Energy Research and Development Division

FINAL PROJECT REPORT

Validated and Transparent Energy Storage Valuation and Optimization Tool

California Energy Commission

Edmund G. Brown Jr., Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently

Validated and Transparent Energy Storage Valuation and Optimization Tool is the final report for Energy Storage Valuation and Optimization Tool project contract number EPC-14-019 conducted by Electric Power Research Institute (EPRI). The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Electric grid energy storage is essential to improving the reliability and affordability of California's electric power system. Large-scale energy storage technology is a way to hold or store electricity when production exceeds consumption. Energy storage has the potential to transform and enhance electric utility planning and operations with more reliability and affordability, particularly when integrated with high amounts of renewable resources. Current software tools that calculate the value of energy storage planning and operation are limited, are proprietary, and/or have not been validated by the stakeholders who require them. A transparent and accessible public model that demonstrates and quantifies the current and future benefits of energy storage will provide substantial value.

The Storage Value Estimation Tool (StorageVET™) is a publicly accessible and customizable model for energy storage benefit-cost analysis. Users can assess a range of energy storage costs and benefits across multiple storage technologies, such as batteries, flywheels, control systems and power electronics) and includes a detailed financial model which can incorporate state or federal financial incentives. These evaluated benefits include day-ahead and real-time wholesale market revenues, avoided retail energy and demand charges, and avoided costs of alternative infrastructure investments. StorageVET™ can also analyze multiple-use applications, such as considering scheduling obligations incurred when the project is a Resource Adequacy capacity resource (utilities purchasing more than their peak load requirements to secure actual, physical commitments of electricity), or when providing transmission and distribution deferral, and distribution operational services. While the model is organized around the California power system and markets, it can easily be adapted to assessment of other regions. Hypothetically, **if** using StorageVET™ improves decision making by enhancing the combination of cost reductions and increased benefits by *1 percent* on average across the energy storage fleet in California; then the minimum baseline value of StorageVET™ is estimated at $36.5 million.

Keywords: Storage Value Estimation Tool (StorageVET™), Energy Storage Valuation Tool, energy storage, storage valuation, storage modeling, cost-benefit analysis

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Introduction

As California progresses towards its goal of 33 percent renewable electricity generation by 2020 and reducing greenhouse gases, electric grid energy storage is essential to improving the reliability and affordability of the state's electric power system. Large-scale energy storage technology is a way to hold or store electricity when production exceeds consumption. Developing this technology for electricity to be available when needed, such as during peak demand times, would be a major breakthrough in electricity distribution. Energy storage systems can also interface between generation and load for more reliable power, and better balance intermittent power (renewable sources such as solar or wind) and make it more easily transmitted. .

California has led in developing and implementing advanced energy storage projects. Despite this policy, advanced large-scale energy storage technologies, have not been widely used, and, more importantly, there appears to be little agreement or well understood on how best to quantify its value. These issues prevent infrastructure investments necessary for more energy storage installations.

Current software tools that calculate the value of energy storage planning and operation are limited, are proprietary, and/or have not been validated by the stakeholders who require them. A transparent and accessible public model that demonstrates and quantifies the current and future benefits of energy storage will provide substantial value.

Project Purpose

The Storage Value Estimation Tool, (StorageVET™) is a publically available software platform that can evaluate diverse energy storage projects consistently, across the different storage connections (transmission-connected, distribution-connected, and customer-sited). The report explores the software platform, how stakeholders were engaged to help shape the platform requirements, the features and functions of the software, and how a user can operate StorageVET™ to solve specific problems and the expected benefits of the software platform. The team also studied how the platform, combined with the information obtained in the platform development process, can be transferred to the public to realize the full potential.

As illustrated by the stakeholder-driven analyses completed by the California Public Utility Commission (CPUC) in the Assembly Bill 2514 energy storage proceeding, without a common, validated analysis platform, future energy storage system analysis would be fragmented and incomplete. The CPUC felt it was essential to build consensus on the methods used to develop and approve the most favorable storage projects. To help resolve this challenge, the Energy Commission released a competitive solicitation for a vendor to develop a new validated and publicly available method and supporting tool to provide more transparent decisions in future energy storage competitive selection rounds as part of the energy storage target set under Assembly Bill 2514 (Skinner, Chapter 469, Statutes of 2010).

Project Process and Results

To more clearly understand the software user needs, the research team used the Energy Storage Integration Council (ESIC) to solicit ongoing input and review from its members.

ESIC is an active technical forum convened by Electric Power Research Institute (EPRI) to safe, reliable, cost-effective and environmentally responsible electric energy storage systems by developing public guidelines and tools. The ESIC stakeholders provided feedback in the initial use case workshops and surveys, participated in the beta testing, and provided critical feedback throughout development process of StorageVET™

The use cases addressed by StorageVETare:

1. Estimate project benefits and costs: The model can determine the potential benefits and costs of an energy storage project given the location, size, and services available to it. This functionality may be useful for various potential investors of energy storage, including utilities, project developers/independent power producers, and electricity end customers. It may also be valuable for regulators reviewing investment decisions.
2. Compare project options: The tool compares multiple potential projects consistently. Differences between projects may be the project specification, location, or services addressed. This information may be valuable to investors or regulators who desire to benchmark multiple project options while using an equivalent set of assumptions and modeling methodologies.
3. Optimize project specification: The model determines 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.
4. Optimize project operations: StorageVET™ uses actual pricing and load data to simulate real operating conditions, and advanced techniques to generate optimal electricity into the grid.

Benefits to California

Energy storage has the potential to transform and enhance electric utility planning and operations with more reliability and affordability, particularly when integrated with high amounts of renewable energy. Because of current costs of energy storage technologies, however, it is crucial to provide economic assessments to support decisions made by developers, utilities, and regulators.

The CPUC directed combined procurement targets of 1.825 gigawatts (GW) of energy storage which will drive billions of dollars of ratepayer investment in energy storage over the next decade. There is clearly significant intrinsic value to a transparent and validated tool that simplifies stakeholder communication and cost-efficient use. Yet it is challenging to accurately quantify the ultimate benefits and cost-savings to the ratepayers that may result from using such a tool. It is a simpler task to establish a conservative minimum baseline for the value of StorageVET™. Hypothetically, **if** using StorageVET™ improves decision making by enhancing the combination of cost reductions and increased benefits by *1 percent* on average across the storage fleet in California; then the minimum baseline value of StorageVET™ is estimated at $36.5 million. In this hypothesis, the net benefit of the storage fleet without StorageVET™ analysis is equal to the capital investment; and the average capital investment is $2,000 per kilowatt (kW) of installed storage capacity.

Considering this value is likely to exceed the minimum baseline, the project development cost could have a significant rate of return for the California's electric ratepayers.

CHAPTER 1: Overview of Project Goals and Objectives

Project Goals and Objectives

Background

Under Assembly Bills AB2514 and AB2868 enacted in 2011 and 2016, California load-serving entities are required to evaluate and procure cost-effective storage technologies. The California Public Utility Commission (CPUC) set a combined target of 1.325 GW of new energy storage for the large investor-owned utilities procured by 2020 and deployed by 2024 (along with other targets for smaller load-serving entities), while the publicly-owned utilities submitted their first assessment of storage procurement to the California Energy Commission (Energy Commission) in 2014, with the next due in 2017. For its jurisdictional utilities, the CPUC has required that a common Consistent Evaluation Protocol (CEP) is filled in for all storage procurement proposals, but it will remain confidential. Moreover, the valuation methods used in actual procurement decisions remain proprietary to the utilities.[1] Hence, there is no tool available for policy-makers, regulators, or market participants to share common assessments of historical or future storage value across different scenarios. As such, despite the advances in storage policy and procurement, the role and valuation of energy storage is not fully understood publicly nor are valuations agreed upon. This is not just a California phenomenon, but has also been noted generally across the country by advisory committees of the US Department of Energy (DOE) (EAC, 2016).

To support informed and cost-effective energy storage deployment, all engaged stakeholders must understand the assessed costs and benefits and optimization of energy storage projects with respect to use, technology, size, and location. A foundation for this common understanding is agreement on valuation results given a set of inputs and modeling methods. This project has developed a modeling tool which advances this objective for California storage applications, and potentially other regions with straightforward extensions.

Project Overview

The project team has developed and deployed a publicly available, web-hosted software model named the Storage Value Estimation Tool, or StorageVET™, and reference databases that support assessment and optimization of energy storage projects, leading to informed decision-making by regulators, utilities, and energy storage project developers. The model was developed collaboratively with an expert project team, open stakeholder processes, and reference data sets. StorageVET™ is also adaptable to certain changes in market designs and valuation methods over time.

1 These methods are described generally in the utility applications but are otherwise not public.

Project Goals

The goals of this project were to:

- Facilitate assessment and communication of the value for energy storage projects.
- Support optimization of energy storage project cost-effectiveness.

Declining storage costs have raised policy and market interest in many potential storage applications over the coming decade, across the transmission-connected, distribution-connected, and customer-sited domains. California is the national leader in implementing storage policies, but there is as yet very little new storage operating on the California grid, and many of the already contracted projects will not come on-line for several years. Initial results of demonstration projects are just now becoming available (e.g., PG&E 2016). StorageVET™ is thus expected to result in the ratepayer benefits of lower costs, increased reliability, and improved safety by making widely available a credible, flexible, and practical tool for determining the value of energy storage projects by technology, use, location, and size in a way that facilitates communication among interested stakeholders. This facilitated communication is crucial to good decision-making on investment in the numerous new energy storage projects anticipated in California.

Greater reliability is expected from improved understanding of energy storage benefits and costs, such that greater use of energy storage may be enabled where it is cost-effective for utility customers and ratepayers. *Lower costs* are expected because the use of this tool could greatly improve stakeholder communication regarding the best investments in storage. *Increased safety* is expected because deploying a flexible resource like energy storage supports public benefits. Many regions, including California, have an interest in utilizing storage as a rapidly deployable resource which can address potential system emergencies or support system resiliency. This tool will contribute to this assessment by providing detailed economic analysis of multiple use applications including emergency deployments at different points of connection.

Project Objectives

Following the goals established earlier, the objectives of this project were to:

- Obtain buy-in from key stakeholders on requirements and approaches
- Leverage prior investments in models and analyses
- Create reference scenarios and data sets through coordination with relevant proceedings
- Develop and deliver a public, transparent, and validated tool as cloud-hosted software
- Achieve broad adoption of software with robust technology transfer activities

Summary of Goal and Objective Attainment

Goals Attained

StorageVET™ supports the project goals by providing the first publicly accessible, cloud-hosted tool for storage optimization, along with advances in the types of products and applications which can be modeled. In particular, StorageVET™ expanded on the capabilities of prior models of the same type, providing a closer correspondence to storage operations and revenues in actual power markets. These developments are expected to bring ratepayer benefits, both by improving accuracy of storage analysis and by allowing a wider set of actors to evaluate storage value and communicate their results.

StorageVET™ leverages the substantial prior developments of the Electric Power Research Institute (EPRI) Energy Storage Valuation Tool (ESVT), and provides a range of new capabilities. When ESVT was first developed, it represented a step forward in storage modeling by providing a complete cost-benefit framework along with a large number of pre-packaged storage technologies and a combustion turbine model as a capacity benchmark. ESVT was used to inform the CPUC's storage proceeding in the early phases (EPRI, 2013). However, ESVT has limitations that would not meet the requirements of a publically available tool. StorageVET™ includes many improvements to the ESVT approach:

- ESVT is an offline platform requiring users to separately license the Analytica software platform. It is not generally available to the public.
- ESVT dispatch simulation can only operate on an hourly time step. It does not accept input data in any other format.
- ESVT does not simulate state-of-charge effects of regulation activity.
- ESVT uses an optimization engine that limits the number of decision variables. This limits flexibility of service selection and time-step granularity.
- ESVT does not evaluate conflicting constraints caused by the selection of multiple services. It does not allow users to prioritize services to resolve conflicts.
- ESVT does not identify limiting storage performance factors in investment deferral use cases.
- ESVT does not include Flexible Ramping and does not allow for the addition of additional services in the future.
- ESVT does not allow for the easy addition of new storage technologies and financial incentives.

To address these limitations, the Energy Commission supported the development of StorageVET™ to establish a publicly accessible, cloud-hosted software tool that leveraged and advanced software code and modeling methods from the ESVT model, but focused on the specific storage valuation needs of California. StorageVET™ includes valuation used in energy storage planning and procurement by utilities; a framework which could consider a broad scope of the CPUC use cases, costs, and benefits; and methods to evaluate storage in the presence of increasing renewable penetration and other changes to power system conditions. Access to StorageVET™ is simplified. Users who desire to preserve confidentiality of their data will be able to download the tool to a desktop, although this approach will require an Analytica™ license. StorageVET™ has implemented modeling advancements over ESVT, including enhanced representation of services and dispatch in the sub-hourly time domain and better representation of decision-making under uncertainty through scenario analysis. Increased automation is implemented to inform optimized project design in a user-friendly manner. Other development objectives were to respond to the stakeholder needs identified through use case workshops, surveys, and other stakeholder engagement meeting. These model attributes, including a detailed comparison to ESVT, are discussed further in Chapter 3.

Objectives Attained

This section provides a checklist of key objectives of the project and how they were achieved, with each relevant chapter identified. Subsequent sections of the report provide many more details.

