financial results of simulations. This spreadsheet enables post-processing and analysis of results data offline.
4

REFERENCE CASES FOR STORAGEVET

This section lays out three key reference cases for energy storage in StorageVET. Note that general model access instructions are contained in the front matter of this User Manual.

The reference cases are primary differentiated by the grid location of each case:

☐ Reference Case #1: Transmission-Connected Storage
☐ Reference Case #2: Distribution-Connected Storage
☐ Reference Case #3: Customer-Sited Storage

To help users become familiar with StorageVET more quickly, the three reference cases have been included in the model. These reference cases can be loaded into the model using the “Quick Start” feature described below.

After loading a Reference Case using the Quick Start, the user can navigate throughout the model to review and adjust case the detailed case parameters and run detailed model results. The user can also utilize the spreadsheet interface feature of the model to import and export case settings, scenario data, and modeling results. Navigating these model features are also described below.

Using Quick Start to Run Reference Cases

Each case can be accessed and loaded into the model through the User Interface (UI) feature called the “Quick Start”. The Quick Start is located in the second main tab of the model. Key pieces of the Quick Start are illustrated in the screen shots stepped through below.

The first step is to click on the “Quick Start” main tab to display the following screen:
Heading to the “Reference Case Selection” area, click the “Select Case” pull down menu to display the list of Reference Cases to choose from and click on “Ref Case #1: Transmission Storage”:

Figure 4–2
Select a Reference Case in Quick Start
This loads the reference case into the model, which populates all the input variables in the model using a model snapshot file. For “Ref Case #1: Transmission Storage”, key case parameters can be viewed by clicking on the “Calc” button next to “Selected Case Summary”. The summary displays in the right hand pane:

Figure 4–3
Display Selected Reference Case Summary Details in Quick Start

The other buttons on the Quick Start display various other summary case setup and results for the selected reference case. For example, selecting “NPV Cost/Benefit Chart” produces the following result in the right hand pane that summarizes the CBA for the reference case:
Figure 4–4
Example Display of Results in Quick Start

By reviewing the reference case examples below, additional UI instructions can be found.

Reference Case #1: Transmission-Connected Storage

Case Description

Reference Case #1: Transmission-Connected Storage represents a 20MW, 4h duration generic lithium-ion battery connected to the grid at the transmission level in CAISO service territory. The storage system provides day-ahead energy and ancillary services to the CAISO system in addition to providing resource adequacy.

Case Setup

Following the steps laid out above in *Using “Quick Start” to Run Reference Cases*, navigate to the Quick Start feature, head to the “Reference Case Selection” area, click the “Select Case” pull down menu to display the list of Reference Cases to choose from and click on “Ref Case #1: Transmission Storage”: 
Select Reference Case #1: Transmission-Connect Storage in the Quick Start

Once Reference Case #1 is selected, use the Quick Start feature to generate and view the case summary, selected services, and results—including both technical and financial outputs.

Below is an example output from Reference Case #1 of the Storage Activity Summary:
Example Storage Activity Summary Results Display in the Quick Start

**Navigate Case Settings**

While summary reference case input data and settings can be displayed in the Quick Start, the Project Specs, General Settings, Transmission, Distribution, Customer, and Financials main tabs contain significantly more details about the reference case parameters in addition to the ability to change the input fields in the UI. For example, going to the Project Specs → Storage Parameters and clicking on the “Sub Table” button in the “Technology Parameter Input” field displays the input table to in the right hand pane.

![Image of Technology Parameter Input Table Display](image)

**Figure 4–7**

**Technology Parameter Input Table Display**

The table can be used to review technology parameters as well as change individual inputs in the table as necessary for a specific case.

In addition to the technology parameter table, there is a “Cycles vs. Depth of Discharge” table available for specifying cycle life degradation:
Figure 4–8
Cycles vs. Depth of Discharge Input Table

The General Setting ➔ Service Selection subtab allows the user to select the following:

- Grid Location
- Primary Control Actor
- Grid Service Selection
- Market Service Territory

Using Reference Case #1, the screenshot below illustrates the Grid Service Selection Table:
Select services to consider in the model by using the checkboxes. Note that the checkbox availability for each grid service is dependent on the Grid Location and Primary Control Actor selections.

To view and select the wholesale market services, first navigate to Transmission ➔ Day Ahead subtab and click the “Calc” button to display Day Ahead Energy Price Selection:
Figure 4–10
Day Ahead Energy Price Selection Display

The same type of display can be utilized for the Ancillary Service Price Selection. Navigate to the other subtabs, such as Transmission → Resource Adequacy Capacity (RA), to view more market service settings.

For review and edit of the financial assumptions, navigate to Financial → Ownership Model subtab to select the Ownership Model Configuration, Project Debt Structure, and Taxes/Inflation assumptions:
Figure 4–11
Ownership Model Financial Assumptions Screen

Other financial assumptions can be set in the Financials → Incentives and Financials → Transfers subtabs

Results Display

Model results details are run and displayed using the Results main tab. The first subtab, Results → Dispatch and Operational Results contains the primary technical results of the model. For example, click on the “Result” (or “Calc”) button of the Storage Activity field to view the results of the storage activity in the right hand pane:
Figure 4–12
Storage Activity Summary in the Dispatch and Operational Results

To view various days of dispatch throughout the set of simulated years, use the ACP table menu buttons above the results table display. Other detailed results outputs can be displayed by clicking the “Calc” or “Result” buttons next to the result field of interest.

For viewing detailed financial results, navigated to Results → Financial Results. On this subtab, click the “Calc” buttons to display the various Cash Flow and Financial Metric outputs. For example, below is the Reference Case #1 Pro Forma Cash Flow output:
Customizing the Case

After walking through the above Reference Case #1 using the pre-loaded setting with the Quick Start feature, explore customization of the case. Any input in the Project Specs, General Settings, Transmission, Distribution, Customer, and Financials main tabs can be edited by the user to create a new model case with new results.

Examples of case customization include but are not limited to the following:

1. Change the Technical Parameters Input Table items
2. Select a different set of grid services
3. Select different CAISO wholesale market prices and loads
4. Change the ownership model and financial assumptions
5. For additional customization, refer to the Spreadsheet Interface Section below

Reference Case #2: Distribution-Connected Storage

Case Description

Reference Case #2: Distribution-Connected Storage represents a 2MW, 2 h duration generic lithium-ion battery connected to the grid at the distribution level in CAISO service territory. The storage system performs a distribution asset upgrade deferral while provides day-ahead energy and ancillary services to the CAISO system in addition to providing resource adequacy.
**Case Setup**

Following the steps laid out above in *Using “Quick Start” to Run Reference Cases*, navigate to the Quick Start feature, head to the “Reference Case Selection” area, click the “Select Case” pull down menu to display the list of Reference Cases to choose from and click on “Ref Case #2: Distribution Storage”:

![Select Reference Case #2: Distribution-Connected Storage in the Quick Start](image)

Once Reference Case 2 is selected, use the Quick Start feature to generate and view the case summary, selected services, and results—including both technical and financial outputs.

Refer to the Reference Case #1 section above for more Quick Start feature utilization.

**Navigate Case Settings**

Reference Case #2 navigation of case settings in the Quick Start, the Project Specs, General Settings, Transmission, Distribution, Customer, and Financials main tabs is similar to the steps above in Reference Case #1.

Specific to Reference Case #2, the settings for distribution asset upgrade deferral are located in the Distribution → Deferral subtab:
For Reference Case #2, a 15MW Sample Feeder load is preset in the model with a 1%/yr growth rate and the asset being deferred has an upper threshold of 14,300kW.

**Results Display**

Reference Case #2 navigation of results is similar to the steps noted above in Reference Case #1. Specific to Reference Case #2, the results for the deferral can be found in Results → Deferral Results. For example, click the “Calc” or “Result” button for Discharge Capacity Requirement to display the deferral requirement in the right hand result pane:
Figure 4–16
Deferral Discharge Capacity Requirement

Other deferral requirements and outputs can be displayed by clicking the “Calc” or “Result” buttons next to the result field of interest on this subtab.

Reference Case #3: Customer-Sited Storage

Case Description

Reference Case #3: Customer-Sited Storage represents a 100kW, 2h duration generic lithium-ion battery connected to the grid at a commercial customer site in PG&E service territory. The storage system performs retail energy time shift and demand charge management.

Case Setup

Following the steps laid out above in Using “Quick Start” to Run Reference Cases, navigate to the Quick Start feature, head to the “Reference Case Selection” area, click the “Select Case” pull down menu to display the list of Reference Cases to choose from and click on “Ref Case #3: Customer Storage”:
Figure 4–17
Select Reference Case #3: Customer-Sited Storage in the Quick Start

Once Reference Case 3 is selected, use the Quick Start feature to generate and view the case summary, selected services, and results—including both technical and financial outputs.

Refer to the Reference Case #1 section above for more Quick Start feature utilization.

Navigate Case Settings

Reference Case #3 navigation of case settings in the Quick Start, the Project Specs, General Settings, Transmission, Distribution, Customer, and Financials main tabs is similar to the steps above in Reference Case #1.

Specific to Reference Case #3, the key settings for customer-sited storage are located in the Customer → Retail Load and Tariff subtab:
For Reference Case #3, a sample Commercial/Industrial (C&I) load is preset in the model with a 1%/yr growth rate with a peak demand of approximately 600kW.

Results Display

Reference Case #3 navigation of results is similar to the steps noted above in Reference Case #1. Specific to Reference Case #3, the results for the retail energy and demand charge management can be found in Results → Customer Site Impacts. For example, click the “Result” button for Net Retail Bill Summary to display the net retail bill in the right hand result pane:
Figure 4–19
Customer-Sited Net Retail Bill Summary Screen

Other deferral requirements and outputs can be displayed by clicking the “Calc” or “Result” buttons next to the result field of interest on this subtab.

Utilizing the StorageVET Spreadsheet Interface

StorageVET includes various paths to import and export modeling input data and results. The key import/export spreadsheet interface is the Case Definition Spreadsheet feature. To navigate to the Case Definition Spreadsheet functionality, go to Data/Scenarios → Case Definition Import/Export here:
Figure 4–20
Spreadsheet Interface: Case Definition Import/Export Screen

The four key functions of the Case Definition Spreadsheet include the following:

1. Case Definition Naming
2. Saving Case Definitions via creation of a model snapshot of settings
3. Import Case Definitions to StorageVET
4. Same Blank Spreadsheet Template

To begin, use the Case Definition Naming Fields to assist with uniquely identifying the spreadsheet for feature reference by filling out the following:

- Sensitivity Run Name
- Base Case Name
- Model Filename
- Project Name

Once the case is named, click on the “Save to Spreadsheet” button under “Save Case Definition from Current Model Settings” to open a dialogue box to save the spreadsheet to the ACP Project Folder:
In general terms, the Case Definition Spreadsheet is formatted in Excel to mirror the UI tab, subtab, and input/outputs in the ACP version of StorageVET:

Follow the instructions embedded in the Case Definition Spreadsheet to navigate and interpret the workbook template.
**Additional User Help**

As mentioned in the introduction to this User Guide:

1. This user guide applies at the time of original release of StorageVET V1.0 in December 2016.
2. The user guide is considered a living document.
3. Instructions for accessing the latest user guide for all future releases of StorageVET can be found at www.storagevet.com.

In addition to the user guide and its future releases, the following resources can be accessed online at www.storagevet.com:

1. Listing of the latest model updates and version releases
2. FAQ
3. Additional model feature help
4. Additional reference case guides
5. Access to related documentation from EPRI, ESIC, and other relevant valuation efforts within the energy storage industry
   a. EPRI member site (for free docs)
   b. ESIC collaboration site
   c. Links to other relevant sites/material on www.storagevet.com
ENERGY STORAGE VALUATION AND DRIVERS

Introduction

StorageVET considers most of the potential sources of revenue accessible to a storage project according to the location, technology, and perspective of the storage operator.

Services are defined by the StorageVET services list, which is presented in Table 5-1. Note that some of these services are unique to the CAISO market (notably the Flexible Ramping Product), whereas others are found in other US wholesale markets.