- Chapter 2: Obtained buy-in from key stakeholders on requirements and approaches through multiple stakeholder engagements to guild the development of use cases for StorageVET™. To this end, the project team:
    - Solicited feedback on use cases, technologies, and services to include in the model from multiple stakeholders through workshops and surveys.
    - Used the Energy Storage Integration Council (ESIC) to advise on model attributes and also provide beta testing.
    - Organized a Technical Advisory Committee which included industry representatives to review the process of the development.
- Chapter 3: Leveraged prior investments in models and analyses by examining and advancing on codes and methods used in ESVT, incorporating authors of ESVT into the StorageVET™ project team and comparing modeled results of similar projects from ESVT and StorageVET™. The project team identified a series of additional capabilities not included in ESVT including new types of wholesale market processes and products which did not exist when ESVT was deployed, such as the CAISO Fifteen Minute Market (begun in 2014) and Flexible Ramping Product (begun in November 2016).
- Chapter 3: Created reference scenarios and data sets through coordination with relevant proceedings as evident in the use cases in the Quick Start module of StorageVET™;
- Chapters 4-5: Developed and delivered a public, transparent, and validated tool as cloud-hosted software;
    - StorageVET™ has undergone robust alpha and beta tests as well as internal quality assurance process.
    - All documents developed in the process are referenced and published, including the development of use cases, extensive details of the model structure and user interface.
- Chapters 5, 7: Projected to achieve broad adoption of software with robust technology transfer activities.
    - Outlined the planned technology and knowledge transfer activities and expected results.

In sum, these model improvements make StorageVET™ the most sophisticated commercial model of its type for the California market, as well as being both publicly available and easily accessible.

CHAPTER 2: Understanding Industry Needs

Purpose

This chapter provides a summary of the process to determine functional and technical objectives for the StorageVET™ model. This was accomplished through a combination of the following:

- Engagement with target users of the model to develop functional and technical requirements.
- Background research of regulatory and technical information pertaining to storage to support model definition.

Methodology to Collect Industry Needs – Workshops/Review/Survey

To support the objective to obtain buy-in from key stakeholders on requirements and approaches, the project team engaged stakeholders at different stages of the project, including two initial use case workshops to collect stakeholders' expected use of the tool, surveys to stakeholders to prioritize the use cases once they were narrowed down, and multiple review and test sessions to go through the functionality of StorageVET™.

Workshops

The project team held two use case workshops on September, 1, 2015 and December, 10, 2015. In the first workshop, the team solicited input about how the users and other storage stakeholders may use the forthcoming tool to make various decisions. The second workshop was focused on how the discussed use cases address the complex aspects storage investment, operations, and system design.

The workshops were organized into three separate breakout sessions, or "tracks", that focused on technology, services, and tool functionality.

Topics discussed in the technology track:

- Which technologies must be included? Which others would be nice to have?
- Costs of storage: what are included in the cost numbers? Are the language and parameters used to characterize all technologies consistent?
- Performance of storage: at which interface of storage is the performance measured? Which parameters impact the cost-effectiveness of storage?

Topics discussed in the grid services track:

- What are the commonalities and conflicts among various service objectives?
- What framework and parameters define a service?
- What service combinations represent the most common use cases?
- How should dispatch be prioritized among multiple services?

Topics discussed in the tool functionality track:

- List and prioritize valuation metrics.
- Prioritize gaps among required metrics, ESVT outputs, and CEP requirements.
- Identify strategies for establishing common valuation outputs.
- Identify and prioritize software functionality to support these outputs.

The discussions at the workshops were organized into functional requirements around use cases, the types of services, and the technologies. The project team summarized the findings in a separate EPRI document *StorageVET™ Use Cases* (Appendix A).

Survey

After collecting feedback from the workshops, the project team organized the use cases under three general types of users: regulators, investors, and operators of energy storage. The project team defined the use cases in terms of parties involved, the required data, the processes of how such decisions are made, and how they can be implemented in StorageVET™. The project team then conducted a survey of stakeholders in February 2016 to determine the priorities for use cases, services, and technologies to be considered in the tool. The respondents identified the following key purposes for a public energy storage valuation tool:

- To validate internal modeling regarding the economic feasibility of energy storage projects to financial institutions and clients.
- To compare results to proprietary economic models for validation.
- To understand the drivers and key applications of Energy Storage Systems from utilities and market perspective.
- To help design systems that better meet customer requirements.
- Provide a common view and consistent methodology of the value of energy storage within a use case and specific location.

The results of this survey are presented later in this chapter.

Technical Advisory Meetings

The project team held four technical advisory meeting throughout the length of the project with ESIC members to get feedback on the prioritized use cases, final functionality of the model and data inputs.

Role of the Energy Storage Integration Council (ESIC) in StorageVET™ Development

This project utilized EPRI's Energy Storage Integration Council (ESIC) to solicit ongoing input and review for this project. The stakeholders in ESIC provided feedback in the initial use case workshops and surveys, participated in the beta testing, and provided feedback throughout development process of StorageVET™.

ESIC is an open, technical forum with the mission to advance the integration of energy storage systems through open, technical collaboration. ESIC began in 2013, sponsored by the Energy Storage Program at EPRI, in collaboration with utilities, vendors, National labs, and industry experts created the Energy Storage Integration Council (ESIC). Its mission is to facilitate safe, reliable, affordable, and environmentally-responsible electricity through the development of publicly available guidelines and tools. ESIC is an active venue, with multiple meetings per month, executed via a combination of in-person meetings and webcasts, with the objective to identify utility and regulatory requirements, discuss technical gaps, and align on common approaches for the effective implementation of energy storage across several topic areas.

ESIC is generally organized into three major working groups: Grid Services and Analysis, Testing and Characterization, and Grid Integration. Specific work product developments are facilitated through more frequent, small group discussions in subgroups. More information about ESIC can be found at the ESIC website: www.epri.com/esic.

StorageVET™ complements several other publicly available tools and guidelines published by EPRI through ESIC. A special "StorageVET™ subgroup" was created under the Grid Services and Analysis working group.

Background Research for StorageVET™

The project team conducted research of the regulatory landscape and market information in California. This background research is summarized in *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model* (Appendix C).

The document provides general descriptions and technical details about the California policy, program and market contexts for energy storage use cases and applications modeled in StorageVET™ and other storage valuation tools. The purpose of the document is to allow StorageVET™ users to gain an understanding of how storage valuation is conducted in California, and how the quantitative results available through the StorageVET™ tool should be interpreted.

This includes details on how storage resources will actually be modeled, operated, and valued by California entities when providing one or more wholesale market services, distribution integration capacity analysis and distribution services, transmission and distribution deferral, and retail rate reductions. In addition, the document explains the correspondence between the StorageVET™ model structure and how actual storage projects are valued. Most of the relevant market designs, rates, and regulatory rules are summarized, along with guidance on further research.

In addition, the document points to recent and ongoing storage demonstration projects in California which may provide valuation results which can be replicated or compared to those from StorageVET™. These include the references in (Rawson and Sanchez, 2015; Pacific Gas and Electric, 2016; Southern California Edison, n.d; Pacific Gas and Electric, n.d; and San Diego Gas and Electric, 2016).

Overview of Findings

The findings from the stakeholder engagement process and the background research are summarized into *StorageVET™ Use Cases* (Appendix A) and *StorageVET™ Functional Requirements and Interface Specification* (Appendix B). The former outlines the types of problems various users can utilize StorageVET™ to solve, the processes of how these decisions are made and the necessary inputs and outputs of each use case. The latter summarizes the requirements on functions and user interface stemming from the use cases.

StorageVET™ Use Cases

The use case document explains how different users may utilize StorageVET™ and the steps they would follow. The methodology used to develop the use cases is commonly used when planning software development. As previously described, the use cases were organized under three types of functional users: regulators, investors, and operators. While it is certainly possible for other types of individuals and entities to use the model, such as researchers, this document describes how these three types of functional users can use StorageVET™ to address a particular type of problem, the stakeholders that are involved, and the necessary information for each use case. In addition, this document also describes the processes that StorageVET™ goes through to solve the use cases, includes starting condition, steps, and end results, as well as exceptions.

StorageVET™ Functional Requirements and User Interface

This document describes the functionality of StorageVET™ software. It is derived mostly from the processes in the StorageVET™ Use Cases document. This document describes the purpose of each function in the StorageVET™ software and how the functions map to the use cases. Its primary use was for the StorageVET™ developers to understand the requirements and how they should be implemented.

Prioritizing Functionality and Data Sources

In the survey discussed earlier, the project team asked various stakeholders to prioritize the use cases. Following the prioritization, the project team examined the interdependencies of the use cases and re-ranked them to meet the project goals and identify tasks that must be completed early in the development process. This ranking by stakeholders and project team are presented in Table 1. More details about each use case can be found in *StorageVET™ Use Cases* (Appendix A).

Table 1: Prioritizing the Steps for Development of the Functionality

Regulator		Ranking by Stakeholders	Ranking by Project Team
1.1.	Design Scenarios and Model Assumptions	Very Important	Very Important
1.2.	Compare ES Project Benefits, Costs, & Risks	Very Important	Very Important
1.3.	Design Incentives		Potentially Important
1.4.	Model / Data Benchmarking	Very Important	Potentially Important
1.5.	Define Benchmark Model for Improving CEP		Potentially Important
Investor			
2.1.	Screen Feasible Locations	Very Important	Very Important
2.2.	Size a Project by Location, Primary Service, and Technology	Very Important	Very Important
2.3.	Benchmark a Proprietary Valuation Method	Very Important	Potentially Important
Operator			
3.1.	Reshape Net Load Profile	Very Important	Very Important
3.2.	Co-Optimize Services Scheduling	Very Important	Very Important
3.3.	Determine Left-Over Storage Capacity	Very Important	Very Important
3.4.	Schedule an Outage		Potentially Important
3.5.	Backup Power		Very Important
3.6.	Power Quality		Potentially Important
3.7.	Calibrate Degradation Model		Potentially Important

Please see Chapter 6 Use Case Ranking in Appendix A for more detailed results of the survey

The data sources that were identified by stakeholders to be included in the StorageVET™ are:

CAISO OASIS data 26 percent

- Weather Data 15 percent
- Green Button Load Data 14 percent
- OPEN EI 11 percent

Mapping of Use Cases

The project team consolidated the use cases that were proposed by the stakeholders because it is possible to utilize one use case for many applications. Table 2 shows the mapping between different use cases for StorageVET™ and those from the perspective of the different potential users of the tool (namely, regulator, investor, and operator). The actual use cases implemented in StorageVET™ are summarized as:

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.

Table 2: Mapping between Stakeholder-Identified Use Cases and StorageVET™ Use Cases

Stakeholder-Identified Use Cases		StorageVET™ Use Cases
Regulators		
1.1.	Design Scenarios and Model Assumptions	Compare project options
1.2.	Compare ES Project Benefits, Costs, & Risks	Optimize project specification
1.3.	Design Incentives	Optimize project specification
1.4.	Model / Data Benchmarking	Optimize project specification
1.5.	Define Benchmark Model for Improving CEP	Optimize project specification
Investors		
2.1.	Screen Feasible Locations	Optimize project specification
2.2.	Size a Project by Location, Primary Service, and Technology	Optimize project specification
2.3.	Benchmark a Proprietary Valuation Method	Estimate project benefits and costs
Operators		
3.1.	Reshape Net Load Profile	Optimize project operations
3.2.	Co-Optimize Services Scheduling	Optimize project operations
3.3.	Determine Left-Over Storage Capacity	
3.4.	Schedule an Outage	Optimize project specification
3.5.	Backup Power	
3.6.	Power Quality	Optimize project operations
3.7.	Calibrate Degradation Model	Optimize project operations

CHAPTER 3:
Software Development

In this chapter, a comparison of ESVT and StorageVET™ is first presented to illustrate the advances developed for the StorageVET™ model. Subsequent sections describe the model structure of StorageVET™, the use cases the tool covers, and an overview on how the tool models grid services and technologies. For more detailed explanation of how StorageVET™ considers grid services and each storage technology refer to *StorageVET™ V1.0 Software User Guide* (Appendix D) and *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to StorageVET™ Model* (Appendix C).

ESVT and StorageVET™

EPRI and E3 developed the Energy Storage Valuation Tool (ESVT) in 2011. At the time, ESVT represented a step forward in storage modeling by providing a complete cost-benefit framework along with a large number of pre-packaged storage technologies and a combustion turbine model as a capacity benchmark. ESVT was used to inform the CPUC's storage proceeding in the early phases (EPRI, 2013). ESVT is written fairly generically to accommodate users in different U.S. wholesale markets. Its optimization time-step is typically hourly, corresponding to the day-ahead wholesale markets, but can also be set by the user and supported with datasets. Among the limitations of ESVT is that non-EPRI member users have to buy a license, and users have to download the Analytica software which also has license requirements.

The one-hour time-step in ESVT limits the ability to model the CAISO real-time markets, which are becoming more important for renewable integration. Furthermore, the generic market product definitions and financial settlement assumptions do not necessarily correspond to the specifications in particular markets. These limitations were considered reasonable at the time for a planning tool, and were not intended to validate actual market participation.

StorageVET™ addresses these limitations by enabling a publicly accessible, cloud-hosted software tool that leverages an advanced software code and modeling methods from the ESVT model with a focus on the specific storage valuation needs in California. The updated tool is also anticipated to offer the opportunity to validate actual market results. Table 3 provides a detailed comparison of the improvements made between ESVT and StorageVET™ when modeling particular market services. More details on how these services are modeled can be found in subsequent chapters and in the appended reports.

Table 3: Key Comparisons Between ESVT and StorageVET™

	ESVT	StorageVET™
Day-Ahead Market		
Energy	24-hour optimization, 1 hour time-step	Model structure is the same as ESVT, but with option to calculate result based on persistence (to measure effect of market price uncertainty)
Regulation	Regulation Up and Regulation Down capacity as separate or combined services	Model structure is the same as ESVT, but with additional options to calculate eligible capacity for different CAISO market participation models (e.g., NGR, NGR-REM)
	Regulation mileage payment not included	Regulation mileage payment included on an hourly basis
	Regulation energy make-up using average day-ahead energy prices	Regulation energy make-up is calculated more accurately based on actual real-time energy prices on 15 minute basis.
	Only one method for modeling Regulation: co-optimized with other services	Two methods for modeling Regulation: co-optimized with other services; and Regulation only under CAISO Regulation Energy Management (REM) rules.
Spinning and Non-spinning Reserves	Modeled as capacity reservation, co-optimized with other services.	Model structure is basically the same as ESVT.
Resource Adequacy capacity scheduling	Storage resource is required to operate in user-defined peak hours	Storage resource can be modeled as either (a) available to operate in user-defined peak hours, or (b) as required to operate in those hours.
Real-Time Market		
Energy	Not modeled	Models Energy dispatch in Fifteen Minute Market (FMM), using 2 hour optimization horizon
Flexible Ramping Product (FRP)	Not modeled	Models FRP as co-optimized with Energy in Fifteen Minute Market (FMM), using 2 hour optimization horizon
Ancillary Services	Not modeled	Day-ahead ancillary service awards can be used as constraints when calculating real-time energy and FRP opportunities

StorageVET™ Architecture Overview

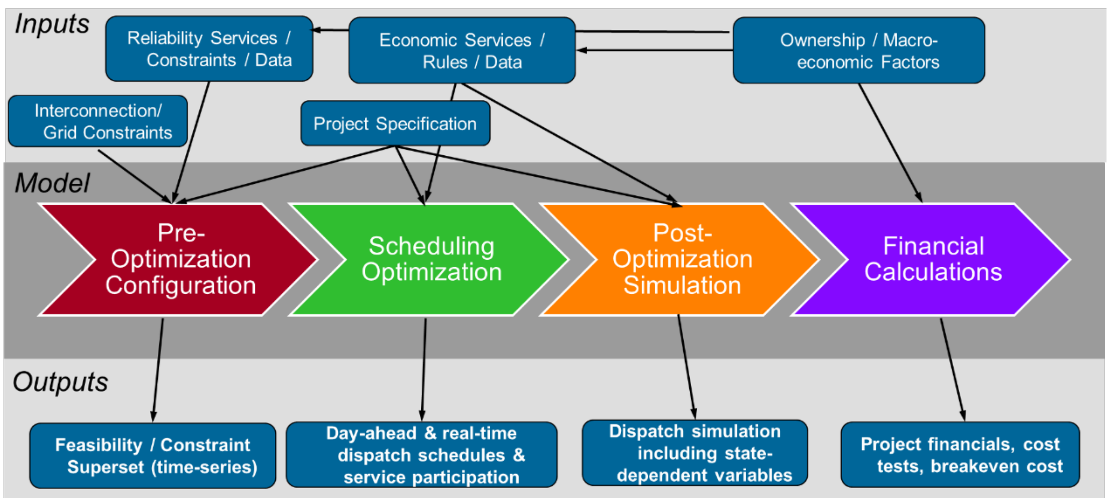
The architecture of StorageVET™ contains four major modules, each with an important purpose toward to the goal of enabling flexibility, modularity, and ability to configure scenario-specific evaluations of energy storage projects.

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 2.

Figure 1: StorageVET™ Functional Modules



Descriptions 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

Scheduling Optimization

The primary purpose of this module is 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 2 and 3 illustrate a co-optimized day-ahead energy storage project schedule, which includes storage participation by grid service.

Figure 2: Illustration of Scheduling Optimization Module Output, Energy Dispatch

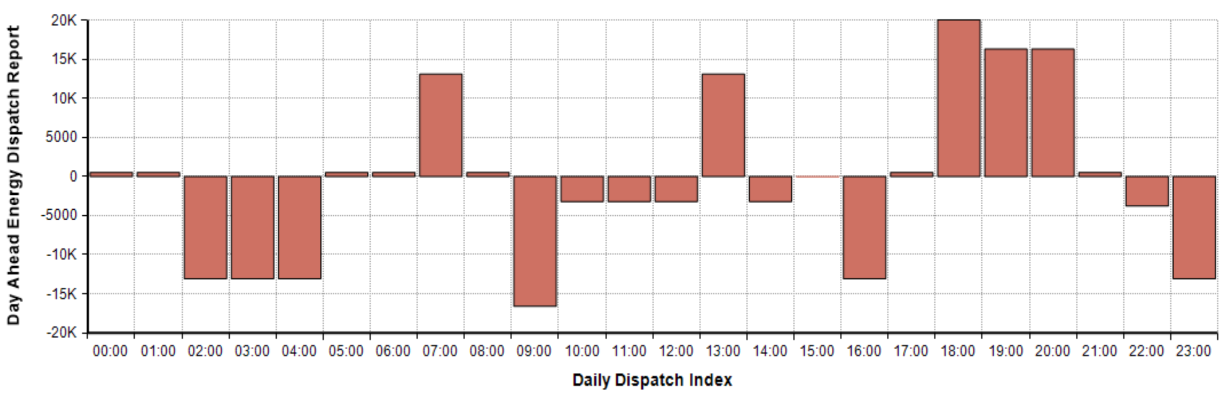
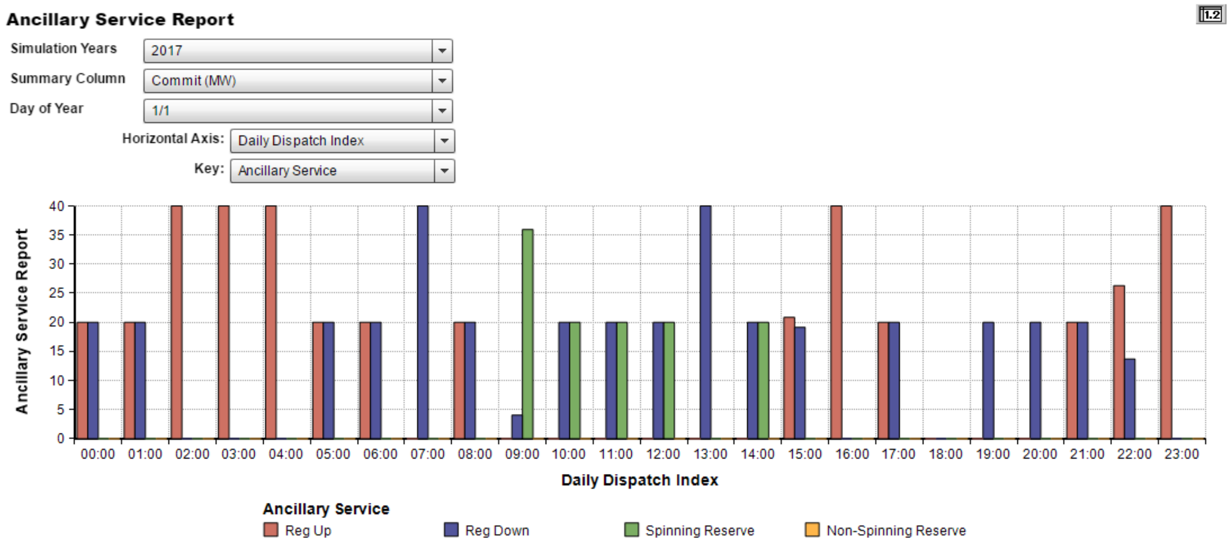


Figure 3: Illustration of Scheduling Optimization Module Output, Ancillary Services



Post-Optimization Simulation

This module incorporated the 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. P_{min} or efficiency as a function of SOC)
- Key outputs
    - Time-series power and energy dispatch of project
    - State-of-charge evolution
    - State of health and degradation

Currently, the most important function of this module is to enable the incorporation of minimum power output levels (often called "P_{min}") 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.

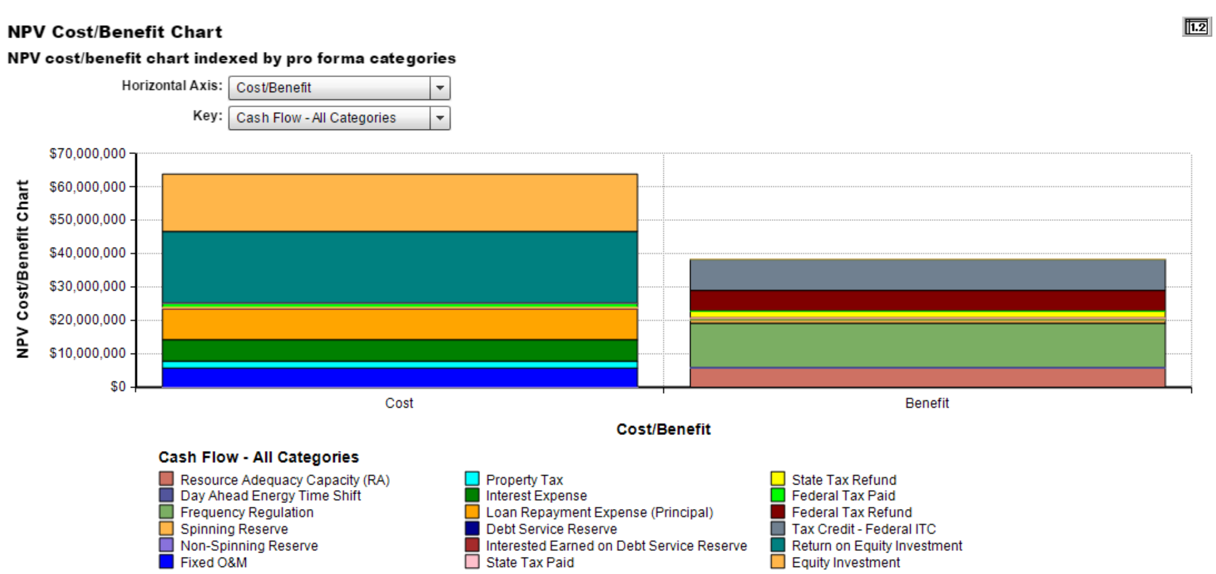
Financial Calculations

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
    - Benefit to cost ratios
    - NPV
    - Net cost of capacity
    - Breakeven CAPEX
    - Project pro forma financials
    - PUC cost tests (for customer programs)

An illustrative output from the Financial Calculations module is provided in Figure 4.

Figure 4: Illustrative Output of the StorageVET™ Financial Calculation Module



StorageVET™ Software Limitations

Many of the limitations of StorageVET™ are because it models the storage technology only, and does not model any system effects due to storage operation, except potentially indirectly. These include the following:

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 does not 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.

Use Cases Supported By StorageVET™

Primary Use Cases with StorageVET™ Standalone Tool

The use cases presented here are the generalized categories mapped to the use cases identified in Chapter 2.

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

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 the optimized project operations under user-defined configuration for services, priorities, and time.
   - Results: The use case produces the net present value (NPV), the benefit-to-cost ratio, the 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.

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

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.

Example Use Cases Supported by Multiple Tools

Using 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 operations 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.

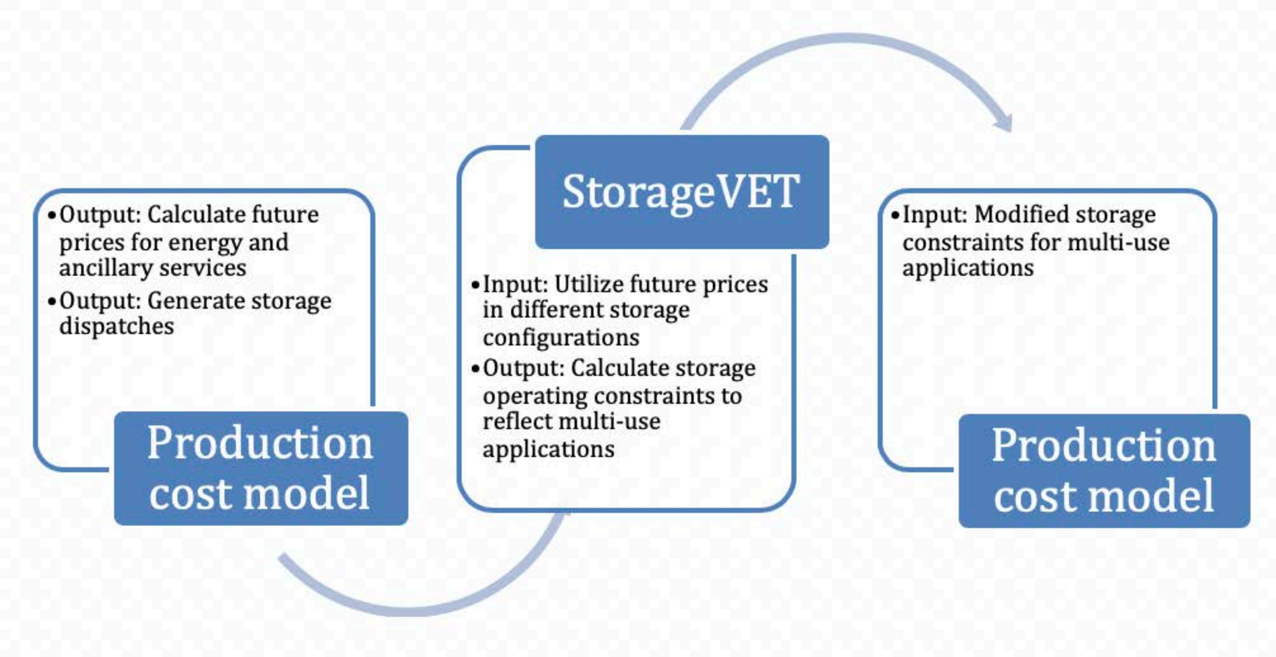
These types of models have been available for decades, but have undergone additional refinements to accommodate more services and improve both short-term and longer-term market and operational forecasting. In addition, some software packages include market bid curves using ISO-released data, and hence 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 (Koritarov et al., 2013; Eichman et al., 2015; California ISO, 2016; and Liu et al., 2016). Some of these are discussed further below.