Table 5-1
Overview of grid services

<table>
<thead>
<tr>
<th>Domain</th>
<th>Timing of Decision</th>
<th>Grid Service Category</th>
<th>Grid Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>3 years to months ahead</td>
<td>Resource Adequacy</td>
<td>Resource Adequacy (Generic and Flexible)</td>
</tr>
<tr>
<td></td>
<td>Day-ahead to real-time</td>
<td>Energy and Ramping</td>
<td>Day-Ahead Energy Time-Shift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ancillary Services</td>
<td>Frequency Regulation, Spinning Reserve, Non-Spinning Reserve</td>
</tr>
<tr>
<td>Transmission</td>
<td>5–15 years ahead</td>
<td>Transmission Planning</td>
<td>Transmission Capacity Investment Deferral</td>
</tr>
<tr>
<td></td>
<td>Months ahead to real-time</td>
<td>Transmission Operations</td>
<td>Transmission Voltage/Reactive Power Support</td>
</tr>
<tr>
<td>Distribution</td>
<td>3–10 years ahead</td>
<td>Distribution Planning</td>
<td>Distribution Capacity Investment Deferral (Load Growth)</td>
</tr>
<tr>
<td></td>
<td>Day-ahead to real-time</td>
<td>Distribution Operations</td>
<td>Distribution Voltage/Reactive power support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Backup Power</td>
</tr>
</tbody>
</table>

Service Categories

This section briefly describes the services listed in Table 5-1 and how each service is implemented in StorageVET.

This section is an excerpt or summary of a larger EPRI report prepared for StorageVET users on the rules and requirements of each service in California, Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to StorageVET™ Model [5] (also available on www.storagevet.com). A section from the report is highlighted at the end of the description for each service to help reader navigate the information.
**Generation**

**Resource Adequacy**

Resource adequacy is a reliability requirement which ensures that there are sufficient generation and non-generation resources available to meet the forecast next-year peak load along with reserve requirements, generally one to three years ahead. In California, to qualify for system or local area resource adequacy, a storage resource is rated at the maximum output which can be sustained for at least four consecutive hours and be available for at least three consecutive days. For flexible capacity, a “bi-directional” storage resource is rated at the output which can be charged for 1.5 hours and discharged for 1.5 hours.

In StorageVET,

- A storage asset eligible to provide resource adequacy receives the monthly capacity payments and either reserves the capacity or is dispatched for the designated hours on the designated days. The storage asset is fully charged up to the capacity eligible for resource adequacy prior to the designated hours.

For further details of CPUC and CAISO’s rules on resource adequacy, refer to the valuation report, chapter 10.

**Energy Time-Shift**

Energy is defined as injections and withdrawals of real power (MWh) at specified locations and in defined time intervals in a wholesale market or a utility dispatch. These locations can be particular busses for injections or, for withdrawals, particular busses (for storage) or aggregations of busses (for retail load).

The Energy product is generally utilized by storage technologies either by participating in the Energy markets only, to provide energy time-shifting or arbitrage, or by jointly providing Energy with other market services or for distribution deferral. Energy time-shift or arbitrage is not a market product, but is rather a primary application of storage technologies within the energy markets or in response to time-varying retail rates (see further discussion below). Energy time-shift value is typically understood as the minimum market value for a storage resource, with all other services implying additional value by jointly providing other services.

Energy time-shift is defined as charging the storage resource during intervals with low (or negative) energy prices and discharging the storage resource during intervals with high energy prices. Energy time-shift is conducted when there are positive net energy market revenues due to charging and discharging net of roundtrip efficiency losses.

In StorageVET,

- The day-ahead energy time-shift is modeled using a 24 hour optimization, with defined starting and ending state of charge at midnight, or other defined dispatch optimization horizon.
  - The real-time energy arbitrage is modeled assuming “perfect foresight” using a 2 hour rolling optimization, in which the first 2 hour period is used for financial settlement and the second 2 hour period is used to determine the optimal SOC at the end of the first 2 hours.
Flexible Ramping

The Flexible Ramping Product (FRP) is an additional reserve in the real-time market to address uncertainty about 15 minute and 5 minute ramping requirements due to factors such as variable wind and solar generation. CAISO procures these ramping reserves from resources bidding into the energy market if it determines that resources already committed to provide energy do not have enough ramping capabilities to fulfill its requirements.

In StorageVET,

- StorageVET jointly optimizes Energy and FRP in the CAISO Fifteen Minute Market, first by conducting “perfect foresight” real-time energy arbitrage along with FRP capacity reserved in the uncertainty award using a 2 hour rolling optimization, followed by ex post settlement of the FRP payment for forecasted movement based on the energy dispatch.

For further details on CAISO’s Flexible Ramping Product, refer to the valuation report sections 8.6 and 11.3.

Frequency Regulation

The CAISO uses Frequency Regulation to follow the real-time imbalance of electricity supply and demand in between 5-minute economic dispatch instructions. The CAISO dispatches Frequency Regulation signal every 4 seconds and separately manages a Regulation Up and a Regulation Down product. The CAISO Regulation market provides both a capacity payment and a mileage payment, with separate hourly market clearing prices for each product.

The CAISO market has several participation models for providing Regulation, which are relevant to different storage technologies. A pumped storage plant would be operated similarly to a conventional generator, with the unit following the regulation signal around a dispatch operating point. Other types of storage technologies, such as batteries, are operated differently because they follow the signal up and down, and can use both charging and discharging modes without transition times, thus amplifying the regulating range. There are two market participation models for these resources: the non-generator resource model (NGR) and the NGR with regulation energy management (NGR-REM) model. In the NGR case, the resource operator manages state of charge through bids or self-management, and the resource can provide Regulation and other services; in the NGR-REM case, the CAISO manages state of charge, but the resource can only provide Regulation.

In StorageVET,

- A storage asset is assumed to follow sample Regulation signals the CAISO has published. StorageVET does not model the Regulation dispatch explicitly. Rather, this is an external calculation which is translated into an energy usage associated with Regulation operations and requiring energy charging to make-up for efficiency losses.
- The user can opt for the storage asset to be a NGR-REM resource that provides only Regulation service and relies on the CAISO to manage its SOC. In this case, the resource optimization is restricted to Regulation only and the assumption that the unit is returned to
50% state of charge in every 15 minute interval. This is used to determine the energy makeup requirement.

- A storage asset can also follow Regulation signals imported by the user. StorageVET calculates the amount of energy absorbed and injected as well as the impact on storage degradations following the customized signals.

For further details of CAISO’s Frequency Regulation product, refer to the valuation report, section 9.2.

**Spinning Reserve**

Spinning reserve is utilized primarily to protect against contingencies, notably unplanned outages of major facilities such as transmission lines or generators. Spinning Reserve is acquired from units that are synchronized and can provide full awarded capacity in 10 minutes. When dispatched, the resource must be capable of sustaining its awarded capacity for 30 minutes. Payments are for capacity reserved ($/MW), with additional real-time market Energy payments during reserve activation.

In StorageVET,

- A storage asset providing spinning reserve is modeled to reserve its awarded capacity for the awarded hours.

For further details of CAISO’s Spinning Reserve product, refer to the valuation report, section 9.3.

**Non-Spinning Reserve**

Similar to spinning reserve, non-spinning reserve is also used to protect against contingencies. Resources must be started (if needed) and synchronized with the full award available in 10 minutes. Hence, the eligible non-spinning reserve capacity is measured as the Start-up time (mins) + Operating Reserve ramp rate (MW/min) × 10 minutes. Energy production must be capable of being maintained for 30 minutes. For most storage technologies, the start-up time of the unit is minimal. There are therefore no operational difference for a storage asset to participate in spinning reserve and non-spinning reserve.

In StorageVET,

- A storage asset providing non-spinning reserve is modeled to reserve its awarded capacity for the awarded hours.

For further details of CAISO’s Non-Spinning Reserve product, refer to the valuation report, section 9.3.

**Transmission**

**Transmission Capacity Investment Deferral**

Storage can be utilized to defer investment in additional transmission capacity. This is done by installing storage assets close to load pockets to provide energy during peak hours to alleviate the burden on transmission lines coming into the load pockets.
In StorageVET,

- A user specifies the conditions on the transmission facility being evaluated, including existing capability, growth in utilization of the facility and hours of forecast congestion, and the expected cost to increase transmission capacity. StorageVET then models how storage assets are dispatched to alleviate the congestion and the number of years the transmission capacity investment can be deferred. The time value of money for the avoided cost of transmission investment is then counted as part of the benefits of the storage asset, for the duration of the deferral.

**Transmission Voltage/Reactive Power Support**

Storage can be utilized to support voltage and provide reactive power along the transmission lines. Depending on the local conditions of the transmission lines, storage assets can be dispatched to provide reactive power and support voltage, without draining the stored energy.

In StorageVET, the user must define a reactive power time-series reservation schedule to provide transmission voltage/reactive power support; this schedule is then honored by the model during optimization to determine other sources of benefits from the project.

**Distribution**

**Distribution Capacity Investment Deferral (Load Growth)**

Storage can be utilized to defer investment in additional distribution capacity. Similar to transmission capacity investment deferral, this is done by installing storage assets close to distribution circuits with load growth to provide energy during peak hours to alleviate the burden on the distribution lines.

In StorageVET,

- A user specifies the conditions on the distribution circuit, including existing capacity, circuit conditions, load growth, and the expected cost to increase distribution capacity. StorageVET then models how storage assets are dispatched to alleviate the conditions during peak hours and the number of years the distribution capacity investment can be deferred. The time value of money for the avoided cost of the distribution investment is then counted as part of the benefits of the storage asset, for the duration of the deferral.

**Distribution Voltage/Reactive power support**

Similar to voltage and reactive power support along the transmission lines, storage provides the same services for distribution circuits. Depending on the local conditions of the distribution circuits, storage assets can be dispatched to provide reactive power and support voltage, without draining the stored energy.

In StorageVET, the user must define a reactive power time-series reservation schedule to provide distribution voltage/reactive power support; this schedule is then honored by the model during optimization to determine other sources of benefits from the project.
Backup Power

Storage can provide backup power to mission-critical locations. For example, in the aftermath of natural disasters when an entire region might go out of power, storage can provide backup power to traffic lights, restaurants, supermarkets, and gas stations to maintain basic functions.

The scheduling of the device for this purpose could require that a minimum state of charge is maintained at all times, or that the storage operator forecasts the highest probability times for outages and develops a time-varying schedule for backup power. In either case, StorageVET can be further used to evaluate multiple applications or multiple-use applications.

Customer Services

Customer-sited storage, depending on its location, can provide a number of services, including retail rate reductions, backup power, and power quality. StorageVET can model these services, individual or jointly, as well as multi-use applications which combine retail customer services with distribution deferral and wholesale market services. StorageVET can also incorporate constraints for customer-sited DERs, such as non-export. This report initially only provides selected details on customer services, with the expectation of additional information in subsequent versions.

Time-of-Use (TOU) Rate Time-Shift

Time-of-use (TOU) utility rates offer a variable rate for energy consumption different times of day, to better reflect wholesale system marginal costs. For utilities which offer TOU rates, StorageVET can be used to evaluate the customer benefits of energy time-shift to reduce rates.

There are other variants on TOU rates. Real-time pricing refers to retail rates which are consistent with actual real-time wholesale energy prices. StorageVET can be used to evaluate whether different variants on TOU rates correspond to optimal utilization of storage resources, and whether some variants are more supportive of optimal multiple-use applications.

Since some customers may face TOU rates and demand charges, StorageVET can allow for co-optimization between these two rate structures.

Demand Charge Management

Demand charges are fixed rate charges associated with hours of highest usage. They can take several structures, including time-related charges associated with demand during particular hours of the month and/or season, and facilities-related charges which are assigned to the highest demand hours in the month or other billing cycle.

StorageVET assumes that demand charges are billed monthly, and can vary by up to a three tier of peak hours, including seasonal differences. There can also be a facilities related demand charge component, which is independent of time. StorageVET can co-optimize demand charge mitigation jointly with wholesale market services. StorageVET assumes that time-related demand charges are billed monthly, and can vary by up to a three tier of peak hours, including seasonal differences.
**Incentives and Rebates**

StorageVET allows the user to incorporate incentives and rebates in the cost accounting for the project finances.

**Valuation Perspectives**

This section describes the valuation perspectives available in StorageVET for storage assets installed at customer sites. The valuation perspectives follow the California Standard Practice Manual in laying out the relevant components in Participant Cost Test, Total Resource Cost Test, Ratepayer Impact Measure, and Program Administrator Cost Test.

- **Avoided Costs**
  Directly avoided costs include wholesale energy, generation capacity, transmission and distribution infrastructure deferral, and distribution losses. System avoided costs that are sometimes included in cost test assessments but not included here include avoided ancillary services (we include market revenues for storage assets from ancillary service participation but not any avoided costs), wholesale price impacts, avoided startup or cycling costs from thermal generators, and any values sometimes included for societal cost tests including avoided greenhouse gas emissions, avoided criteria pollutants, or avoided land and water impacts.

- **Market Revenues**
  Market revenues include ancillary services (frequency regulation, spinning reserves, non-spinning reserves), day-ahead energy market revenues, real-time energy market revenues, and generation capacity payments.¹

- **Bill Savings**
  Bill savings revenues include reduced energy and demand charges achieved through energy storage dispatch.

- **Utility Transfer Payments and Incentives**
  Transfer payments include incentives for storage installation as well as any payments for utility asset control.

- **Other State Incentives**
  Other state incentives included rebates or tax credits for storage installation.

- **Other Federal Incentives**
  Other federal incentives included rebates or tax credits for storage installation.

---

¹ Market revenues and energy and capacity avoided costs are calculated using the same methodologies in StorageVET.
Table 5-2
Benefit and cost components included in regulatory cost tests

<table>
<thead>
<tr>
<th>Category</th>
<th>Participant Cost Test</th>
<th>Total Resource Cost Test</th>
<th>Ratepayer Impact Measure</th>
<th>Program Administrator Cost Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoided Costs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Market Revenues</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bill Savings</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Utility Transfer Payments</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Other State Transfer Payments or Incentives</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Federal Incentives</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Value Stacking, Compatibility, and Priority

This section describes value stacking, one of the primary objectives of StorageVET, how StorageVET achieve value stacking by considering several types of compatibility, and provides examples of feasible value stacking in StorageVET.

Value Stacking

Value stacking refers to the aggregated values a storage asset providing a combination of services can bring. Since each service has its own requirements on the capacity, energy, and availability of the storage asset, a storage asset cannot provide all the services all the time. In StorageVET, value stacking is achieved by defining a list of services based on the storage asset’s location, timing, and ownership. StorageVET then follows a service priority list defined by the user to check for any conflicts and assign services to the storage asset.

Types of Compatibility

The available services for a storage project may vary in terms of location and ownership. StorageVET models service availability in terms of these specifications through compatibility matrices. These matrices map locations and ownership to compatible services.

Location

The location of a StorageVET project can be chosen from the following options:

- Transmission
- Distribution
- Behind-the-meter

Each of these locations has a set of grid services that can be offered.
Table 5-3
Mapping between feasible services and location of storage asset

<table>
<thead>
<tr>
<th>Service/Location</th>
<th>Behind-the-meter</th>
<th>Distribution</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Adequacy Capacity</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Day Ahead Energy Time Shift</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Real Time Energy Time Shift</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Frequency Regulation</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Non-Spinning Reserve</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Regulation Energy Management</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flexible Ramping</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Investment Deferral</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Transmission Voltage/Reactive Power Support</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Losses Reduction</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Voltage Control</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Retail Demand Charge Reduction</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Retail Energy Time Shift</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power Quality</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Backup Power</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Demand Response Program Participation</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PV Self-Consumption (FITC Eligibility)</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

If a position is set to zero, the service is not compatible with the location, whereas if the position is set to one, the service is actually available at the location.

Timing

Some services can be accessible to the project at the same time, provided there are no overlapping operational requirements presented by different services. StorageVET has a built-in feasibility logic that checks the possibility to provide two services during the same time period, for example a month. To this end, each service that imposes operational constraints on the project is assigned a priority level, and the lower priority constraints are verified against higher priority ones. If a new constraint renders the operation infeasible, then such service is turned off for the corresponding month, and the tool will provide a summary of the conflicting requirements.

The following table shows an example of the priority matrix used for the feasibility logic to establish operational constraints and determine the services that can be offered.

Table 5-4
Example of the priority matrix defined by the user

| User Constraints |
|------------------|---|
| 3                |   |
The table is subject to modifications, but it is clear that local reliability services are set to have priority.

**Ownership–Regulatory/Business Model**

In a similar way as location compatibility, ownership also constrains the list of possible services to be accessible to the project.

**Table 5-5**
**Mapping between feasible services and ownership of storage asset**

<table>
<thead>
<tr>
<th>Service/Ownership</th>
<th>Customer-Owned</th>
<th>Utility-Owned</th>
<th>IPP-Owned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Adequacy Capacity</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Day Ahead Energy Time Shift</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Real Time Energy Time Shift</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Frequency Regulation</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Non-Spinning Reserve</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Regulation Energy Management</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flexible Ramping</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Investment Deferral</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Transmission Voltage/Reactive Power Support</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Losses Reduction</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Voltage Control</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Retail Demand Charge Reduction</td>
<td>1</td>
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<td>0</td>
</tr>
<tr>
<td>Retail Energy Time Shift</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power Quality</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Backup Power</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Demand Response Program Participation</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Types of Value Stacking

Planning Value + Operation Value

Planning and operation revenues can be considered for value stacking, whenever a set of well-defined coexistence rules are defined. For example, resource adequacy can be offered along with market services, provided the commitment of capacity due to resource adequacy is not superseded by the market participation. To this end, StorageVET calculates operational constraints on the storage system that are required to provide resource adequacy, such as energy and dispatch reservations, and these constraints are imposed in the market optimization problem.

In this setting, the resource is being compensated for providing resource adequacy, but resource adequacy imposes energy reservation or dispatch constraint that may reduce the ability to provide more profiting services during certain periods of time.

Since resource adequacy is a long-term commitment, it takes priority over market services and other short-term commitments, and this is reflected by the pre-optimization nature of the resource adequacy modeling, which limits the ability to achieve economic objectives.

Simultaneous (e.g. Sell Energy While Peak Shaving)

Typically, during peak-shaving hours, energy prices will be high representing the scarcity of the resource. The optimization formulation of StorageVET will dispatch the storage system as to discharge during high price hours, thus, getting the value of discharging energy while obtaining compensation for contributing with the peak-shaving objective. If the value of peak-shaving is being considered, it is modeled as a capacity reservation, which in most cases aligns with the economic objective of selling energy at the best possible price. Therefore, even if peak-shaving takes priority upon the economic objectives, the associated lost value is very low.

Daily or Seasonally Distinct (e.g. DR Program in Summer Only)

1. Compatibility
2. Prioritization

Reserve Part of Storage for One Service While Using the Rest for Others (e.g. Backup Power Reservation During Market Participation)

A determined amount of the energy in the storage system can be reserved for backup power. This might limit the ability of the storage system to provide market services that require energy during large periods of time, but the services can still be offered in a smaller amount.

As a reliability service, backup power reservation takes priority, and whenever an outage takes place, it is assumed that no market services can be provided.

Stacking Benefits Between Customer, Distribution, and Transmission Domains

If the traditional utility planning and operations silos are transcended, storage assets may be operated in a way that benefits multiple stakeholders or functions with a single project. For
example, customer objectives could be addressed, while taking into account distribution operating constraints and providing market services at the same time.

The service prioritization follows the rules established by the prioritization logic in order to choose the services that provide reliability and abide by constraint; then, it co-optimizes services are subject to the pre-optimization constraints.

**Additional References**

The following additional references can be used for further information on the market services available in StorageVET. Full references and links can be found in the reference section at the end of the document.

California ISO (CAISO), Business Practice Manual (BPM) for Market Operations, updated periodically [14] – the standard reference on CAISO wholesale market operations, focused on market entities, day-ahead and real-time market procedures, and the full network model.


California Public Utilities Commission (CPUC), Resource Adequacy compliance materials webpage, updated annually [16] – all the materials for compliance with the CPUC RA program, including for energy storage.
6
STORAGEVET TECHNOLOGIES, PROJECT COST, AND PERFORMANCE

Definitions

For the purpose of economic valuation, a storage system is represented by three elements incorporated in the StorageVET model, and used for optimization or for simulation: a physical model, parameters, and a cost model. These elements represent operational characteristics of the various technologies that impact system performance and indirectly, the valuation result.

At the end of this section, there is a set of annotated references which the user can refer to for additional information on technologies, cost, and performance. We do not necessarily endorse the data found in these papers, but they can be referred to for comparison with the data within StorageVET.

Figure 6–1
Components of a storage technology model

- Physical model: Set of equations and constraints that represent the interaction and evolution in time of the physical variables that represent a storage system. It includes relationship between state of charge and energy flows in and out of device. It also includes a degradation model that indicates how the system ages. The physical model is determined by the storage technology parameters and the system size.

- Cost model: Mathematical characterization of the capital cost, along with O&M costs for a storage system.
Parameters: Set of values determined by the technology, size, and configuration of a storage system that define the particularities of such system model. They can be divided between physical parameters and financial parameters.

Most energy storage systems can be represented under the same physical and cost model structure. The difference between different technologies will be entirely represented by the relative values of the parameters.

In what follows, we will present the main storage models that are used in StorageVET, and we will relate each model with the set of technologies that can be modeled with it.

**Parameter Summary**

Table 6-1
Mapping between storage technologies and parameters

<table>
<thead>
<tr>
<th>Electrochemical</th>
<th>Charge Capacity</th>
<th>Discharge Capacity</th>
<th>Energy Capacity, SOC Bounds</th>
<th>Charge Efficiency</th>
<th>Discharge Efficiency</th>
<th>Housekeeping Power</th>
<th>Heat Rate</th>
<th>Self-Discharge Rate</th>
<th>Charge Ratio</th>
<th>Min. Charge</th>
<th>Min. Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Ion</td>
<td></td>
<td></td>
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<tr>
<td>Sodium Sulfur</td>
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<tr>
<td>Lead Acid</td>
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<tr>
<td>Zinc Bromide</td>
<td></td>
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<tr>
<td>Liquid Metal</td>
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<tr>
<td>Na Ion</td>
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<tr>
<td>Vanadium Redox</td>
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<tr>
<td>Zinc Bromide</td>
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<td>Fe Cr</td>
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<tr>
<td>Mechanical</td>
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<tr>
<td>Pumped Hydro</td>
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<td></td>
<td></td>
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<tr>
<td>CAES, adiabatic</td>
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<tr>
<td>CAES, non-adiabatic</td>
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<tr>
<td>Flywheels</td>
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<tr>
<td>Thermal</td>
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<tr>
<td>Water Heaters</td>
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<tr>
<td>Thermal Brick Systems</td>
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</tr>
</tbody>
</table>
The table above relates storage technologies with the corresponding set of parameters that is used for modeling. It can be seen that the technology models can be grouped into 6 fundamental models:

**Model 1**: Electrochemical, flywheels (EZ Tech)

**Model 2**: Pumped hydro

**Model 3**: CAES non-adiabatic

**Model 4**: Thermal

**Model 5**: Vehicle to grid

**Model 6**: Combustion turbine

In the following, we present the mathematical formulation of Model 1, which is the base for all storage technologies. All storage technologies are modeled as slight modifications of Model 1, which are introduced and explained in the subsequent sections.

A special case is the combustion turbine model, which significantly varies from Model 1, therefore is introduced as a standalone model.