Flow Chart Conceptual Methodology

Figure 5 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 5: Conceptual Framework for StorageVET™ Use 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, mentioned 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.

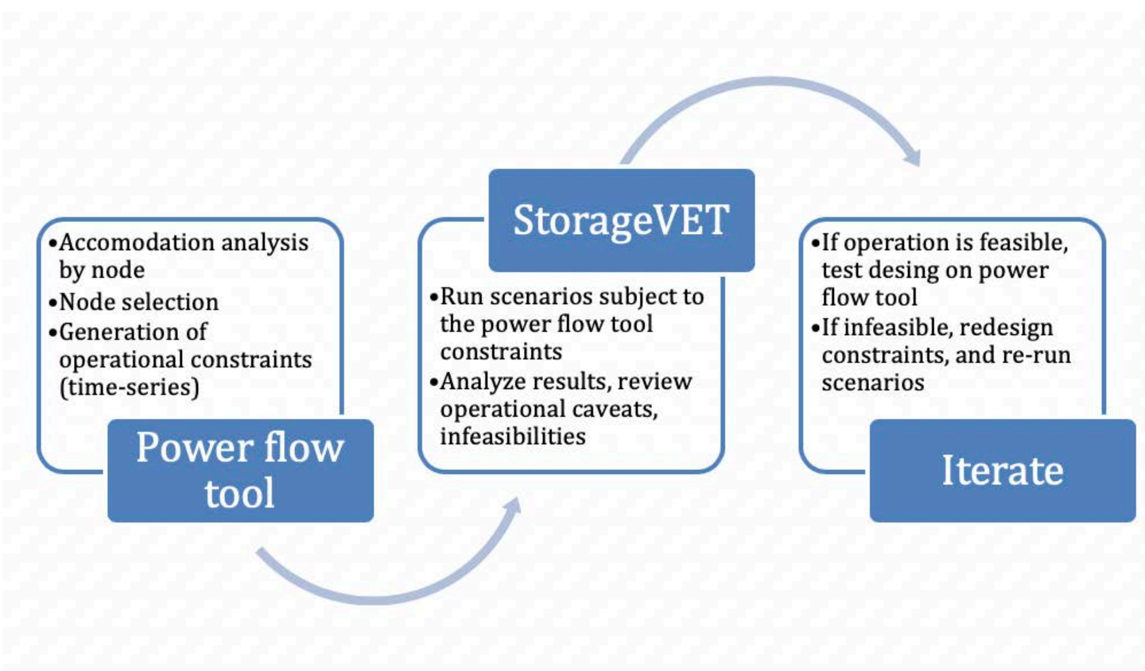
In other cases, the decision about storage applications in the production cost model may depend on market rules which can be better assessed initially with StorageVET™. For example, in the CAISO, while there is one frequency regulation control signal, there are several participation models for providing 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,* (EPRI, 2016, 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 (Figure 6).

Figure 6: 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.

Overview of Energy Storage Applications Covered

In this section, the types of grid services covered in StorageVET™, how various technologies are modeled, and the more-detailed optimization procedures are explained.

Storage Services and Applications

A service or application refers to a particular defined aspect of the electric power system. There are several different categories of these services and applications. Generally, a service is defined by a regulator, utility, or market operator, and has specific requirements for storage resource eligibility and operations.

Table 4 lists the services represented in StorageVET™. For more details about each service, see EPRI reports prepared for StorageVET™ users, *StorageVET™ V1.0 Software User Guide* (Appendix D), or on the rules and requirements of each service in California, *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to StorageVET™ Model* (Appendix C).

Table 4: Overview of Grid Services Covered in StorageVET™

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

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).

Table 5: Mapping Between Feasible Services and Location of Storage Asset

Service/Location	Behind-the-Meter	Distribution	Transmission
Resource Adequacy Capacity	1	1	1
Day-Ahead Energy Time Shift	0	1	1
Real-Time Energy Time Shift	0	1	1
Frequency Regulation	1	1	1
Spinning Reserve	1	1	1
Non-Spinning Reserve	1	1	1
Regulation Energy Management	0	1	1
Flexible Ramping	0	1	1
Investment Deferral	0	1	1
Transmission Voltage/Reactive Power Support	0	1	1
Losses Reduction	0	1	0
Voltage Control	0	1	0
Retail Demand Charge Reduction	1	0	0
Retail Energy Time Shift	1	0	0
Power Quality	1	0	0
Backup Power	1	0	0

Service/Location	Behind-the-Meter	Distribution	Transmission
Demand Response Program Participation	1	0	0
PV Self-Consumption (FITC Eligibility)	1	0	0

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 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 6 shows an example of the priority matrix used for the feasibility logic to establish operational constrains and determine the services that can be offered.

Table 6: Example of the Priority Matrix Defined by the User

User Constraints	3
Deferral	4
RA (Availability)	5
RA (Dispatched)	6
DR	7
Voltage Support	8
Backup Power	9
Interconnection Constraints	2
PV Related Constraints	1
Placeholder 2	10

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 (see Table 7).

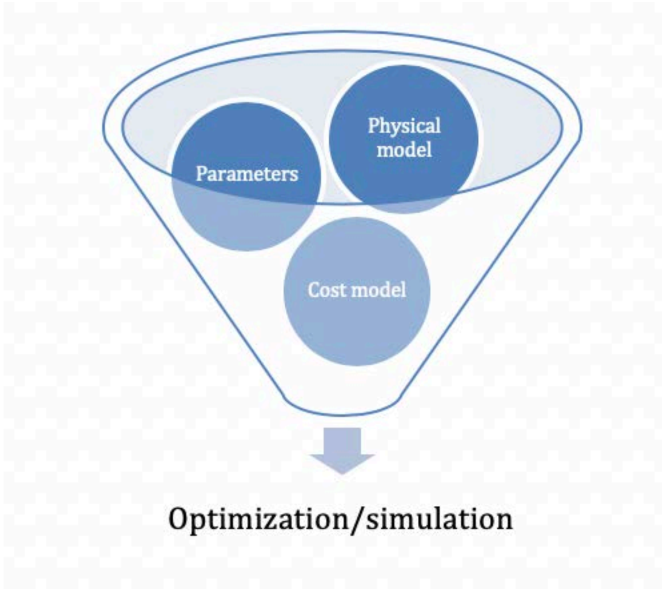
Table 7: Mapping between Feasible Services and Ownership of Storage Asset

Service/Ownership	Customer-Owned	Utility-Owned	IPP-Owned
Resource Adequacy Capacity	1	1	1
Day-Ahead Energy Time Shift	0	1	1
Real-Time Energy Time Shift	0	1	1
Frequency Regulation	1	1	1
Spinning Reserve	1	1	1
Non-Spinning Reserve	1	1	1
Regulation Energy Management	0	1	1
Flexible Ramping	0	1	1
Investment Deferral	0	1	0
Transmission Voltage/Reactive Power Support	0	1	0
Losses Reduction	0	1	0
Voltage Control	0	1	0
Retail Demand Charge Reduction	1	0	0
Retail Energy Time Shift	1	0	0
Power Quality	1	0	0
Backup Power	1	0	0
Demand Response Program Participation	1	0	0
PV Self-Consumption (FITC Eligibility)	1	0	0

Technologies

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 (Figure 7). These elements represent operational characteristics of the various technologies that impact system performance and indirectly, the valuation result.

Figure 7: 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 defines 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.

Parameter Summary

Table 8: Storage Technologies with Corresponding Parameters Used for Modeling

		Charge Capacity	Discharge Capacity	Energy Capacity, SOC Bounds	Charge Efficiency	Discharge Efficiency	Housekeeping Power	Heat Rate	Self-Discharge Rate	Charge Ratio	Min. Charge	Min. Discharge
Electrochemical	Li-Ion	■	■	■	■	■	■		■			
	Sodium Sulfur	■	■	■	■	■	■		■			
	Lead Acid	■	■	■	■	■	■		■			
	Zinc Bromide	■	■	■	■	■	■		■			
	Liquid Metal	■	■	■	■	■	■		■			
	Na Ion	■	■	■	■	■	■		■			
	Vanadium Redox	■	■	■	■	■	■		■			
	Zinc Bromide	■	■	■	■	■	■		■			
	Fe Cr	■	■	■	■	■	■		■			
Mechanical	Pumped Hydro	■	■	■	■	■	■		■		■	■
	CAES, adiabatic	■	■	■			■		■	■	■	■
	CAES, non-adiabatic	■	■	■			■	■	■	■	■	■
	Flywheels	■	■	■	■	■	■		■			
Thermal	Water Heaters	■	■	■	■	■						
	Thermal Brick Systems	■	■	■	■	■						
	Chilled Water	■	■	■	■	■						
	Ice	■	■	■	■	■						

Other Technologies	Vehicle to Grid											
	Combustion Turbine											

The table above relates storage technologies with the corresponding set of parameters that is used for modeling. 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

For details on specific parameters, operational constraints and mathematical formulation of each model, refer to Chapter 6 of *StorageVET™ V1.0 Software User Guide* (Appendix D).

CHAPTER 4: Software Review

Review Methodology

During the software development process, the project team organized two user tests to collect feedback on StorageVET™'s user interface and modeling process. The alpha test was carried out under a controlled environment where the testers guided the users through specific test cases within designated time; the users only had access to the model within the sessions. The beta test was released to a broader group within ESIC over five weeks; the users were able to access the model on their own time and run their own cases with pre-loaded data sets, though the functionality to upload user-supplied time series data was not available in the beta model. In addition to the two external user tests, the project team carried out its own quality assurance and control processes to ensure the usability of the tool.

Alpha Testing Process

Alpha testing sessions for StorageVET™ occurred from July 26, 2016 to July 28, 2016 with representatives from Ameren Illinois, Southern California Edison Co., Black & Veatch Corp., Strategen, PacifiCorp, Highview Power Storage, and Xcel Energy Services, Inc.

Participants were given Reviewer privileges to the Analytica Cloud Player server to access, open, and run the StorageVET™ Alpha version. Via WebEx, participants would share their screen and operate the StorageVET™ Alpha version on their own computers with verbal guidance from EPRI staff.

During the Alpha testing session, participants stepped through two to three test cases, considering applications for both the utility-side and customer-side of the meter energy storage.

Test Case 1

Testers selected a customer-sided location and control battery energy storage system and set its capacity, duration, and efficiency. Testers also selected the retail tariffs, day-ahead energy prices, and system loads, along with their associated annual growth rates. Once set, testers viewed the resulting impact of the installed battery energy storage system by analyzing the changes in net load, TOU energy charges, and demand charges.

Test Case 2

Next, testers took the role of a utility and therefore could commit to different services, specifically wholesale day-ahead energy shift, frequency regulation, and spinning and non-spinning reserves. Testers also selected the appropriate ancillary service prices and increase the battery's capacity. The dispatch optimization was run again for new results and to analyze the effect of the battery energy storage system on the services of interest.

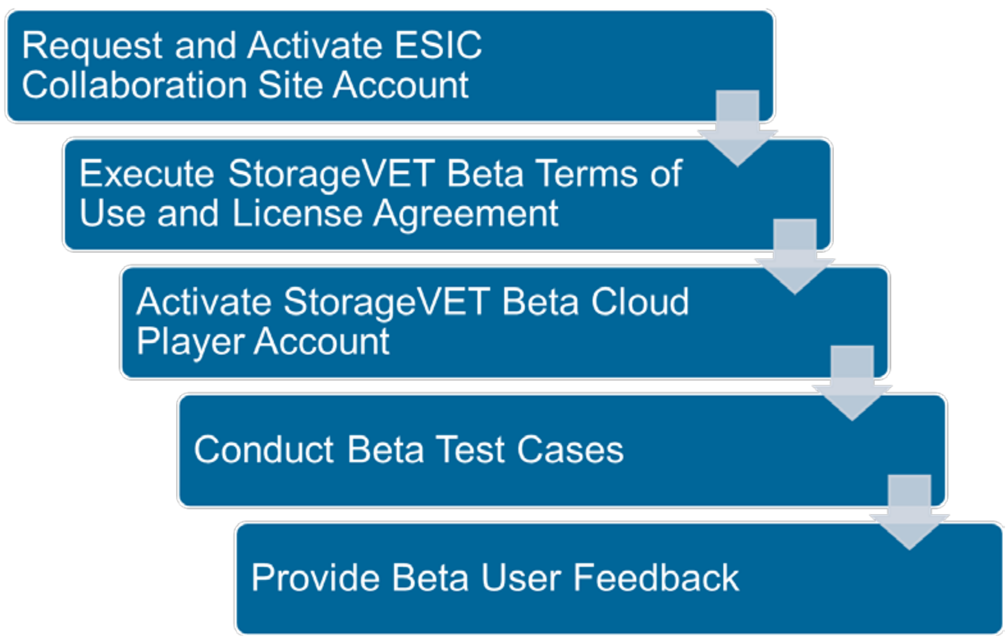
Lastly, testers selected the investment deferral service option and configured the necessary inputs to conduct an investment deferral analysis, including selecting a deferral site load and the capacity to be deferred. The investment deferral results will determine if, when, and why investment can no longer be deferred.

Beta Testing Process

Beta testing for StorageVET™ occurred from September to mid-October. Prior to and during the testing period, the project team hosted several webinars within ESIC StorageVET™ subgroup to guide interested parties through the registration process, demonstrate several test cases with StorageVET™ Beta, and solicit feedback on any difficulties encountered during testing. To stress-test the server hosting the cloud-based StorageVET™, the project team gradually released access to participants. There were a total of 29 participants from utilities, storage manufacturers, consulting firms, and national labs.

Participants must review the steps outlined in Figure 8 to access the web-based model. With the cloud player account, participants could access the model anytime during the testing period, modify existing use cases in StorageVET™ Beta or create new use cases from scratch.

Figure 8: Key Steps to Become a Beta Tester



To further engage Beta testing participants, the project team ran a case using different durations of batteries to provide several wholesale market services with ESVT, StorageVET™, and a proprietary storage valuation model developed by National Renewable Energy Lab (NREL). The project team compared the dispatch and financial results side-by-side and led discussions on the different aspects of the models that might have led to different results.

Additional beta testing and training occurred at a half-day in-person workshop at Energy Storage North America (ESNA) on October 4, 2016 in San Diego, California. Nineteen participants went through the half-day training. There was not significant overlap with formal beta testers described above and the ESNA workshop participants, which allowed for expanded opportunities to receive diverse feedback from stakeholders. The ESNA workshop also presented the opportunity to test high user volumes and simultaneous calculation loads on the StorageVET™ host server.

QA/QC Approach

The quality control process was planned in several steps:

1. Test individual modules within StorageVET™ for general integration within the global model
2. Assess StorageVET™ simulated results within modules with expected field data results
3. Conduct stress and compliance testing

Test Individual Module Integration

For each introduction or revision of an individual module, test for the following integration functionality:

- Test core calculation modules on the desktop Analytica software
- Load model on Analytica Cloud Player
- Confirm that all User Interface tabs, subtabs, and input/output fields behave as expected
- View default data for reasonableness
- Test user data upload/download functionality
- Run StorageVET™ with various service combinations, including but not limited to the service combination table illustrated below:

Table 9: Example Service Combination Test Table

Retail TOU Energy			
Retail TOU Energy	Retail Demand Charges		
Wholesale Energy			
Wholesale Energy	Ancillary Services		
Wholesale Energy	RA		
Wholesale Energy	Deferral		
Wholesale Energy	Ancillary Services	RA	
Wholesale Energy	Ancillary Services	Deferral	
Wholesale Energy	Ancillary Services	RA	Deferral
Retail TOU Energy	Ancillary Services		
Retail TOU Energy	Ancillary Services	Demand Response	
Retail TOU Energy	Ancillary Services	Storage + PV	

Retail TOU Energy				
Retail TOU Energy	Ancillary Services	Demand Response	Storage + PV	
Retail TOU Energy	Retail Demand Charges	Ancillary Services		
Retail TOU Energy	Retail Demand Charges	Ancillary Services	Demand Response	
Retail TOU Energy	Retail Demand Charges	Ancillary Services	Storage + PV	
Retail TOU Energy	Retail Demand Charges	Ancillary Services	Demand Response	Storage + PV

- Test dispatch outputs, revenue outputs and financial outputs including but not limited to the following:
  - Storage Activity Detail
  - Monthly Revenue Summary
  - State of Charge Evolution
  - Service Conflict Reports
  - Cycle Counting
  - State of Health
  - Pro Forma Cash Flows
  - Cost-Benefit Analysis Results
  - Cost Test Results

Comparative Results Testing

- Secure available project data and results for test cases.
- Run StorageVET™ with project data to generate simulated results.
- Compare project results to StorageVET™ simulated results.
- Analyze similarities, differences, and key drivers.
- Consider alternative approaches to StorageVET™ simulations where appropriate.
- Iterate as necessary.

Stress and Compliance Testing

Stress and compliance testing included the following steps:

- Access: test how the user logs into and opens the StorageVET™ model in the Analytica Cloud Player environment, multi-user server load, simultaneous model instance calculation server load, and general online performance.
- Software documentation: check documentation for data requirements, application feature descriptions, and general formatting.
- User interface: check features such as resizing the windows, whether all information is accessible, changing data appearance settings, accessing embedded Help features.
- Stress testing: test the software's ability to handle errors, including testing ranges of input numbers, following solved example problems but changing

sequence, trying different login combinations, testing whether changes in databases disrupts the application, etc.

Alpha Test Feedback

The feedback for StorageVET™ Alpha was typically broadly scoped and the progress of the tool was generally well received. The most common feedback was related to the visual and user interface improvements from ESVT and the desire for convenient input data import functionality.

Other feedback and concerns included:

- Validation is critical, especially utility validation
- Technology specifications similarities with other programs
- Ability to flexibly test tariffs, e.g. calendar month vs. utility billing schedule
- Inclusion of solar PV assets along with ESS
- Degradation analysis for ESS
- Better explanation of services and their benefits
- Limited viewable window area for graphs, tables, and controls

Beta Test Feedback

Participants in the beta test were asked to provide feedback through a web interface. The overall impression for StorageVET™ Beta, including model transparency and trustworthiness of the results are positive. Participants also provided feedback on what technologies, services, and use cases were important (Figure 9).

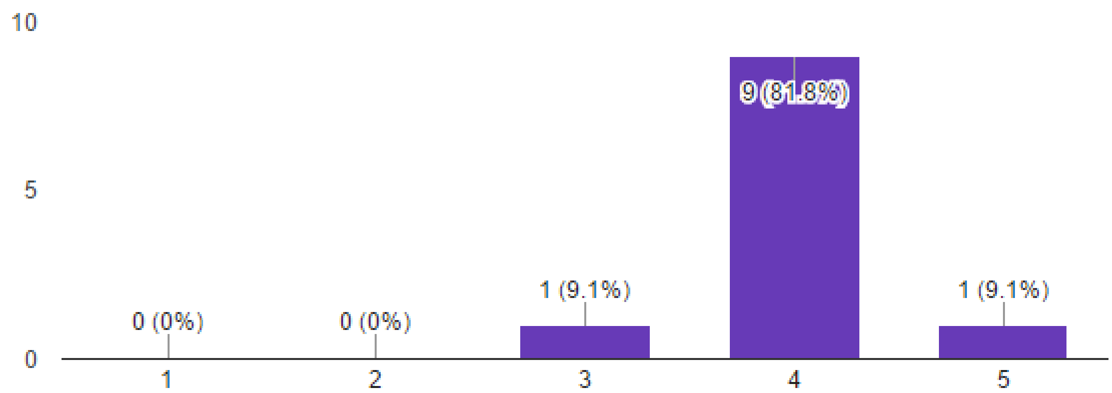
Other feedback included:

- Several participants had difficulty accessing StorageVET™ Beta on the cloud server.
- General feedback on how the results are presented.
- Complexity of the tool and level of difficulty for a user not familiar with modeling to generate quick results.

During beta testing, user feedback surveys were conducted at the end of the beta test period. Survey content ranged from general impressions of StorageVET™ to ranking the importance of grid services, technologies, and use cases.

The first question asked the users to rate their overall impressions of StorageVET™ from 1-5 with 5 being the best impression:

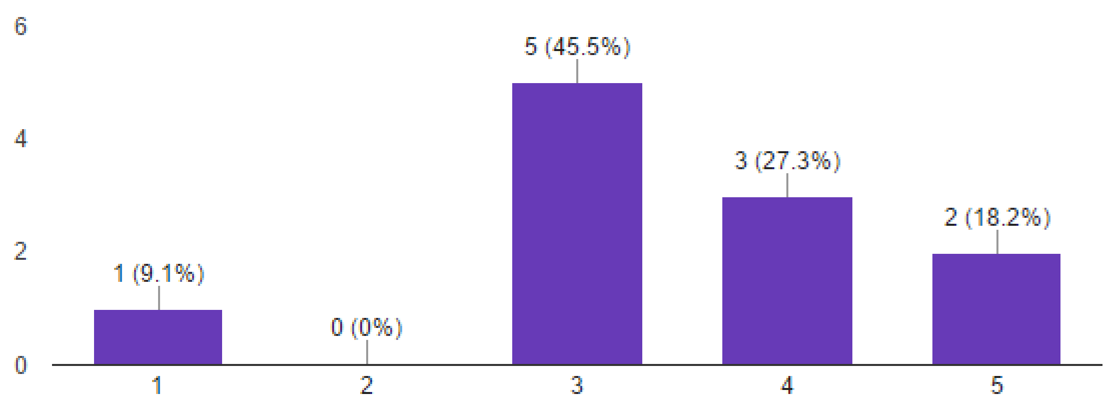
Figure 9: Beta Feedback Survey Results-Overall Impression of StorageVET™



As illustrated above, a score of 4 was the median response.

Ease of access to the beta model was given a broader response, as demonstrated in the survey results (Figure 10):

Figure 10: Beta Feedback Survey Results-Ease of Access to StorageVET™



With respect to ranking the importance of grid services, technologies, and use cases covered in the StorageVET™ model, responses were generally evenly distributed with results similar to the initial use case workshops at the beginning of the project.

QA/QC Results

QA/QC testing resulted in the identification two key focus areas for further refinement and testing:

1. User Access
2. Development Software vs. Online User Interface Compatibility

User Access

User access proved to be a pain point during beta testing. The steps to become a beta tester were particularly cumbersome and several users had challenges with accepting the terms of use. Taking the lessons learned during beta testing, the account setup processes was simplified and the terms of use was revised and converted to a "click through" approach.

In addition to a cumbersome beta tester process, the capabilities of the test server where StorageVET™ Beta was hosted also presented issues. The test server had limited computational power relative to the demands of multiple users of StorageVET™. This limited the number of simultaneous users and dramatically decreased the stability of the user's online session.

To address the limitation of the test server, a replacement high performance server was procured for the production version of StorageVET™. Initial testing of the high performance server has yielded substantial improvements to user access. For example, recent training sessions have loaded the high performance server with more than 20 simultaneous users.

Development Software vs. Online User Interface Compatibility

The difference between the desktop environment for software development and the online server platform for the user interface created additional levels of QA/QC testing. Additional complexity was introduced with the utilization of an industrial optimization engine (Gurobi) on the server.

To debug with these complexities present, the QA/QC process had to be adjusted to include multiple test stages to isolate bugs:

1. Desktop Analytica Optimizer
2. Analytica Cloud Player
3. Analytica Cloud Player with Gurobi optimization

Addition Results of QA/QC Test Cases

Additional QA/QC testing provided important insights into debugging throughout each pre-production version of the model. Where applicable, actual grid storage projects were used to generate test cases. While the details of these storage projects are proprietary, the learnings and iterative formulations were incorporated into the model.

These test cases, based on actual grid storage projects, focused primarily on the types of grid services available to the projects. These included, but were not limited to the following grid services:

- Resource Adequacy (RA)
- Demand Response (DR)
- Frequency Regulation
- Day-Ahead and Real-Time Wholesale Market Participation
- Retail Demand Charge Management

Other test case review for QA/QC included stacking service benefits, reviewing dispatch results, and quantifying expected cycling.

Whenever unexpected results occurred during QA/QC test cases, alternative approaches to StorageVET™ simulations were considered where appropriate. For example, this process proved particularly valuable for defining and dispatching for RA and DR events using energy storage.

CHAPTER 5: Software Completion, Delivery, and Documentation

This final report only briefly describes the need for StorageVET™, how stakeholders were engaged in the development process, the high-level architecture and intended use of StorageVET™. Readers who wish to learn more details about the tool will find the supplemental documents in the appendix helpful. In this chapter, a summary of the supplemental documents is presented along with how a user can find them helpful.

Overview of User Documentation

- *StorageVET™ Use Cases*

  This document describes the different types of problems a user can utilize StorageVET™ to solve. In planning the software, the project team envisioned three types of primary functional users: regulators, investors, and operators. While it is certainly possible for individuals and entities to use the model, such as researchers, this document describes how the three types of functional users can use StorageVET™ to address a particular type of problem, the stakeholders that are involved, the necessary information, the process that includes starting condition, steps, and end result, as well as exceptions and how the modeled is structured. In later implementation, the use cases were consolidated into four categories, mapped out in Chapter 2. A user can use this document as a guide to identify the types of problems she/he wishes to solve, understands the necessary information, and the conceptual steps StorageVET™ takes to solve them.

- *StorageVET™ Functional Requirement and Interface Specification*

  This document describes the functionality of StorageVET™ software. It is derived mostly from the process section in the StorageVET™ use cases document. This document describes the purpose of each function in the StorageVET™ software and how the functions map to the use cases. Its primary use was for the StorageVET™ developers to understand the requirements and how they should be implemented.

  While this document was intended for the developers of StorageVET™, a more sophisticated user wishing to understand the algorithm behind StorageVET™ can use this document as a guide to map out the different functions in the program.