**Model 1: Electrochemical, Flywheels**

**Performance Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEEEE_EE_CC</td>
<td>%</td>
<td>Charging efficiency</td>
</tr>
<tr>
<td>EEEEE_DD</td>
<td>%</td>
<td>Discharging efficiency</td>
</tr>
<tr>
<td>EEEEE_EE_EE</td>
<td>%</td>
<td>Roundtrip efficiency</td>
</tr>
<tr>
<td>SSSSCC_MINIMINIM</td>
<td>%</td>
<td>Maximum state of charge</td>
</tr>
<tr>
<td>SSSSCC_MINIMINIM</td>
<td>%</td>
<td>Minimum state of charge</td>
</tr>
<tr>
<td>PPCCMWPP_CC</td>
<td>MWh</td>
<td>Maximum power capacity when charging (at the grid) (CAISO: Pmax)</td>
</tr>
<tr>
<td>PPCCMWPP_DD</td>
<td>MWh</td>
<td>Maximum power capacity when discharging (at the grid) (CAISO: Pmin)</td>
</tr>
<tr>
<td>SSSCCMPP</td>
<td>MVA</td>
<td>Maximum power capacity of the inverter</td>
</tr>
<tr>
<td>EEEECE_MPP</td>
<td>MWh</td>
<td>Discharge Energy capacity of the system at Point of Common Coupling (PCC)</td>
</tr>
</tbody>
</table>
We model the time evolution of a storage system as a discrete-time dynamic system that presents (possibly time-varying) input and state constraints.

The equation that represents the dynamic evolution of the SOC of the storage system is:

$$SSSOC(t_t) = SSSCC(t_t - 1) + \frac{CC,GG(t_t)}{EECCMPP} - \frac{1}{EECCMPP}DD,GG(t_t) - SSEESEE_D01 \cdot SSSCC(t_t - 1) - SSEESEE_D02 \cdot HHPPP$$

for all $t_t$. Notice that the product $EECC,DD$ is equivalent to the roundtrip efficiency $EECC,RR$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SSSOC$</td>
<td>%</td>
<td>Energy state of charge at the end of time interval $t_t$.</td>
</tr>
<tr>
<td>$CC,GG(t_t)$</td>
<td>MW</td>
<td>Charging power during time interval $t_t$ (at the PCC).</td>
</tr>
<tr>
<td>$DD,GG(t_t)$</td>
<td>MW</td>
<td>Discharging power during time interval $t_t$ (at the PCC).</td>
</tr>
<tr>
<td>$QQ,GG(t_t)$</td>
<td>VAR</td>
<td>Amount of reactive power provided at time interval $t_t$.</td>
</tr>
<tr>
<td>$SSSSHH(t_t)$</td>
<td>%</td>
<td>State of health of storage system.</td>
</tr>
</tbody>
</table>

### Cost Parameters

**Table 6-3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CCSSRRR_1$</td>
<td>$</td>
<td>Capital cost fixed.</td>
</tr>
<tr>
<td>$CCSSRRR_2$</td>
<td>$/MWh</td>
<td>Capital cost variable.</td>
</tr>
<tr>
<td>$CCSSRRR_3$</td>
<td>$/year</td>
<td>Operation and maintenance fixed cost.</td>
</tr>
<tr>
<td>$CCSSRRR_4$</td>
<td>$/kWh discharge</td>
<td>Operation and maintenance variable cost.</td>
</tr>
</tbody>
</table>

### Variables

**Table 6-4**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SSSOC$</td>
<td>%</td>
<td>Energy state of charge at the end of time interval $t_t$.</td>
</tr>
<tr>
<td>$CC,GG(t_t)$</td>
<td>MW</td>
<td>Charging power during time interval $t_t$ (at the PCC).</td>
</tr>
<tr>
<td>$DD,GG(t_t)$</td>
<td>MW</td>
<td>Discharging power during time interval $t_t$ (at the PCC).</td>
</tr>
<tr>
<td>$QQ,GG(t_t)$</td>
<td>VAR</td>
<td>Amount of reactive power provided at time interval $t_t$.</td>
</tr>
<tr>
<td>$SSSSHH(t_t)$</td>
<td>%</td>
<td>State of health of storage system.</td>
</tr>
</tbody>
</table>
**Operational Constraints**

**Table 6-5**
Storage modeling constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SSSCC_{min} \leq SSSCC(t) \leq SSSCC_{max}, \forall t$</td>
<td>Min and max bounds on SOC</td>
</tr>
<tr>
<td>$PPCHWPP_{GC} \geq CC_{GC}(t) \geq 0, \forall t$</td>
<td>Bounds on the charging capacity</td>
</tr>
<tr>
<td>$PPCHWPP_{DD} \geq DD_{GC}(t) \geq 0, \forall t$</td>
<td>Bounds on the discharging capacity</td>
</tr>
<tr>
<td>$\frac{CC_{GC}(t) - CC_{GC}(t-1)}{\Delta t} \leq 1, \forall t \neq 1$</td>
<td>Ramping capacity constraints</td>
</tr>
<tr>
<td>$CC_{GC} \cdot CC_{DG} = 0, \forall t$</td>
<td>Power cannot flow in both directions at the same time</td>
</tr>
<tr>
<td>$CC_{GC}^2(t) + QQ_{GC}^2(t) \leq SSCPWPP^2$</td>
<td>Real and reactive power cannot violate the maximum apparent power capacity of the inverter</td>
</tr>
</tbody>
</table>

Note: Some of the constraints introduced above may not apply for the time granularity that we consider in the model. For example, all the storage technologies included in StorageVET have a ramping time that is shorter than the 5-min resolution that the simulations allow. Therefore, for practical effects, we might safely neglect the ramping capacity constraints.

**Specific Details for Electrochemical Batteries**

**Battery**

Electrochemical storage covers all of the existing battery technologies.

Electrochemical storage presents a very fast response, being able to go from maximum charge to maximum discharge in less than a second. This implies that there is

For example, battery technologies are usually not subject to ramping limitations on the operational timeframes of electric power systems, i.e., they can go to any charge/discharge power in a very short time. In that case, constraint C4 must be neglected.

Given the fast ramping capacity of electrochemical storage technologies, no ramping rate constraint is considered in the dispatch optimization of no less than 5 minute time. In our framework, it is represented by setting PD5 and PD6 equal to infinity. This leads constraint C4 to be trivially satisfied.

If the efficiency parameter of the electrochemical storage is modeled as roundtrip efficiency, the charge/discharge efficiencies must be set as follows:

$$EEEE_{CC} = EEEE_{DD} = \sqrt{EEEE_{RRR}}.$$  

---

2 For optimization purposes, this constraint can be neglected, and it can be shown that the optimal solution to the problem satisfies the constraint whenever one of the efficiency parameters is strictly less than one.
Battery Degradation

Degradation of a battery is usually dependent on two factors: age and number of charge-discharge cycles. This means that the lifetime of the battery ends either due to having reached certain number of operation years or due to having executed certain amount of cycles.

![Figure 6-2](image)

**Figure 6–2**
**Example of a degradation curve for a battery**

By age, a battery needs replacement when the maximum lifetime has been reached. By charge-discharge cycles, characterizing the battery life is slightly more complicated. Generally, manufacturers provide degradation information as a curve of Number of cycles during lifetime vs depth of discharge of the cycles, like the one shown in Figure 6-2. It means that the degradation is characterized only for batteries operating under a regime of constant depth of charging-discharging cycles. Figure 6-3 shows the SOC of a battery operating on cycles of 10% depth.

![Figure 6-3](image)

**Figure 6–3**
**SOC of a battery operating on constant depth cycles**

However, in reality a battery intended to provide grid services will hardly operate under constant depth cycles. Figure 6-4 shows the SOC of a battery that is being used to provide power to a load connected to a PV array.
Clearly, under real operation, it is difficult to identify how many operation cycles have elapsed, and quantifying the degradation of a battery over time requires a special approach. A rainflow counting algorithm [17] is used to estimate how many charging-discharging cycles has the battery undergone during certain time period (e.g., a day).

The outcome of the rainflow algorithm is the number of cycles that the battery underwent, and their depth. This information is used to characterize the battery state of health after a period of operation. The battery health is characterized by a number in the interval \([0,1]\), hereinafter denoted by \(SSHH HH\). The battery is said to have \(SSHH HH = 1\) when it is new, and it is considered to need replacement when \(BBHHH = 0\).

Let \(\{xx_{ji}\}\) be the list of depths of discharge that has been found in a time interval. Let us index this time interval with \(nn\). Let \(MM_{ji}\) be the amount of cycles of depth \(xx_{ji}\) found over the same time interval. Also, let \(yy_{ji}\) be the number of cycles that correspond to the battery lifetime for an operation at \(xx_{ji}\) depth of discharge, according to the information the degradation curve (e.g., Figure 6-2). Then, the health depletion of the battery at the end of the time interval is given by:

\[
SSHH HH_{ni} = SSSHH HH_{ni0} - \sum_{i} \frac{MM_{ji}}{yy_{ji}}
\]

where \(SSHH HH_{ni0}\) is the battery health at the beginning of the time interval.

**Model 2: Pumped Hydro Storage**

Pumped hydro is another large capacity technology for grid-level energy storage. It consists of a water reservoir that is filled using an electric pump, and generates energy using a hydraulic turbine. The energy capacity of the storage system is dictated by the volume of the reservoir.

---

3 Info about modeling pumped hydro storage have been taken from the report “Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest,” 2009.
Most pumped hydro storage systems use a pump/turbine, which is a synchronous machine that is able to generate power given a mechanical power input, but it can also be fed electric power to pump water. The ability to perform the two functions with the same machine comes at a cost: the generation efficiency varies significantly in terms of head and power output.

Parameters to take into account on top of the generic storage model can be found in the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PP_{MMMM_CC}$</td>
<td>kW</td>
<td>Minimum operating charge</td>
</tr>
<tr>
<td>$PP_{MMMM_DD}$</td>
<td>kW</td>
<td>Minimum operating discharge</td>
</tr>
</tbody>
</table>

Additionally, the pumping mode of the machine might present a limitation on the minimum amount of power that the pump can take.

Keeping the above considerations in mind, we model pumped hydro storage in StorageVET using the generalized storage model, including the following constraints:

$$ PP_{MMMM_CC} \leq CC_{GG}(tt) \leq PPCMMPP_{CC}, \forall tt $$

$$ PP_{MMMM_DD} \leq DD_{GG}(tt) \leq PPCMMPP_{DD}, \forall tt $$

Similarly, the charge/discharge efficiencies are no longer scalar input parameters, but functions:

$$ EEEE_DD(tt) = gg_{DD}( DD_{GG}(tt) ), \forall tt $$

$$ EEEE_CC(tt) = gg_{CC}( CC_{GG}(tt) ), \forall tt $$

The way the functions $gg_{CC}$, $gg_{DD}$ should be input by the user is through a data table that can be interpolated to approximate the value of the function.

**Model 3: Compressed Air Energy Storage (CAES)**

Compressed-air energy storage systems are a very important option of grid-level energy storage, characterized by their large power and energy capacity. It consists of a large hermetic space where compressed air is stored. Air is pumped into the reservoir using a compressor, and the same air is used for the combustion in a generation turbine.
The two main features of the CAES model that differ from the generic storage model introduced above are the presence of a fuel input that must be taken into account for the operational cost, and the existence of lower bounds for the power charged/discharged by the system.

Additional parameters to consider:

### Table 6-7
CAES dedicated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( PP_{MM} ) ( CC )</td>
<td>kW</td>
<td>Minimum operating charge</td>
</tr>
<tr>
<td>( PP_{MM} ) ( DD )</td>
<td>kW</td>
<td>Minimum operating discharge</td>
</tr>
<tr>
<td>( HHRR )</td>
<td>BTU/kWh</td>
<td>Heat rate</td>
</tr>
<tr>
<td>( EE )</td>
<td>kWh(<em>{out})/kWh(</em>{in})</td>
<td>Energy charge ratio</td>
</tr>
</tbody>
</table>

### Table 6-8
CAES dedicated variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( EE_{MM}(t) )</td>
<td>BTU</td>
<td>Fuel intake for discharge</td>
</tr>
</tbody>
</table>

Moreover, the following relations must hold:

\[
EE_{MM}(t) = DD_{GG}(t) \cdot HHRR
\]

\[
EE_{EE_{EE}_{EE}} = EE_{EE_{EE}}_{DD} = \sqrt{EE_{RR}}
\]

\[
DD_{G} \in \{0\} \cup [PP_{NNNNNN}_{DD}, PP_{CCMNPP}_{DD}]
\]

\[
CC_{G}(t) \in \{0\} \cup [PP_{NNNNNN}_{CC}, PP_{CCMNPP}_{CC}]
\]

The fuel must be taken into account in the cost of discharging.