- *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model*

  The document provides general descriptions and technical details about the California policy, program and market contexts for energy storage use cases and applications modeled in StorageVET™ and other storage valuation tools. The purpose of the document is to allow StorageVET™ users to gain understanding of how storage valuation is conducted in California, and how the quantitative results available through the tool should be interpreted. Notably, this includes details on how storage resources will actually be modeled, operated, and valued by California entities when providing one or more wholesale market services, distribution integration capacity analysis and distribution services, transmission and distribution deferral, and retail rate reductions. In addition, the document explains the correspondence between the StorageVET™ model structure and how actual storage projects are valued. Most of the relevant market designs, rates, and regulatory rules are summarized, along with guidance on key references for further research.

- *StorageVET™ V1.0 User Guide*

  This document is a starter guide on the objectives of StorageVET™, its use cases, user interface, along with example cases demonstrating the flow through its interface. It also discusses the mathematical formulation of the covered services and technologies, the model architecture and the detailed optimization process.

- *StorageVET™ Software Review*

  This document describes the detailed review processes of the alpha/beta user tests and EPRI's quality assurance approach.

- *StorageVET™* Technology and Knowledge Transfer Report

  This document lays out the plan of how StorageVET™ and its corresponding documents will be transferred to the storage community through workshops and training sessions and how to introduce more users to the tool.

- Reference Scenarios (complete inputs/outputs)

  The document goes through a detailed example of simulating the costs and benefits of a storage project using StorageVET™. It goes through the set of available inputs, how the user might adjust them, the set of results from the model, and how to interpret them.

- Project Benefits

  This document describes the intended benefits of StorageVET™ to regulators, utilities, and end customers.

- Documentation within StorageVET™ Interface

  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:

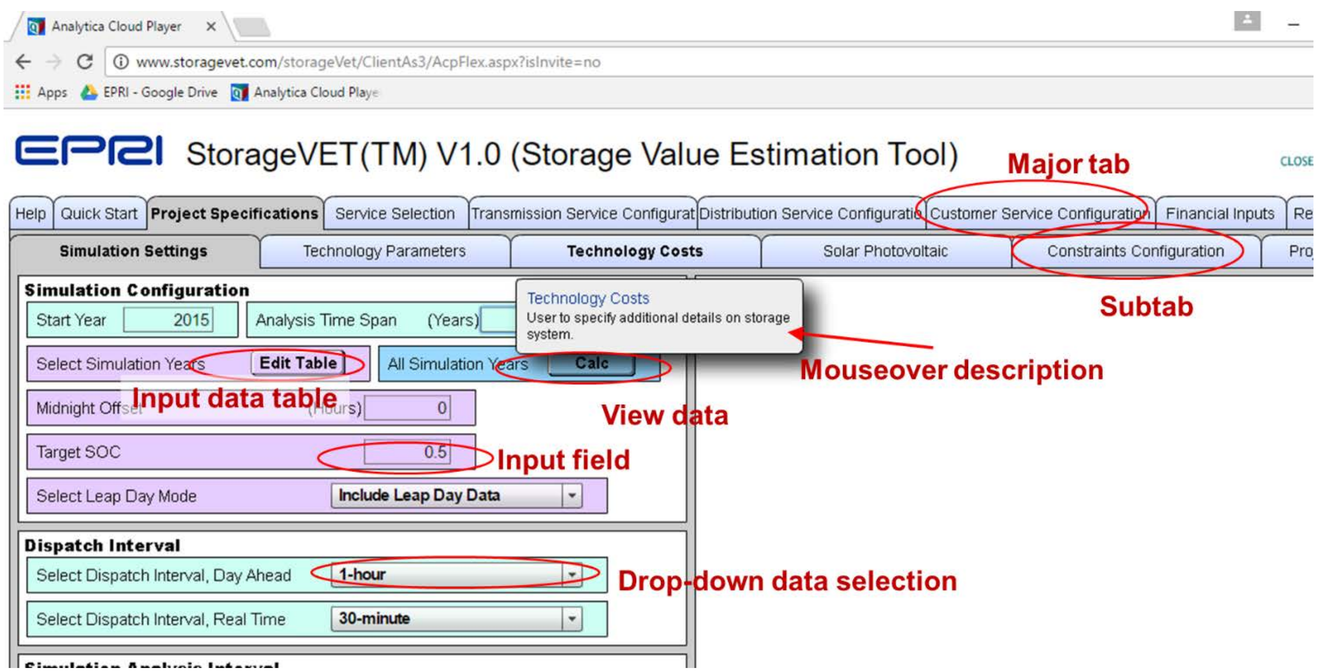
  - Major tab: Major tabs reside on the top row of the ACP UI for StorageVET™. These contain the major categories for user inputs and outputs to the model. Typically, the user should start on the left tab and sequentially move right through model configuration and results.
  - Subtab: Subtabs provide navigation to more granular categories of inputs and outputs in the model. They are nested within the major tabs.
  - Mouse-over description: Mouse-over 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 have the mouse hover over a word. If there is a description, a window will pop up with further information to support clarity.
  - Input data 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: 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.

These elements of the StorageVET™ UI are highlighted in Figure 11.

Figure 11: StorageVET™ ACP User Interface



Ongoing Support and Maintenance

EPRI has committed to providing support and maintenance for the web-hosted software for a period of two years after the project end date. StorageVET™ software will be hosted through the portal www.storagevet.com in 2017 and 2018 as part of a post-project commitment. This includes provisioning the underlying Analytica and solver software to run StorageVET™, the third party server that the software resides on, and associated maintenance and support agreements. It also includes a continuing role for EPRI to collect information about bugs and functionality issues and manage a portal website.

Server Provisioning (2 Years)

EPRI has specified a powerful cloud server with sufficient capability to host a number of simultaneous users and runs of StorageVET™ by the user community. Server needs are evolving with adoption and the expectation is that certain specifications may evolve over the course of the support and maintenance period. As of January 2017, the server has the following specifications, hosted by Hivelocity Ventures Corporation:

- Dual dedicated processor: 2 x Intel E5-2699 v3 Octdeca- Core Haswell Xeon (18 core processor(s))
- Memory: 256GB
- Hard drive: 3.64TB

The server specifications have been updated twice in the course of this project to attain better performance of the software. Findings from training sessions provided the team with important information to provision the best combination of cost and performance. It is expected that as actual user behavior is better understood, the server specifications may be tuned further.

Analytica Cloud Player™ (ACP) Maintenance and Support

EPRI has provisioned Analytica Cloud Player from Lumina Decision Systems for a period of two years to enable the continuous hosting of StorageVET™ in 2017 and 2018, at no cost to users. This software was purchased by EPRI in an early phase of the project to support testing, but continuing maintenance is required to receive support and upgrades of the software.

The license renewal also includes continued support and maintenance of the Gurobi Solver platform, an import component of the Analytica tool which enables StorageVET™ to quickly optimize hourly or sub-hourly time-series optimization.

EPRI Ongoing Maintenance and Support Role

EPRI intends to use StorageVET™ to support core research and associated projects in the future, with several analysis projects currently in process or upcoming. As a result, EPRI will continuously provide minor updates and bug fix releases over the term of the maintenance period. Occasionally, with the help of the user community, EPRI also expects to add certain features during the two year period.

Open Source Version of StorageVET™ in 2017

EPRI desires to organize a community of StorageVET™ users. Advanced users will have the opportunity to deepen their engagement in the project upon release of an open source tool. After the use of StorageVET™ is well-understood from early adopters, EPRI intends to release an open source version of the model which can be downloaded from GitHub or similar open source software collaboration site. Use of the open source version of the tool will require user purchase of an appropriate version of Analytica from Lumina Decision Systems for either model use or modeling building. In both cases, the user will need a version with an optimization solver (more info at www.lumina.com). This version will also help to address any sensitivity with StorageVET™ users that do not wish to share their proprietary data. More information about open source release will be made available at www.storagevet.com.

CHAPTER 6: Project Benefits

In this chapter, a summary of the benefits to different stakeholders is presented. To better quantify these benefits, the project team also conducted an analysis to compare reference cases with and without StorageVET™ with the following steps:

1. List and describe general benefits associated with types of project stakeholders
2. Conduct a detailed review of reference cases and results using StorageVET™
3. Use the reference cases to quantify project benefits with and without StorageVET™

While interpreting these project benefits, it is important to recognize that many of them will result from the development of a user community for the model. However, all of them are possible applications, either directly with StorageVET™ or by using the model jointly with other models or primarily as a public reference point. Many of these applications have been discussed by stakeholders during the project.

Overview of Benefits to Project Stakeholders

Regulators

For regulators in California, below is a list of relevant proceedings StorageVET™ can help to inform.

- **Long-Term Procurement Proceeding (R.16-02-007):** Proceeding may provide reference scenarios for storage which could be used to better inform analysis in StorageVET™.
- **Resource Adequacy (R.11-10-023):** StorageVET™ may inform proceeding as to the effectiveness of storage to provide equivalent Resource Adequacy as traditional generation. It may also inform the proceeding of energy storage net market value to determine the Resource Adequacy benchmark net Cost of New Entry value.
- **Self-Generation Incentive Program (R.12-11-005):** Energy storage is an important resource in the SGIP program, and currently a primary path for customer adoption of energy storage. StorageVET™ may inform regulators and utilities of customer value propositions and inform decision-making around incentives or requirements for participation to maximize ratepayer value.
- **Renewables Portfolio Standard (R.11-05-005):** StorageVET™ may inform the role of storage by performing cost-effectiveness evaluations in the context of future renewable target scenarios. Additionally, scenarios developed in this proceeding may inform reference scenarios in StorageVET™.
- **Energy Storage (R.15-03-011):** StorageVET™ may be used to benchmark cost-effectiveness of storage investment decisions as a publicly available, transparent tool. Additionally, in consideration of new or updated policy, StorageVET™ may inform expectations due to changes in the program.

- **Smart Grid (R.08-12-009):** StorageVET™ may inform the proceeding as to economically feasible use cases for storage and the minimum communication and control requirements to practically achieve them.
- **Customer Data Access Program (D.11-07-056, D.13-09-025):** Data compatibility between StorageVET™ and this program may facilitate use and value of the software to customers and ratepayers.
- **Distribution Resources Plans (R.14-08-013):** This proceeding may value from evaluation of storage cost-effectiveness in cases where a utility distribution need has been identified which may be addressable by energy storage.

Utilities

StorageVET™ can potentially help utilities:

- Identify and deploy cost-effective advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air-conditioning.
- Provide consumers with a public reference point to evaluate timely information, such as retail rate options and granularity of data available for assessment of behind-the-meter systems, and control options.
- Related to the prior uses, by evaluating operations of customer-sited systems (including integrated PV and storage); the model could help with identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.
- Conserve energy by efficient resource use or by reducing or shifting system load.
- Development of new storage resources across the integrated grid and processes to integrate those technologies.
- Improve operating efficiency and reliability or otherwise reduce operating costs of storage facilities.

Energy Storage Developers

StorageVET™ can help developers:

- Streamline the development process by reducing the efforts needed in planning such as screening the feasible locations, and optimizing for size and intended services for the project.
- Benchmark how utilities and potential investors would evaluate storage projects.

End Customer

StorageVET™ can help end customers better understand the benefits and costs of energy storage. When end customers decide to install energy storage in their homes, they can:

- Use StorageVET™ to help end customers understand the savings before plunging for the investment—saving on utility bills by opting into time-of-use rates, using energy stored from off-peak hours

- Understand and confirm the optimal utilization of existing roof-top solar installations by storing excess energy generated.
- Quantify the value of back-up power in case of emergency.

Quantification of Benefits

The quantifiable benefit of StorageVET™ to ratepayers includes improved project cost-effectiveness outcomes as a result of StorageVET™, leading to changes in the decision to undertake a project or changes in project specifications. While a baseline for the impact of one new modeling tool would clearly be difficult to determine, the before and after results are discussed as compared to earlier, simpler models. Following this approach, reference cases and results from StorageVET™ are detailed below. Then, a discussion of how these reference case results offer improved outcomes by incorporating refinements in requirements or the consideration of additional benefits versus more rudimentary approaches to project specification is presented.

Reference Case Results

Overview

Several cases with StorageVET™ were modeled to illustrate how the model can be used to evaluate various energy storage configurations and storage value streams. This section describes the assumptions and results of these cases with a focus on how users could benefit from performing similar analyses in the model. It aims to provide readers with an understanding of a few of the many capabilities and use cases of StorageVET™.

The cases leverage several assumptions from public sources and internal tools to create these illustrative scenarios. The REFLEX model developed by Energy and Environmental Economics, Inc. (E3, n.d.) and an internal regression model were utilized to develop a future market price scenario. The team used representative cost and performance inputs for energy storage that are within the range quoted in public sources. Nevertheless, these cases are intended purely to be illustrative examples and do not in any way represent an 'expected' cost-benefit analysis for any particular technology or use case.

The results of these illustrative examples were reviewed and found to be reasonably close to results produced by ESVT and by Excel spreadsheet models. Storage dispatch roughly match results of similar cases in ESVT. Financial calculations for depreciation, taxes, debt, and equity investment matched those of ESVT and of a spreadsheet financial pro forma with one exception—return on equity (ROE). StorageVET™ V1.0 uses a simplified approach to ROE that will be considered for more robust calculation upgrades in future releases.

Cases presented below may vary in User Interface from the current version of StorageVET™ available at www.storagevet.com. Therefore, differing displays may be shown in screenshots here.

Illustrative Cases

Six illustrative cases are presented in the following sections. All six cases reflect transmission-sited, IPP-owned storage participating in CAISO markets. The technical and financial implications of various market price scenarios, market service participation, and storage durations are compared. The potential benefits of increased dispatch modeling granularity are also explored.

Two electricity market price scenarios are analyzed: The *Current Scenario* and the *Reference 50% RPS Scenario*. The Current Scenario reflects current market conditions and no implementation or enforcement of more aggressive policies going forward. The Reference 50% RPS Scenario reflects implementation of current state policies and goals, such as a 50 percent renewable portfolio standard, and expected future trends in market conditions. Descriptions of how these scenarios were developed are outlined in more detail below. These scenarios are embedded in StorageVET™ and enable users to explore storage value and operation under two different policy and load trajectories. The Reference 50% RPS Scenario also demonstrates StorageVET™'s dispatch years and revenue interpolation functionality.

To inform the relative value and behavior of storage providing particular market services, results are presented for cases in which storage offers only Resource Adequacy (RA) and Day-Ahead (DA) energy arbitrage and cases that include storage provision of ancillary services (A/S) and Real-Time (RT) energy arbitrage. The RT energy arbitrage under hourly and five-minutely dispatch granularities was explored.

Also explored, is the impact of storage technology duration on value and dispatch. This analysis is indicative of how users may use StorageVET™ to compare technologies.

Table 10 summarizes the key assumptions that differ across the six illustrative cases.

Table 10: Key Assumptions of Illustrative Cases

Case Number	Market Price Scenario	Market Services	Battery Duration	Dispatch Granularity
1	Current	RA, DA	Two hours	Hourly
2	Reference 50% RPS	RA, DA	Two hours	Hourly
3	Reference 50% RPS	RA, DA, A/S	Two hours	Hourly
4	Reference 50% RPS	RA, DA, A/S	Four hours	Hourly
5	Current	RA, DA, RT	Two hours	Hourly
6	Current	RA, DA, RT	Two hours	Five minute

Illustrative Results

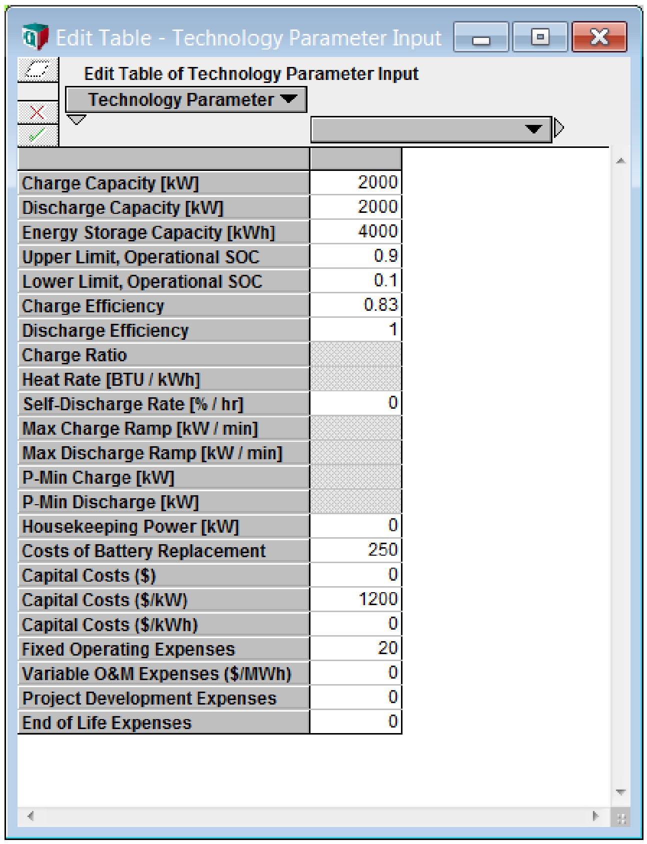
Two-Hour Duration: Resource Adequacy and Day-Ahead Energy – Current Scenario

First, an illustrative case of transmission sited storage with two hours of duration providing two services is presented: 1) resource adequacy and 2) day-ahead energy time shift.

The cost and performance specifications for a 2 MW, 2 Hour Li-Ion batteries come from the EPRI 2016 Energy Storage Cost Study Executive Summary and the CPUC Storage

Proceeding 2013 Cost Effectiveness Study. EPRI provided lower and upper state of charge limits of 10 percent and 90 percent, respectively. A 30-year life is assumed, with periodic replacement costs, to include the full 30-year debt-term assumed in StorageVET™ for this case. Figure 12 depicts these assumptions in the StorageVET™ *Technology Parameters* user input. The total system costs are $1,200/kW or $600/kWh installed, with a periodic replacement cost of $250/kW every ten years during the 30-year life.

Figure 12: Technology Parameters



Technology Parameter	
Charge Capacity [kW]	2000
Discharge Capacity [kW]	2000
Energy Storage Capacity [kWh]	4000
Upper Limit, Operational SOC	0.9
Lower Limit, Operational SOC	0.1
Charge Efficiency	0.83
Discharge Efficiency	1
Charge Ratio	
Heat Rate [BTU / kWh]	
Self-Discharge Rate [% / hr]	0
Max Charge Ramp [kW / min]	
Max Discharge Ramp [kW / min]	
P-Min Charge [kW]	
P-Min Discharge [kW]	
Housekeeping Power [kW]	0
Costs of Battery Replacement	250
Capital Costs ($)	0
Capital Costs ($/kW)	1200
Capital Costs ($/kWh)	0
Fixed Operating Expenses	20
Variable O&M Expenses ($/MWh)	0
Project Development Expenses	0
End of Life Expenses	0

The monthly values for resource adequacy are stored in the RA Price Data table, shown in Figure 13. CAISO net cost of new entry prices is in the second column, expressed in $/kW-Month.

Figure 13: Resource Adequacy Values for 2015

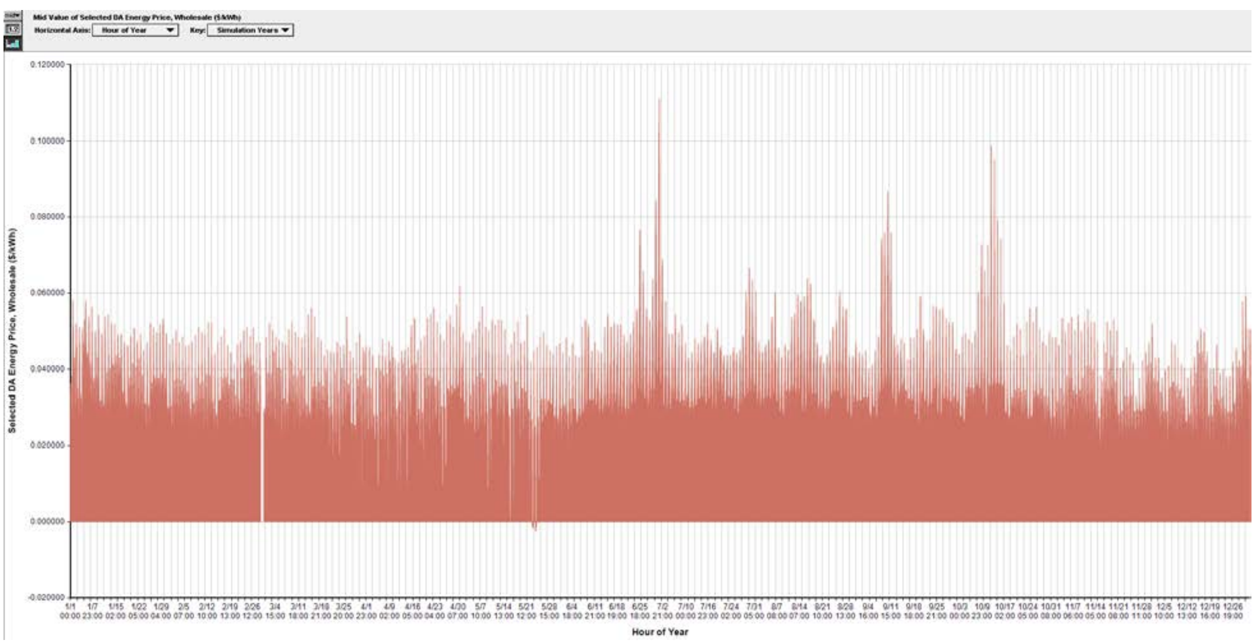
Edit Table - RA Price Data

Edit Table of RA Price Data ($/kW-month)

Month	NYC Default Reference 2015	CAISO Net CONE (E3) 2015
JAN	8.75	2.51
FEB	8.71	2.04
MAR	6.98	2.08
APR	6.99	2.08
MAY	15.96	3.28
JUN	15.36	5.4
JUL	14.88	31.2
AUG	15.18	40.15
SEP	14.74	18.37
OCT	14.67	4.56
NOV	6.11	3.65
DEC	6.16	4.02

Figure 14 displays 2015 day-ahead hourly energy prices for the Current Scenario. The energy prices escalate at 2 percent per year in StorageVET™.[2]

Figure 14: 2015 Day-Ahead Energy Prices

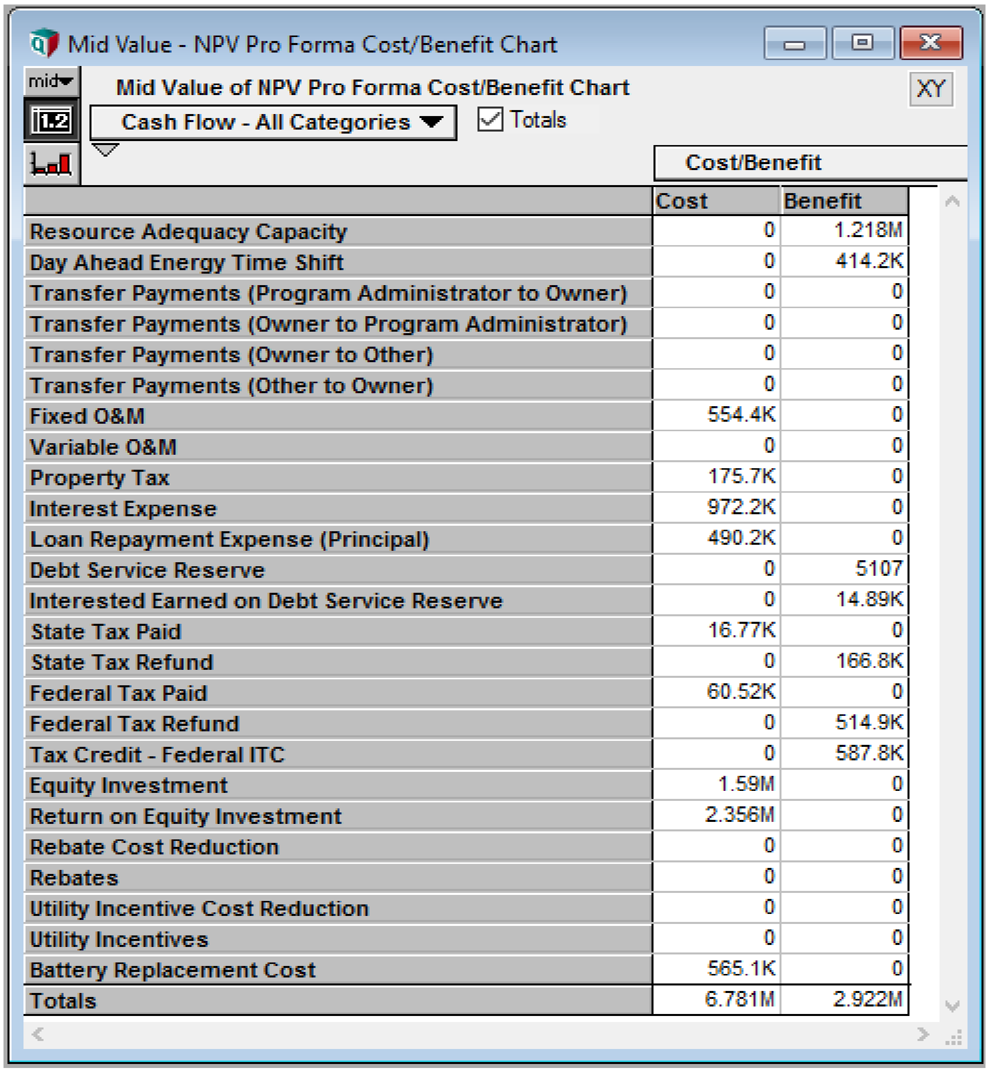


The Weighted Average Cost of Capital (WACC) used for discounting costs and benefits is about 7 percent. With these inputs, StorageVET™ produces the net present value (NPV) costs and benefits shown in Figure 15. The values over the life of the project are present

2 Note that the small gap of no prices is for February 29th.

valued to the development year for the project. The resulting NPV TRC costs are $6.8 million, as compared to benefits of $2.9 Million. The capital and financing costs are the interest expense (on debt), loan repayment of principal, equity investment, and return on equity investment (to shareholders). Ongoing expenses include annual fixed O&M and battery replacement costs. Taxes are a cost in some years and a benefit in other years, when there is a net tax refund to the project. In this scenario, the battery earns $1.2 million in resource adequacy payments and $414 thousand from arbitrage the day-ahead energy market.