**Model 4: Thermal Storage (Ice/Water Heater) (Not fully implemented in StorageVET V1.0)**

A thermal storage system can be represented as a standard storage system with fixed discharge, where the discharge is determined by the thermal load that must be served. The energy capacity of the thermal storage is determined by the amount of energy required to take the maximum
amount of fluid (water) that the storage can hold, from ambient temperature to operational
temperature (e.g., 32ºF for ice, or 120ºF for water heaters). In a similar manner, the thermal load
can be translated to kW.

This model may lead to simultaneous charge and discharge of the storage thermal storage, which
can be seen as the storage system not having enough energy to supply the thermal load, thus
getting the additional required energy from the grid, e.g., water bypassing the water heater
storage to go directly to the user.

The additional parameter to be taken into account is:

**Table 6-9**  
**CAES dedicated variable**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS_RHH</td>
<td>kWh</td>
<td>Thermal load</td>
</tr>
</tbody>
</table>

The only additional constraint to take into account for thermal storage is:

\[ DD_{SG}(\text{it}) = SS_{RHH}(\text{it}) \]

**Model 5: Electric Vehicles (V1G) (Not fully implemented in StorageVET V1.0)**

Electric vehicles following a V1G interconnection can perform smart charge to take advantage of
dynamic prices or provide grid support. It does not consider injecting power into the grid.
Modeling an electric vehicle only requires fixing the discharge in order to represent a usage
schedule, and adding a parameter that represents whether the electric vehicle is connected to a
power outlet.

The additional parameters to be taken into account beyond the standard storage model are the
following:

**Table 6-10**  
**Electric vehicles dedicated parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS_USSERR</td>
<td>kW</td>
<td>Planned battery discharge due to usage</td>
</tr>
<tr>
<td>CSSMNNM_KXQDD</td>
<td>{0,1}</td>
<td>Indicates whether the electric vehicle is connected to a power outlet. Zero means disconnected, and one means connected.</td>
</tr>
</tbody>
</table>

**Model 6: Combustion turbine**

A combustion turbine is not considered an energy storage system, therefore it requires a different
modeling approach. The following table contains the parameters that characterize a combustion
turbine in StorageVET.
Table 6-11
Combustion turbine dedicated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>𝐻𝐻𝐻𝐻𝑅𝑅</td>
<td>BTU/kWh</td>
<td>Heat Rate</td>
</tr>
<tr>
<td>𝐺𝐺_𝑀𝑀𝑀𝑀𝑀𝑀</td>
<td>MW</td>
<td>Minimum power output</td>
</tr>
<tr>
<td>𝐺𝐺_𝑀𝑀𝑀𝑀𝑀𝑀</td>
<td>MW</td>
<td>Maximum power output</td>
</tr>
<tr>
<td>𝐵𝐵𝐵𝐵𝐵𝐵</td>
<td>MW/min</td>
<td>Maximum ramping rate</td>
</tr>
<tr>
<td>𝐸𝐸_𝑃𝑃</td>
<td>$/MMBTU</td>
<td>Price of fuel</td>
</tr>
<tr>
<td>𝑅𝑅</td>
<td>°F</td>
<td>Ambient temperature</td>
</tr>
</tbody>
</table>

The relevant variables for the combustion turbine model are:

Table 6-12
Combustion turbine dedicated variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>𝐸𝐸_𝑈𝑈(𝑡𝑡)</td>
<td>MW</td>
<td>Fuel input rate</td>
</tr>
<tr>
<td>𝐺𝐺_𝑆𝑆(𝑡𝑡)</td>
<td>MW</td>
<td>Power output</td>
</tr>
<tr>
<td>𝐷𝐷_𝐸𝐸(𝑡𝑡)</td>
<td>%</td>
<td>Derating factor of the output</td>
</tr>
<tr>
<td>𝐸𝐸_𝐶𝐶(𝑡𝑡)</td>
<td>$</td>
<td>Fuel cost at time interval 𝑡𝑡</td>
</tr>
</tbody>
</table>

The equations modeling a combustion turbine are:

\[
𝐺𝐺_𝑆𝑆(𝑡𝑡) = \frac{𝐸𝐸_𝑈𝑈(𝑡𝑡)}{𝐻𝐻𝐻𝐻𝑅𝑅}
\]

\[
𝐸𝐸_𝐶𝐶(𝑡𝑡) = 𝑃𝑃_𝑆𝑆(𝑡𝑡) \cdot 𝐸𝐸_𝑃𝑃(𝑡𝑡)
\]

Since the derating factor depends on the ambient temperature data, it must be calculated as:

\[
𝐷𝐷_𝐸𝐸(𝑡𝑡) = \hat{f}(𝑅𝑅(𝑡𝑡))
\]

The user must provide at least two data points \((𝑅𝑅(𝑡𝑡), 𝐷𝐷_𝐸𝐸(𝑡𝑡))\) within a relevant ambient temperature range, in order to determine \(f\) via interpolation.

The power output is subject to the following constraints:

Table 6-13
Combustion turbine dedicated constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>𝑃𝑃_𝑆𝑆(𝑡𝑡) ∈ {0} ∪ {𝑃𝑃_𝑀𝑀𝑀𝑀𝑀𝑀, 𝑃𝑃_𝑀𝑀𝑀𝑀𝑀𝑀 \cdot 𝐷𝐷_𝐸𝐸(𝑡𝑡)}</td>
<td>Min and max power output constraints</td>
</tr>
<tr>
<td>(</td>
<td>𝑃𝑃_𝑆𝑆(𝑡𝑡) - 𝑃𝑃_𝑆𝑆(𝑡𝑡-1)</td>
</tr>
</tbody>
</table>

The first constraint implies that either the turbine is not generating any power or it is generating power above a minimum value.
Figure 6–7
CT model

Figure 6-8 shows the flow diagram that represents the generation process of a combustion turbine as modeled in StorageVET.

**PV + Storage System**

The model for PV in StorageVET is limited to taking the PV power output provided by the user. It can be computed using freely available tools such as PVWatts⁴. The user-provided PV power is used as an input to the optimization problem defined around the storage system.

![Diagram of PV + Storage System]

Figure 6–8
PV + storage setup

If the storage system shares inverter with the PV system, the following constraint must be included:

\[
(D_G(t) - C_G(t) + P_{PPP}(t))^2 + (Q_G(t))^2(t) \leq S_{SSC_{MPP}}^2
\]

*Note: In general, for this model, it will be assumed that the inverter capacity can accommodate all the PV generation, i.e., if the generation is higher than the inverter capacity, then it is assumed to be curtailed.*

---

Additional References

The following additional references can be used for further information on modeling the energy storage technologies available in StorageVET. Full references and links can be found in the reference section at the end of the document.


STORAGEVET MODEL ARCHITECTURE

The present and future objectives of StorageVET, described in the section 1, were incorporated in the architecture design to enable flexibility and modularity of the model for user definition, as well as future evolutions of the model.

Architecture Overview

The architecture of StorageVET contains four major modules, each with an important purpose toward to the goal of enabling flexibility, modularity, and ability to configure scenario-specific evaluations of energy storage projects.

These modules include:

- Pre-optimization configuration
- Scheduling optimization
- Post-optimization simulation
- Financial Calculations

The architecture of the tool and the relationship of each module with key model inputs and outputs are represented in Figure 7-1 below.

Introduction of StorageVET Modules

Pre-Optimization Configuration

The primary purpose of this module is to collect all technical and reliability-related service constraints and check their feasibility, prior to continuing to the schedule optimization of the energy storage
Key inputs to this module include
- Storage sizing
- Interconnection and grid constraints
- Deferral loads and DG output
- Resource adequacy
- Other long-term commitments

Key outputs to this module
- Superset of time-series dispatch constraints (power and energy)
- Identification of violations or infeasibilities

The reconciliation of energy storage project technical constraints, grid constraints, and reliability service constraints is illustrated in the Venn diagram in Figure 7-2 below.

Figure 7–2
Illustration of key StorageVET modeling constraint categories in “Pre-Optimization Configuration” module

**Scheduling Optimization**

The primary purpose of this module is to optimize time-series service participation and energy storage dispatch scheduling, subject to constraints which were collected and reconciled in the “Pre-Optimization Configuration” module. Depending on the scope of energy storage project objectives (services) which have been selected by the user for evaluation, this module may accommodate one or two optimization schedules. A first pass is typically a one-day or multiple-day look ahead. A second pass is incorporated if real-time energy market participation is selected, which evaluates the commitments of the day-ahead schedule and evaluates whether the storage may access additional value, either based on uncommitted power or energy capabilities, or through the “buy-out” of the day-ahead market schedules that clear.

Key inputs:
- User grid service selection
Market service price data and rules (as applicable for case)
Customer tariff (as applicable for case)
Storage performance, efficiency
Soft constraints (e.g. penalties for PV self-consumption, degradation)
Real-time energy prices and ramping constraint

Key outputs:
- Optimized time-series dispatch schedule (separate and sequential day-ahead and real-time optimizations, as applicable to case)

Figures 7-3 and 7-4 below illustrate a co-optimized day-ahead energy storage project schedule, which includes storage participation by grid service.

---

**Figure 7–3**
Illustration of Scheduling Optimization module output, energy dispatch

---

**Figure 7–4**
Illustration of Scheduling Optimization module output, ancillary services
**Post-Optimization Simulation**

The purpose of this module is to incorporate most complex performance relationships which can be used to refine the dispatch of the energy storage project and evolution of its state. Energy storage systems contain unique and complex interrelationship between performance, state-of-charge, current dispatch power levels, and ambient conditions. Incorporation of all of these characteristics into the current version of the StorageVET model would cause significant complications for data gathering, usability, and computational intensity of the tool. However, the existence of these relationships should not be ignored. This module provides the flexibility for the model to incorporate and test these relationships, without forcing the optimization problem to multiply in size.

- **Key inputs**
  - State-dependent performance parameters that would otherwise results in non-linear or mixed integer optimization (e.g. Pmin or efficiency as a function of SOC)

- **Key outputs**
  - Time-series power and energy dispatch of project
  - State-of-charge evolution

Currently, the most important function of this module is to enable the incorporation of minimum power output levels (often called “Pmin”) for technologies with that constraint. This more notably includes pumped hydro storage (PHS) and compressed air energy storage (CAES), whose turbine-based mechanical systems contain minimum pumping/compression and minimum generation levels. Incorporation of these parameters into the optimization is feasible, but it requires mixed integer programming (MIP), which is dramatically more computationally expensive than linear programming.

**Financial Calculations**

The final major module of StorageVET is responsible for the collection of all optimization and simulation dispatch outputs and, furthermore, the conversion of those time-series outputs into financial model. This module incorporates key ownership and financing attributes, along with macroeconomic factors, to develop a project level pro forma financial statement. Additionally, it performs a number of additional calculations for quick metrics and comparison that may be of interest to a user.

- **Key inputs**
  - Ownership and financing information, project term
  - Inflation, discount rate
  - Project cost information

- **Key outputs**
  - B/C ratios
  - NPV
  - Net cost of capacity
  - Breakeven CAPEX
An illustrative output from the Financial Calculations module is provided in Figure 7-5 below.

**Figure 7–5**
Illustrative output of the StorageVET financial calculation module

Additional details for each of these modules, and, specifically how they incorporate service objectives defined in StorageVET, can be found in the following section.

**Incorporation of StorageVET Services by Module**

**Services in Pre-Dispatch Configuration Module**

The pre-dispatch configuration module is used in StorageVET to model some scenario features and value streams that do not require a dispatch, but rather impose on the storage system some operational requirements that have to be satisfied.

In addition, the module performs a compatibility checkup for the constraints that model pre-dispatch services, in order to guarantee that there is no infeasibility due to overlapping. If overlapping occurs, a prioritization logic is used to define the relative importance of each service.

Pre-Dispatch services

- Deferral
- Resource Adequacy
- Demand Response
- Voltage Support / Power Quality
- Custom User Constraints
- Backup power
Overview of Feasibility Check

The feasibility check implemented in StorageVET tests if the constraints imposed by the services do not overlap.

**Figure 7–6**

Feasibility check process

The first step in the feasibility check is to establish a prioritization of all the services and features imposing operational constraints. It is important that all the services and features have a different priority level.

Once the priority has been defined, the algorithm takes the highest priority element and runs a self-consistency check on its constraints.

Self-consistency check: For a single service or feature that imposes constraints, it is necessary to verify that if no other constraints were imposed, there would be a dispatch solution that satisfies all the constraints. If no solution can be found, the service or feature is disabled for the corresponding month.

The next step is a recursion that takes services and features in order of priority, and validates, self-consistency, and feasibility given that the constraints associated to the higher priority services are enforced. If the constraints of the new service or feature make the problem infeasible, they are deactivated for the specific month when the infeasibility occurred.

The outcome of this process is a set of constraints associated to the list of services or features, which define a feasible set for the dispatch optimization module, as well as a summary of conflicts that flags the incompatibilities encountered for the different services, which correspond to constraints that were disabled.
The summary of conflicts is a useful outcome to establish the price of services such as Resource Adequacy, since for months when the resource adequacy-related constraints are not satisfied, it is considered that the service is not offered, and therefore, no value is assigned to it.

**Services in Dispatch Optimization Module**

The dispatch optimization module takes as inputs the storage system parameters, namely energy capacity, power capacity, physical constraints, as well as operating constraints, prices for ISO market services, and tariff rates if the system is located behind the meter, in order to produce a dispatch that maximizes the combined operation revenue. The operation revenue is formulated as a linear optimization problem that can be efficiently solved using algorithms available in Analytica.

The dispatch optimization module includes two optimization layers: first, it optimizes over the day-ahead (DA) market [services, and later, it optimizes over the real-time market services, subject to the previously obtained solution for the day-ahead market.

Figure 7–7

**Interaction between StorageVET core modules**

Figure 7-7 shows the information flow across the dispatch optimization module. Each optimization pass considers a different set of services to address, which is consistent with the CAISO market operation.

The first optimization pass, corresponding to the DA market optimization computes a dispatch for the following services:

- Day-ahead energy time shift (energy arbitrage)
- Demand charge management (if behind the meter)
- Frequency regulation
- Spinning reserves
- Non-spinning reserves

The day-ahead optimization takes into account the storage system dynamics, including the impact of performing frequency regulation on the SOC. This implies that it is assumed that certain amount of energy is being drawn from the storage system by performing frequency regulation during one hour. That energy is accounted for in the day-ahead optimization,

7-7
therefore, it is priced according to the DA energy prices. Spinning and non-spinning reserves are assumed to not impact the SOC.

Once the DA dispatch has been calculated, a second pass of optimization is carried out based on RT market prices, in order to capture additional revenues that could align with unused capacity of the storage system. StorageVET considers the following services on the real-time dispatch optimization:

- **Real-time energy time shift**

In order to calculate the dispatch for this service, StorageVET satisfies:

1. Day-ahead energy schedule commitments can be replaced with another service in real-time, subject to the requirement it must be “bought out” at real-time energy price.
2. All committed ancillary services dispatch (Frequency regulation, spinning, and non-spinning reserves) is satisfied.
3. All the pre-dispatch constraints included in the day-ahead optimization are satisfied.

The outcome of the dispatch optimization module is a set of time series that represent the day-ahead and real-time dispatch for the corresponding co-optimized services. This outcome is communicated to the output module, which formats the raw dispatch data for visualization purposes, and calculates the revenues associated to the dispatch.

**Services in Post-Optimization Simulation**

The purpose of the post-optimization simulation module is to capture the impact of services/features that are very complicated to be included in the dispatch optimization. The complications associated to these features are mainly non-linearities and non-convexities of the modeling equations.

The post-dispatch simulation module includes the following set of services/features:

- Flexible ramping
- Federal investment tax credit (FITC)
- Self-generation incentive program (SGIP)
- Battery degradation
- Dispatch adjustment for technologies with discontinuous dispatch ranges (CAES, PHS, CT)

The post-optimization simulation takes the dispatch generated in the optimization module and based on it computes the non-linear state evolution of the storage system (SOC with variable efficiency), or, in the case of discontinuous dispatch ranges, it calculates a sub-optimal dispatch that satisfies such ranges.
REFERENCES


[21] California Public Utilities Commission (CPUC), "Decision 13-10-040, Decision adopting energy storage procurement framework and design program," 17 October 2013. [Online]. Available: http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M079/K533/79533378.PDF.
<table>
<thead>
<tr>
<th>ACRONYMS</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACP</td>
<td>Analytica Cloud Player</td>
</tr>
<tr>
<td>CAES</td>
<td>compressed air energy storage</td>
</tr>
<tr>
<td>CAISO</td>
<td>California Independent System Operator</td>
</tr>
<tr>
<td>CEC</td>
<td>California Energy Commission</td>
</tr>
<tr>
<td>CEP</td>
<td>Consistent Evaluation Protocol</td>
</tr>
<tr>
<td>CPP</td>
<td>critical peak pricing</td>
</tr>
<tr>
<td>CPUC</td>
<td>California Public Utilities Commission</td>
</tr>
<tr>
<td>CT</td>
<td>combustion turbine</td>
</tr>
<tr>
<td>DA</td>
<td>day ahead</td>
</tr>
<tr>
<td>DAM</td>
<td>day-ahead market</td>
</tr>
<tr>
<td>DR</td>
<td>demand response</td>
</tr>
<tr>
<td>EIM</td>
<td>energy imbalance market</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>ESIC</td>
<td>Energy Storage Integration Council</td>
</tr>
<tr>
<td>ESS</td>
<td>energy storage system</td>
</tr>
<tr>
<td>ESVT</td>
<td>Energy Storage Valuation Tool</td>
</tr>
<tr>
<td>FITC</td>
<td>federal investment tax credit</td>
</tr>
<tr>
<td>I/O</td>
<td>input/output</td>
</tr>
<tr>
<td>IFM</td>
<td>integrated forward market</td>
</tr>
<tr>
<td>ISO</td>
<td>independent system operator</td>
</tr>
<tr>
<td>LMP</td>
<td>locational marginal price</td>
</tr>
<tr>
<td>LSE</td>
<td>load serving entity</td>
</tr>
<tr>
<td>MCC</td>
<td>marginal cost of congestion</td>
</tr>
<tr>
<td>MCE</td>
<td>marginal cost of energy</td>
</tr>
<tr>
<td>MCL</td>
<td>marginal cost of losses</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>MIP</td>
<td>mixed integer programming</td>
</tr>
<tr>
<td>NBT</td>
<td>net benefit test</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>PCC</td>
<td>point of common coupling</td>
</tr>
<tr>
<td>PCM</td>
<td>production cost models</td>
</tr>
<tr>
<td>PHS</td>
<td>pumped hydro storage</td>
</tr>
<tr>
<td>PQ</td>
<td>power quality</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
</tr>
<tr>
<td>RA</td>
<td>resource adequacy</td>
</tr>
<tr>
<td>RIM</td>
<td>ratepayer impact measure</td>
</tr>
<tr>
<td>RTM</td>
<td>real-time market</td>
</tr>
<tr>
<td>RTP</td>
<td>real-time pricing</td>
</tr>
<tr>
<td>SGIP</td>
<td>self-generation incentive program</td>
</tr>
<tr>
<td>SOC</td>
<td>state of charge</td>
</tr>
<tr>
<td>SOH</td>
<td>state of health</td>
</tr>
<tr>
<td>StorageVET™</td>
<td>Storage Value Estimation Tool</td>
</tr>
<tr>
<td>T&amp;D</td>
<td>transmission and distribution</td>
</tr>
<tr>
<td>TOU</td>
<td>time of use</td>
</tr>
<tr>
<td>UI</td>
<td>user interface</td>
</tr>
</tbody>
</table>
DETAILED USE CASES

The StorageVET tool for storage and other distributed technologies is a public, transparent modeling tool that allows diverse users to undertake cost-benefit analysis using a web-based platform. The tool supports several use cases that involve distinct actors with diverse objectives. The use cases described in this section were identified through a series of workshops and surveys with storage stakeholders. They were later consolidated into the four general cases supported by StorageVET as described in section 1. A mapping between the two is also provided in this section.

Potential Users and Functional Roles

**Regulators**

The regulatory responsibility may benefit substantially from having a reference model, scenarios, and process for evaluating energy storage systems. Accordingly, the following use cases focus on the development and benchmarking of ESS models and scenarios and then on an ESS evaluation process that is facilitated by these reference components.

**Energy Storage Prospective Investors/Owners**

An Investor/owner can be a merchant organization or a regulated utility. The goals of these organizations may differ; however, the use of StorageVET is very similar in each use case. The main differences between entities is their primary performance goal, and StorageVET produces performance reports from all relevant perspectives as a means for being useful to all Stakeholders.

**Energy Storage Operators**

While the expected near-term use of StorageVET is for evaluating Storage Project proposals from the perspectives of Investors and Regulators, ESS operations form the important basis for generating revenues and other benefits from an ESS. Accordingly, a certain level of functionality for simulating ESS operations is present in order to fully represent ESS benefits.

**Use Case Summary**

Tables C-1 through C-3 show the different use cases for StorageVET, from the perspective of the different potential users of the tool, namely, regulator, invertor, and operator. These use cases are mapped to the four general cases that are supported by StorageVET:

1. Estimate project benefits and costs: Given a predetermined set of services, technology, location, and operation policy, calculate the project value over a fixed period of time.
2. Compare project options: Compare multiple potential projects on a consistent basis. Differences between projects may be the project specification, location, or services provided.
3. Optimize project specification: Given a set of different project specifications, find the project specification (size, configuration, technology, location) that maximizes the value over all the alternatives.
4. Optimize project operations: Given a project specification, find the optimal operation that maximizes the value over the project lifetime.

**Regulator Use Cases**

**Overview**

Regulators may benefit substantially from having a reference model, scenarios, and process for evaluating energy storage systems. This capability can be used for policy development, oversight of planning functions, and storage procurement evaluation, among other functions. Accordingly, the following use cases focus on the development and benchmarking of ESS models and scenarios and then on an ESS evaluation process that is facilitated by these reference components.

**Table C–1**

**Regulator use cases**

<table>
<thead>
<tr>
<th>Regulator</th>
<th>Specific Use Case</th>
<th>StorageVET General Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>Design Scenarios and Model Assumptions</td>
<td>Compare project options</td>
</tr>
<tr>
<td>1.2.</td>
<td>Compare ES Project Benefits, Costs, &amp; Risks</td>
<td>Optimize project specification</td>
</tr>
<tr>
<td>1.3.</td>
<td>Design Incentives</td>
<td>Optimize project specification</td>
</tr>
<tr>
<td>1.4.</td>
<td>Model/Data Benchmarking</td>
<td>Optimize project specification</td>
</tr>
<tr>
<td>1.5.</td>
<td>Define Benchmark Model for improving standardized reporting functions, such as the CPUC’s Consistent Evaluation Protocol</td>
<td>Optimize project specification</td>
</tr>
</tbody>
</table>

**Design Scenarios and Model Assumptions**

The Regulator creates StorageVET scenarios for purposes of robust investment outcomes and reasonable operating strategies (incentives and projects).

**Compare ES Project Benefits, Costs, & Risks**

The Regulator compares energy storage filings using StorageVET quantitative outputs, given default inputs and Consistent Evaluation Protocol (CEP) end-use choices.

**Design Incentives**

The Regulator designs parameters for a given incentive program framework. The Regulator has ranked Projects that pass the Ratepayer Impact Measure (RIM) test but do not pass the Net Benefit Test (NBT), because they have higher costs than benefits, and the Regulator wants to explore a variety of incentives to encourage investors to proceed with their projects.

**Model/Data Benchmarking**

StorageVET is used as a tool for comparing the results of two models of ESS performance: one model is treated as a benchmark, and the other is StorageVET. The challenge is determining the differences between the results of the two models, without disclosing confidential information. The inputs to the two models are assumed to be consistent and available in StorageVET format.
If there are any differences between the inputs, they should be noted and explained for their potential impact on the outputs.

**Define Benchmark Model**

The Regulator may seek to directly utilize or require that regulated entities, such as utilities with storage procurement requirements, utilized standardized calculation and reporting methods, including accepted Benchmark Models. In pursuing this approach, the Regulator would aim to ensure that such an approach is complete, transparent, readily available, well defined, and fit for the purpose.

An example of such an approach is the CPUC’s Consistent Evaluation Protocol (CEP) (the CEP was first defined in [21], with updates in the IOU storage applications), which contains a set of standardized quantitative input values and blank outputs to be completed by the utilities when submitting proposed projects for procurement approval. CEP information also includes qualitative information that is beyond the scope of this use case. Examples of the categories of CEP information are proposer identification, project duration, efficiency, O&M, and technology. The CEP itself is not a model, but rather a reporting mechanism using standardized inputs.

With the more complex modeling capabilities embodied in StorageVET, the CEP structure could be expanded by a Regulator to conduct more detailed comparisons in transparent fashion. StorageVET is capable of taking these input values and producing the required output values, and it may include more information than is in the current CEP (e.g., modeling the flexible ramping product). For instance, there may be additional important inputs, and StorageVET also contains configurable modeling equations, objective functions, and processes for simulating ESS projects. This complete set of information is necessary for producing well-specified output and may act as a supplement to the CEP.

**Investor Use Cases**

**Overview**

This section treats the Investor role in general, where an Investor can be a merchant organization or a regulated utility. The goals of these organizations may differ; however, the use of StorageVET is very similar in each use case. The main differences between entities is their primary performance goal, and StorageVET produces performance reports from all relevant perspectives as a means for being useful to all Stakeholders.

**Table C–2**

Investor use cases

<table>
<thead>
<tr>
<th>Investor</th>
<th>Specific Use Case</th>
<th>StorageVET General Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.</td>
<td>Screen Feasible Locations</td>
<td>Optimize project specification</td>
</tr>
<tr>
<td>2.2.</td>
<td>Size a Project by Location, Primary Service, and Technology</td>
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<td>2.3.</td>
<td>Benchmark a Proprietary Valuation Method</td>
<td>Estimate project benefits and costs</td>
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Screen Feasible Locations
An Investor has a given planning area and wants to create a short list of specific locations for deeper analysis. This use case may be implemented through a database query using threshold characteristics for load shapes, load growth, energy price, marginal capacity cost, available capacity, frequency, and energy requirement/duration. Screening through engineering judgment may also be used as a course filter/criterion.

Size a Project by Location, Primary Service, and Technology
An Investor wants to design an ESS project that is expected to be most valuable when given the location and a specific technology. StorageVET runs scenarios with different storage sizes and compares them to obtain the scenario with the best cost/benefit.

Benchmark a Proprietary Valuation Method
An Investor wants to identify and explain significant differences between the Investor’s proprietary results and those of StorageVET. This use case is similar to Model/data benchmarking, but is more reflective of the perspective of the Investor for satisfying the Investor’s needs, as opposed to the Regulator’s needs.

Operator Use Cases

Overview
The use cases in this section describe the various ways that an ESS operator might utilize StorageVET as a decision support system in ESS operations. Some are essential to evaluating ESS benefits, while others are more forward looking.

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Operator use cases

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Reshape Net Load Profile
An ESS Operator, at an aggregation point, wants to reshape net load over a set future time period.

Scheduling an ESS can be achieved through financial incentives and through constraints on the way it operates. In this use case, an operational constraint is added to the dispatch formulation to represent an external limitation on the ESS power input and output. This external limitation
represents a requirement or limit on an aspect of the power system that is not internal to the ESS, and in this example it is called an aggregation point, at which there is a power flow criterion. The ESS should operate in such a way as to avoid violating this criterion.

Co-Optimize Services Scheduling

The Storage Operator uses day-ahead forecasts to determine services to offer for the coming day.

Scheduling an ESS can be achieved through pricing data and through constraints on the way it operates. In this use case, pricing data are used to guide scheduling over the near-term operating horizon. StorageVET is able to decide automatically for each time period which services bring the highest value, according to the chosen incentive (objective function).

Determine Left-Over Storage Capacity

Given primary obligations, determine what capability and availability remain for secondary uses.

StorageVET is given ESS capabilities and a schedule of primary service obligations and determines a schedule of residual ESS capability that can be used for added near-term value. Primary obligations could be providing power quality or backup power (see case for Power Quality and Backup Power).

Schedule an Outage

Determine a period of time in the near future during which it is most economical to schedule an outage.

This use case supports the Operator in making decisions about ESS maintenance. The Operator has in mind some near-term requirement (time window) for conducting maintenance on all or part of the ESS. The maintenance may require a partial or full derating of the ESS capabilities. This requirement is evaluated over the scheduling horizon, and various options for scheduling maintenance are ranked and compared by StorageVET. The maintenance horizon may be extended to weeks, compared to the operating horizon of days.

Backup Power

The Operator ensures that domestic power is available according to a given service agreement.

The ESS is used to provide backup power services, and the requirements for these services can vary over time, depending on how the external system is operating and other conditions, like weather. StorageVET is used to schedule the ESS for this service.

Power Quality

The Operator uses ESS to maintain power quality according to a given service agreement.

The ESS is used to provide power quality (PQ) services, and the requirements for these services can vary over time, depending on how the external system is operating and other conditions, like weather. StorageVET may be used to provide information useful to schedule the ESS for this service.
Calibrate Degradation Model

The Operator wants to update a set of ESS degradation model parameters that accurately represents the observed ESS degradation.
GRID SERVICES DEFINITIONS

This appendix provides brief definitions of the services modeled in StorageVET. Users should consult the more detailed accompanying reference document, *Energy Storage Valuation in California* [5], for additional technical details and explanations.

**Spinning Reserves**

*Definition*

Spinning Reserve is a generation capacity that is already operating and synchronized to the system that can increase or decrease generation within 10 minutes.

*Service Procurement*

Spinning reserve is on the same hierarchy level as other market services. Spinning reserves are procured by the ISO on an hour by hour basis in a competitive market. Energy storage may be capable of bidding in the spinning reserve market to supply spinning reserves. Its bidding and dispatch is co-optimized with other day-ahead market services, including energy and ancillary services. System must reserve at least one hour of duration and the storage capacity (kW) bid when it agrees to provide this reserve. System may not be discharging at full capacity or otherwise obligated to possibly discharge during hours when it is providing this reserve.

*Technical Overview*

Spinning reserves are the fastest available reserve capacity, since the generators providing them are already generating power. They can begin responding immediately to a contingency event. Because many energy storage technologies can be synchronized to grid frequency through their power electronics, energy storage could provide a service equivalent to spinning reserve while idle. Furthermore, an energy storage system that is charging energy may be capable to provide a magnitude of spinning reserve equivalent to the sum of its charging and discharging power.

*Storage Solution*

Storage bids capacity into synchronous reserves markets and is paid based on hourly market clearing prices for being available. Both the storage system’s charge and discharge capacity may be bid into this service. It is also paid the market price of energy for discharging. Batteries that are charging are allowed to bid the sum of their Charging Capacity and their Discharge Capacity.

*Benefit Quantification*

Synchronous Reserve Benefit = Synchronous Reserve Bid * Synchronous Reserve Price

*Success Criteria*

All batteries are assumed to ramp quickly enough to effectively be synchronous. CAES/pumped hydro systems must already be operating in pump/charge mode or less than full capacity to provide this service, otherwise, they would bid into non-synchronous reserve.
**Non-Spinning Reserves**

**Definition**
Non-synchronous reserve is an ancillary services product that consists of off-line generation that can be ramped up to capacity and synchronized to the grid in less than 10 minutes when responding to a dispatch signal. Storage is eligible to provide this service by charging and discharging in response to the ISO signals.

**Service Procurement**
System must reserve at least one hour of duration and the storage capacity (kW) bid when it agrees to provide this reserve. System may not be discharging at full capacity or otherwise obligated to possibly discharge during hours when it is providing this reserve. The storage system bids capacity into non-synchronous reserves markets and is paid based on hourly market clearing prices for being available. The storage system attempts to maintain a full charge so that it can offer its full discharge capacity in all hours. If a system is discharged, it also receives the energy price during the hour of discharge, which is represented by electricity sales in the NPV benefit table.

**Technical Overview**
Non-spinning reserves typically have minutes to respond to a contingency. Energy storage would be equally capable of providing non-spinning or supplemental reserves, but these services are typically lower value than spinning reserve because they are easier for traditional generators to accomplish and have lower opportunity cost.

**Storage Solution**
Energy storage would be equally capable of providing non-spinning or supplemental reserves, but these services are typically lower value than spinning reserve because they are easier for traditional generators to accomplish and have lower opportunity cost. Spinning and non-spinning reserve are modeled as a contingency reserve service, so ESVT awards this capacity-based service value to energy storage, as long as it has at least one hour of energy stored to respond if called in a contingency scenario. A charging energy storage system may earn up to two times its capacity if it meets the one hour requirement. During charging, a storage system can respond in two parts: removing its load from charging and then providing its discharge capacity.

**Benefit Quantification**
Non-Synchronous Reserve Benefit = Non-Synchronous Reserve Bid * Synchronous Reserve Price

**Frequency Regulation**

**Definition**
Frequency Regulation ensures the balance of electricity supply and demand at all times, particularly over time frames from seconds to minutes. When supply exceeds demand the electric grid frequency increases and vice versa.
**Storage Solution**

Since energy storage can both charge and discharge power, it has the potential to play a valuable role in managing grid frequency. Many energy storage technologies have demonstrated to be faster and more accurate than other grid alternatives at correcting these frequency deviations.

**CAISO Market Model**

CAISO has two regulation products: Regulation Up and Regulation Down. The Regulation Up and Regulation Down products are defined as capacity (MW) and mileage (MW-min) procured in hourly intervals in the DAM and RTM. Regulation Up is regulation provided when generating above a dispatch point or discharging above a SOC point. From a fully charged dispatch point, a storage resource can only provide Regulation Up. Regulation Down is regulation provided when reducing the energy production seen by the power system (reducing discharge or charging) below a dispatch point or SOC managed by the CAISO or self-managed by the storage operator. From a full discharged point, a storage resource can only provide Regulation Down. A resource can elect to provide one or both of these services. The CAISO Regulation market provides both a capacity payment and a mileage payment, with separate hourly market clearing prices.

**Service Procurement**

The CAISO procures a variable quantity (MW) of Regulation Up and Regulation Down capacity and mileage in each hour through the IFM, with any residual quantities procured in the RTM. Both Regulation Up and Regulation Down are procured through a reservation of Regulation reserve capacity on bid-in or self-provided resources to meet both the needed regulating range and a system mileage target. Selection of the bid-in units is based on the least bid cost of capacity bids, opportunity cost bids, and mileage bids. In this process, there are different hourly prices calculated for capacity and mileage.

**StorageVET Representation**

The StorageVET model does not represent the quantity of Regulation procured, nor calculate the effect of storage operations on Regulation procurement. StorageVET represents an eligible range for Regulation capacity, and treats the Regulation Up and Regulation Down capacity procurement from the resource as a decision variable. StorageVET treats mileage procurement as a secondary fixed payment for any capacity sold.

**Resource Adequacy**

**Definition**

The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. It is also a requirement in resource planning on longer time-frames, such as utility integrated resource plans. It is a function of many factors, including location on the transmission or distribution network, technology type, and time of year, operational attributes, and the modeling method used for determining the rating. Depending on the region, LSEs can also use load management – energy efficiency, behind-the-meter energy and storage resources – to reduce the RA obligation.
**Storage Solution**

Energy Storage systems possess the ability to ramp much more quickly than traditional resources, the ability to regulate across the entire charge and discharge range of the resource, the ability to add controllable load to the grid in times of local renewable over-generation, and the ability to be distributed into areas where local capacity is most needed. The valuation and counting methods for RA and capacity do not currently account for these benefits, and may require additional development in order to appropriately account for the capacity value that energy storage can provide to the grid.

**Calculation of Resource Adequacy Requirements**

Resource Adequacy requirements are calculated as the sum of all differentiated capacity resources by type and location needed to achieve the reliability standard or metric. The various capacity resources are:

- **System Capacity**
  
  System RA requirements are determined based on the each LSE’s CEC adjusted forecast plus a 15% planning reserve margin.

- **Local Capacity**
  
  Local RA requirements are determined by the CAISO using an annual study which calculates the capacity needed to meet a 1 in 10 weather year and an (N-1-1) contingency. A local capacity resource can meet an LSE’s system capacity requirements, but not vice-versa.

- **Flexible Capacity**
  
  The methodology develops a minute-by-minute net load forecast for the next year and then calculates the highest monthly system net load ramp of 3 hours duration. It also adds additional reserves equal to the higher of the single largest contingency or 3.5% of the peak load.

California agencies are also evaluating new metrics which are suited to a power system increasingly dominated by renewable resources, most of which are variable energy resources.

**CAISO Wholesale Energy Time Shift**

**Definition**

It is the means by which end-use electric customers can reduce their electricity usage over a given time period, shift that usage to another time period, or contribute to grid reliability as a balancing resource in response to a price signal, to a financial incentive, to an environmental condition or to a reliability signal. It is also known as Demand Response. Customers who have the ability should have the choice to sell their demand response to a Demand Response Provider or to the CAISO.

**Types**

The different types may include programs and tariffs that reduce peak consumption, shift usage to off-peak hours and/or are used to adjust demand. These programs may be offered by an LSE or other third party Demand Response Provider. Rates more dynamic than Time-of-Use (TOU) rates, such as Critical Peak Pricing (CPP) and Real-Time Pricing (RTP), are tools of Energy
Time Shift which will be utilized by customers differently and impact the market distinct from programs where incentives are paid to participants.

**Objectives**

**Enhance Reliability and Infrastructure**
- Decrease controlled outages, such as rolling blackouts, during power system emergency situations
- Defer the need for investment in generation, transmission, and distribution by decreasing peak demands
- Interact with intermittent renewable resources to assist in their integration and in order to help meet Renewable Portfolio Standards

**Manage Electricity Costs**
- It can give customers an opportunity to have greater control over their energy use, and enable more effective response to dynamic tariffs and prices which reflect the time-varying cost of energy
- Demand response tariffs that dynamically incorporate the cost of providing electricity service can encourage consumers to adjust their usage and, in the aggregate, lower overall wholesale electricity costs for all customers
- Enhance market efficiency and help mitigate wholesale market power

**Reduce the Environmental Impact Caused by Electricity Usage**
- Demand response can reduce electricity use during peak periods when the least efficient generation units would be operating, which may thereby reduce greenhouse gas and other air emissions
- Demand response via permanent load shifting can help integrate intermittent, non-peak time, renewable resources into the electric grid and benefit the system load factor

**Technical Overview**

All customers are provided with cost-effective advanced metering systems capable of supporting time-varying tariffs with metering done on an hourly basis or better, and with minimal hardware upgrades necessary to participate in various dynamic pricing tariffs. The advanced metering systems will support the ability to automatically retrieve energy usage/data information and provide the customer with timely access to this retrieved data.

**Customer Time of Use (TOU) Energy Time Shift and Demand Charge Savings**

**Definition**

**Time of Use (TOU) Energy Savings**

It is the methodology of buying energy at a low price and selling at a higher price. The appropriate modeling showed that this benefit was not significant in many residential tariffs, since there is no TOU energy charge on the bill.
Demand Charge Management

It refers to a service offered by energy storage, or other measures, to reduce the demand charge portion of a customer electric bill. A demand charge is a charge levied proportional to the peak customer instantaneous demand each month. Typically the value of reducing demand charges exceeds the value of energy time-shifting, under current national tariff structures.

Storage Solution

Energy storage can store energy during periods when the customer demand is low and discharge to shave off peak customer load periods, which in some cases could be infrequent and short duration. The primary value driver of customer-sited, customer controlled energy storage systems comes from reducing peak demand to lower customers’ electricity bills, mostly through demand charge reduction, with some benefit potential from time of use (TOU) energy charge shifting from peak to off-peak. A secondary benefit may be improved customer reliability during a grid outage event, but the system needs to be configured to safely provide behind the meter power. When integrated with on-site solar according to IRS rules, a customer sited storage system may additionally be eligible for the 30% Federal Investment Tax Credit (FITC) and accelerated five year MACRS depreciation for renewable energy systems.

ESVT Modelling

ESVT first optimizes the energy storage charging and discharging behavior to minimizing the demand charges, which are assessed by the peak power rate over the course of a month. It accomplishes this by looking ahead in the month and identifying the lowest peak load target that can be accomplished by the energy storage. Next, if the customer also has a time-of-use energy rate, the energy storage will be charged and discharged to take advantage of time-shifting (arbitrage) opportunities. For enhanced reliability value of energy storage, the ESVT has the capability to reserve a certain amount of energy at all times in case of outage. However, this power reservation is typically not economic, so cases were modeled to calculate the value of incidental reliability by hour.

Tariff Reduction

When the storage system is operated to provide both demand charge reduction and TOU time-shift, it is dispatched to reduce the overall demand charge first, and maximize TOU time-shift savings within the constraints of demand charge management. In cases where the system is also operated to enhance power reliability, this service has the highest priority over the other two customer bill saving services. Because of the uncertain nature of power outage events, a storage system needs to be ready whenever the outage hits, or it would lose its reliability value.

Voltage Support

Definition

It is the ability to produce or absorb reactive power to maintain a specific voltage level under both steady-state and post contingency operating conditions subject to the limitations of the resource’s stated reactive capability. Voltage support is typically provided by generators but can also be provided by transmission devices such as static var compensators or tap-changing transformers.
**Technical Overview**

Generating Units providing Voltage Support must have automatic voltage regulators which can correct the bus voltages to be within the prescribed Voltage Limits and within the machine capability in less than one minute.

**CAISO Market Model**

There is no ancillary service market for voltage support or reactive power provision. Resources that provide are often provided cost-based payments or make-whole payments when they are needed and do not earn sufficient revenue from energy markets. If by providing reactive power the resource must adjust its active power output, market rules may provide the generator with a lost opportunity cost for the revenue it foregone in the energy market.

**Payment Structure**

The total payments for each scheduling coordinator for voltage support in any settlement period shall be the sum of the opportunity costs of limiting energy output to enable reactive energy production in response to a CAISO instruction. The opportunity cost shall be calculated based on the product of the energy amount that would have cleared the market at the price of resource-specific settlement interval LMP minus the higher of the energy bid price or the default energy bid price. If applicable, the scheduling coordinator shall also receive any payments under any long-term contracts due for the settlement period. Exceptional dispatches for incremental or decremental energy needed for voltage support procured through exceptional dispatch will be paid the higher of:

- resource specific settlement interval LMP
- energy bid price
- default energy bid

Reliability-must-run units providing voltage support are compensated in accordance with their reliability-must-run contract.

**Black Start**

**Definition**

The procedure by which a generating unit self-starts without an external source of electricity thereby restoring a source of power to the balancing authority area following system or local area blackouts. While this is conceptually a service that could be provided by energy storage, the exact specifications of a limited energy resource have not been well-defined, and it is typically considered to be a low value, incremental opportunity for energy storage.

**Technical Overview**

No Load served by the Black Start Generating Unit or by any designated Generating Unit or by any transmission facility used for Black Start service may be restored until the CAISO has confirmed that the need for such service has passed. Each supplier of Black Start capability must ensure that normal and emergency voice communications are available to permit effective. Each Black Start Generating Unit must provide sufficient reactive capability to keep the energized transmission bus voltages within emergency Voltage Limits over the range of no load to full
load. Each Black Start Generating Unit must be capable of sustaining its output for a minimum period of twelve hours from the time when it first starts delivering Energy.

**Starting Constraints**

Each Black Start Generating Unit must be able to start up with a dead primary and station service bus within ten minutes of issue of a Dispatch Instruction by the CAISO requiring a Black Start. These resources must be capable of starting without outside power supply and must also maintain rated output for a significant period of time.

**CAISO Market Model**

CAISO requests black-start service proposals and will then have cost-based recovery mechanisms in place for these resources. Typically, there are cost-based rates that are given to resources which are able to provide this service.

**Frequency Response**

**Definition**

It is an automatic change in active power output in response to a frequency change. It is required to maintain the frequency within statutory and operational limits.

**Technical Overview**

**Primary Frequency Control**

Frequency control is the immediate autonomous response that reacts to locally sensed frequency deviations, typically through turbine governors or sometimes automatic load curtailment relays. It is used to stabilize system frequency to some level above the setting of under-frequency load shedding relays.

Each supplier of Black Start capability must ensure that normal and emergency voice communications are available to permit effective. Each Black Start Generating Unit must provide sufficient reactive capability to keep the energized transmission bus voltages within emergency Voltage Limits over the range of no load to full load. Each Black Start Generating Unit must be capable of sustaining its output for a minimum period of twelve hours from the time when it first starts delivering Energy.

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**CAISO Market Model**

CAISO requests black-start service proposals and will then have cost-based recovery mechanisms in place for these resources. Typically there are cost-based rates that are given to resources which are able to provide this service.
Demand Response

Definition
It refers to a range of programs which alter the load realized for CAISO or utility operations in response to an economic or reliability dispatch instruction. While program rules are in development, storage of various configurations can be used for certain DR programs, either to modify load or to support the dispatch ability of DR resources into the wholesale market.

Types
Load Modifying Demand Response
It includes activities addressing the demand side of the supply-demand balance equation seek to modify the load shape by changing end-use consumption patterns, thereby reducing the need for additional and costly generation or transmission infrastructure. Such activities will both reduce overall energy consumption and alter the system or local load profile to reduce the severity of power demand peaks and valleys. These changes can benefit locally constrained areas as well as the overall transmission system. One strategy for this path is to provide locational and time-varying market signals to elicit demand-side responses that can respond to system conditions in a timely manner. For example, in conditions of over-generation, appropriate signals could trigger consumers to modify their consumption, such as the charging of electric vehicles or absorbing excess generation via various forms of battery energy storage.

Supply Resource Demand Response
The supply side of the supply-demand equation identifies a portfolio of resources in specific locations that will provide the operational capabilities necessary to reliably operate during both normal and emergency power grid conditions. Resource sufficiency must be assessed in light of grid physics and the portfolio of supply-side resources that are expected to be in service over the course of the planning period. This path focuses on clarifying resource types and locational attributes and the planning and study processes that will quantify resource requirements. It also examines the procurement processes that ensure the resources will be available when needed.

Operational Overview
Demand Response resources will contribute to the low-carbon flexible capacity needed to maintain real-time system balance and reliability while also supporting the integration of increasing levels of renewable energy resources. Anticipating the magnitude, type, timing and geographic distribution of these rapidly growing resources is as critical as solving the challenges of short-term and long-term forecasting of load variability as large numbers of resources inject energy into literally thousands of locations on the grid.

Flexible Ramping Product

Definition
The Flexible Ramping Product is procured in both the Fifteen Minute Market and in the 5-minute real-time economic dispatch. The FRP provides additional upward and downward ramping range.
Energy Locational Marginal Prices (LMPs)

**Definition**

Energy LMPs are calculated at over 3000 pricing nodes (PNodes) within the CAISO and pricing nodes in the EIM. These prices are calculated on 1-hour time-frames in the day-ahead market and both 15-minute and 5-minute time-frames in the real-time market.

**Mathematical Formulation**

Locational Margin Price (LMP) = \{Marginal Cost of Energy (MCE) + Marginal Cost of Congestion (MCC) + Marginal Cost of Losses (MCL)\}

**Technical Overview**

Marginal Cost of Energy

It is the component of the LMP that reflects the marginal cost of providing Energy from a CAISO-designated reference location.

Marginal Cost of Congestion

It reflects the effect of the marginal congestion cost on the LMP. It can be positive or negative depending on the location of the PNode with respect to the reference location, and whether injections at the location increase or decrease congestion.

Marginal Cost of Losses

It is the LMP component which represents the cost to suppliers of marginal losses at the PNode. It can be positive or negative depending on the location of the PNode with respect to the reference location, and whether injections at the location increase or decrease congestion.

**StorageVET Representation**

The full LMP is conventionally used to calculate energy time-shift/arbitrage or energy usage for provision of ancillary services. The LMP Marginal Congestion and Marginal Loss costs could be used as indicators of whether storage operations are likely to impact those components.
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