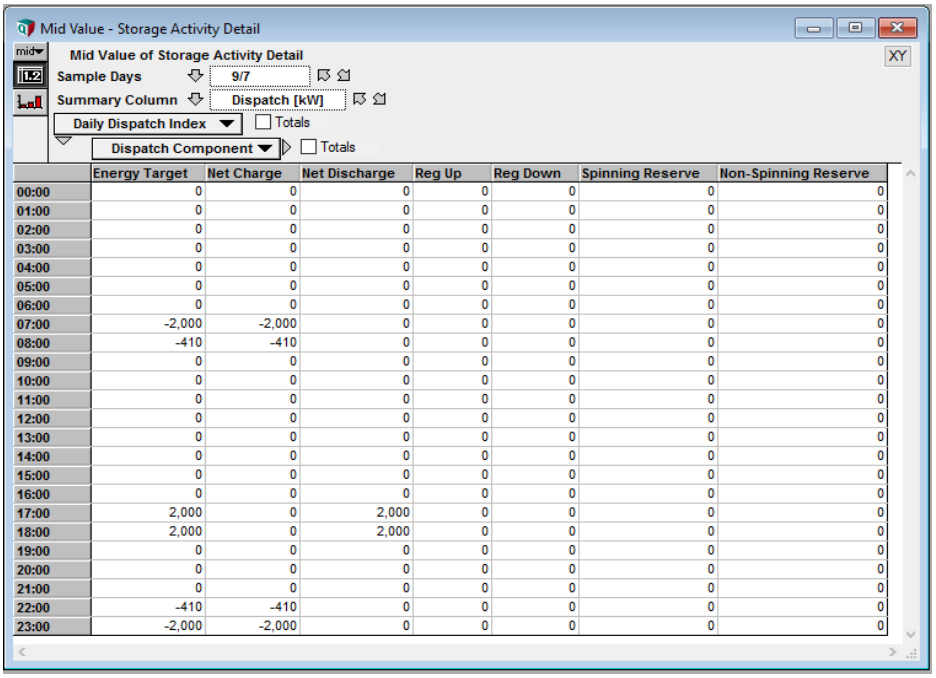
Figure 15: NPV Total Resource Cost Test Costs and Benefits



	Cost	Benefit
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	414.2K
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	16.77K	0
State Tax Refund	0	166.8K
Federal Tax Paid	60.52K	0
Federal Tax Refund	0	514.9K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Totals	6.781M	2.922M

The storage dispatch for a single day can be viewed in the *Storage Activity* table. Figure 16 shows dispatch on high load day of September 7th. Storage charges in the morning from 7-9 am and discharges for two hours at the evening peak starting at 5 pm. Note that the battery charges at 11 pm, carrying a partial charge over to the next day.

Figure 16: Illustrative Dispatch for September 7



	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0
06:00	0	0	0	0	0	0	0
07:00	-2,000	-2,000	0	0	0	0	0
08:00	-410	-410	0	0	0	0	0
09:00	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0
17:00	2,000	0	2,000	0	0	0	0
18:00	2,000	0	2,000	0	0	0	0
19:00	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0
22:00	-410	-410	0	0	0	0	0
23:00	-2,000	-2,000	0	0	0	0	0

The charging behavior is different on spring days, such as April 14th, as shown in Figure 17. In this case, the battery discharges early in the morning during a period of prices above $30/MWh (not shown) and charges during a period of low prices below $10/MWh from 9 am to noon. The battery discharges at 1 pm when the energy price is $10/MWh and charges again at 2 pm when the price drops to $8.22. Finally, the battery discharges again during the evening peak.

The net dispatch for several days in April is shown in Figure 18.

Figure 17: Illustrative Dispatch for April 14

Mid Value - Storage Activity Detail

Mid Value of Storage Activity Detail

Sample Days: 4/14

Summary Column: Dispatch [kW]

Daily Dispatch Index / Dispatch Component

	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	0	0	0	0	0	0	0
01:00	-410	-410	0	0	0	0	0
02:00	-2,000	-2,000	0	0	0	0	0
03:00	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0
05:00	2,000	0	2,000	0	0	0	0
06:00	2,000	0	2,000	0	0	0	0
07:00	0	0	0	0	0	0	0
08:00	0	0	0	0	0	0	0
09:00	-2,000	-2,000	0	0	0	0	0
10:00	0	0	0	0	0	0	0
11:00	-819	-819	0	0	0	0	0
12:00	-2,000	-2,000	0	0	0	0	0
13:00	1,660	0	1,660	0	0	0	0
14:00	-2,000	-2,000	0	0	0	0	0
15:00	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0
18:00	2,000	0	2,000	0	0	0	0
19:00	2,000	0	2,000	0	0	0	0
20:00	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0
22:00	-410	-410	0	0	0	0	0
23:00	-2,000	-2,000	0	0	0	0	0

Figure 18: Net Dispatch for April 2016

Mid Value - Dispatch Solution

Mid Value of Dispatch Solution (kW)

Month: APR

Simulation Years: 2016

Daily Dispatch Index / Day of Month

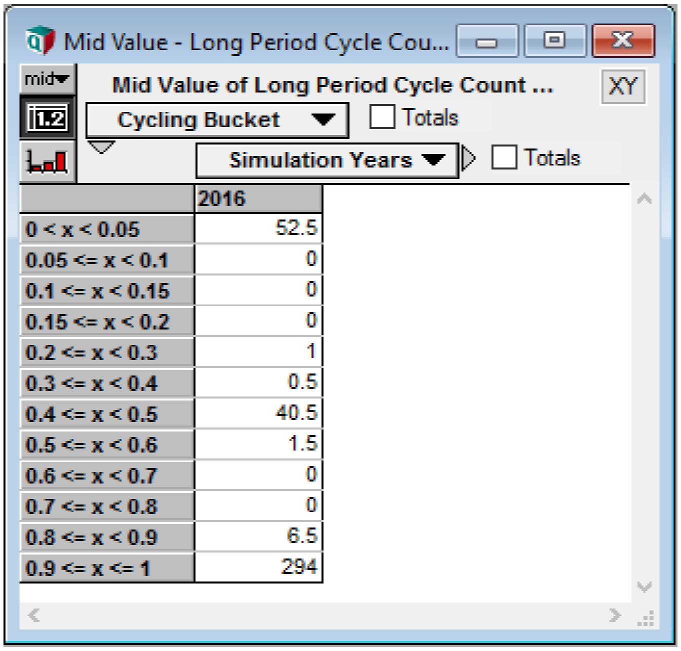
	1	2	3	4	5	6	7	8	9	10
00:00	-409.6	0	0	0	0	0	0	0	0	0
01:00	-2000	-409.6	0	0	0	-409.6	-409.6	-409.6	-409.6	-409.6
02:00	0	-2000	-2000	0	0	-2000	-2000	-2000	-2000	-2000
03:00	0	0	-409.6	0	0	0	0	0	0	0
04:00	-227.4f	-227.4f	-227.4f	0	0	0	-227.4f	-227.4f	-227.4f	-227.4f
05:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
06:00	2000	2000	2000	0	0	2000	2000	2000	2000	2000
07:00	0	0	0	0	0	-227.4f	0	0	0	0
08:00	0	-2000	-2000	-2000	0	-2000	0	0	0	0
09:00	-2000	-2000	-2000	-2000	-2000	-819.3	0	-2000	-2000	-2000
10:00	0	-819.3	-819.3	0	980	-2000	0	0	-819.3	0
11:00	-819.3	0	0	0	-2000	0	0	0	0	0
12:00	-2000	0	0	-819.3	0	0	-2000	-2000	0	0
13:00	0	0	0	0	-2000	0	-819.3	-819.3	0	-819.3
14:00	0	0	0	0	0	0	-2000	0	-2000	-2000
15:00	0	0	0	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0
18:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
19:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
20:00	-454.7f	-454.7f	-454.7f	-454.7f	-682.1f	-454.7f	-454.7f	-454.7f	-454.7f	-454.7f
21:00	0	0	0	0	0	0	0	0	0	0
22:00	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	-2000	-409.6
23:00	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-409.6	-2000

	11	12	13	14	15	16	17	18	19	20
00:00	0	0	0	0	0	0	0	0	0	
01:00	0	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	0	0	
02:00	-2000	-2000	-2000	-2000	-2000	-2000	-2000	0	0	
03:00	0	0	0	0	0	0	0	0	0	
04:00	1660	2000	-227.4f	-227.4f	-227.4f	-227.4f	-227.4f	0	0	
05:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	[illegible]
06:00	0	0	2000	2000	2000	2000	2000	0	0	
07:00	0	0	0	0	0	0	0	0	0	
08:00	0	-819.3	0	0	-2000	-2000	-2000	-2000	-2000	[illegible]
09:00	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-2000	[illegible]
10:00	1660	-2000	0	0	-819.3	-819.3	0	0	-819.3	
11:00	0	0	0	-819.3	0	0	-819.3	-819.3	0	
12:00	-2000	0	-2000	-2000	0	0	0	0	0	[illegible]
13:00	-2000	0	-819.3	1660	0	0	0	0	0	
14:00	-819.3	0	0	-2000	0	0	0	0	0	
15:00	0	0	0	0	0	0	0	0	0	
16:00	0	0	0	0	0	0	0	0	0	
17:00	0	0	0	0	0	0	0	0	0	
18:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	[illegible]
19:00	2000	2000	2000	2000	2000	2000	2000	2000	2000	[illegible]
20:00	-454.7f	-454.7f	-454.7f	-682.1f	-454.7f	-454.7f	-454.7f	-454.7f	-454.7f	[illegible]
21:00	0	0	0	0	0	0	0	0	0	
22:00	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	-409.6	-2000	-409.6	[illegible]
23:00	-2000	-2000	-2000	-2000	-2000	-2000	-2000	-409.6	-2000	[illegible]

These results demonstrate a user's ability to see summary storage operation results or dig into the more granular hourly dispatch results.

StorageVET™ also outputs cycle statistics, which provide insight into dispatch behavior and degradation impacts. Figure 19 shows the number of cycles per cycle depth interval for Case #1. The two-hour battery demonstrates dispatching primarily for day-ahead energy arbitrage tends to prefer very deep cycles to maximize the arbitrage potential.

Figure 19: Cycle Counts for Storage Dispatch

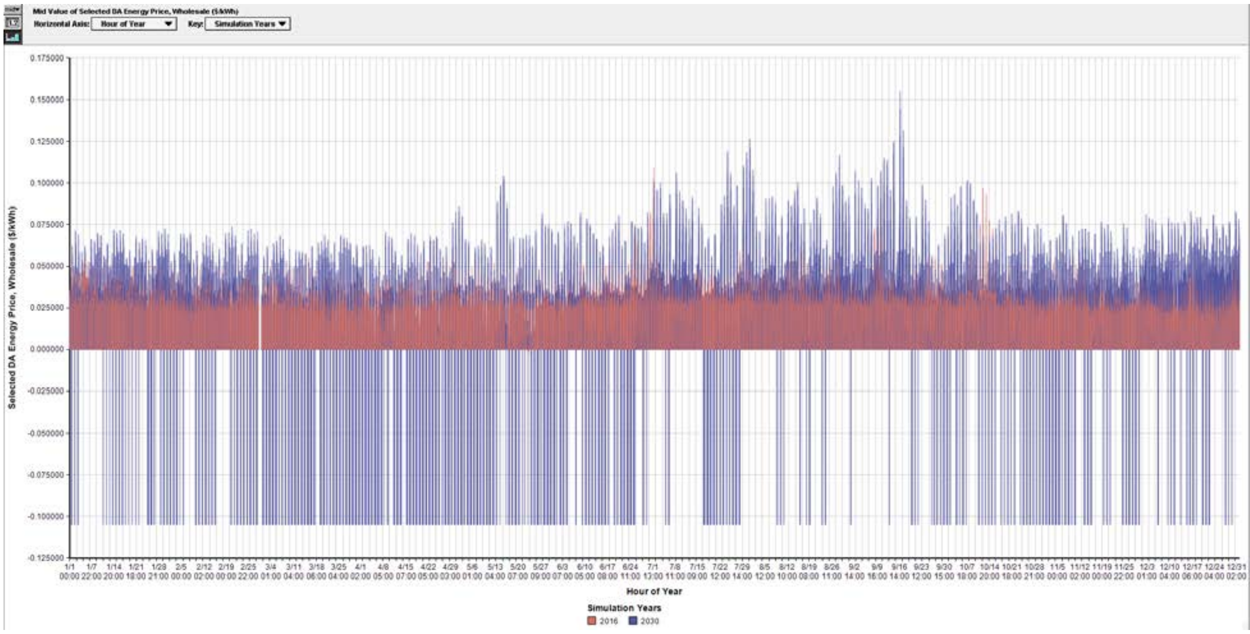


	2016
0 < x < 0.05	52.5
0.05 <= x < 0.1	0
0.1 <= x < 0.15	0
0.15 <= x < 0.2	0
0.2 <= x < 0.3	1
0.3 <= x < 0.4	0.5
0.4 <= x < 0.5	40.5
0.5 <= x < 0.6	1.5
0.6 <= x < 0.7	0
0.7 <= x < 0.8	0
0.8 <= x < 0.9	6.5
0.9 <= x <= 1	294

Two-Hour Duration: Resource Adequacy and Day-Ahead Energy – 50% RPS Scenario

The results above are compared with those of the same battery performing the same services under a 50% RPS Scenario. Instead of simply escalating 2015 prices, the REFLEX model was used to develop a 2030 price scenario that reflects increased renewable generation and electric vehicle charging. Large amounts of renewable generation and limited flexible resource solutions, such as storage, produce higher price variations and numerous negative prices due to system generation exceeding load. Figure 20 compares the 2015 Current prices to the 2030 Reference 50% RPS prices. As shown, over generation occurs particularly frequently in the spring when electricity demand is relatively low and solar generation and hydro-generation is relatively high.

Figure 20: 2015 and 2030 Day-Ahead Energy Prices

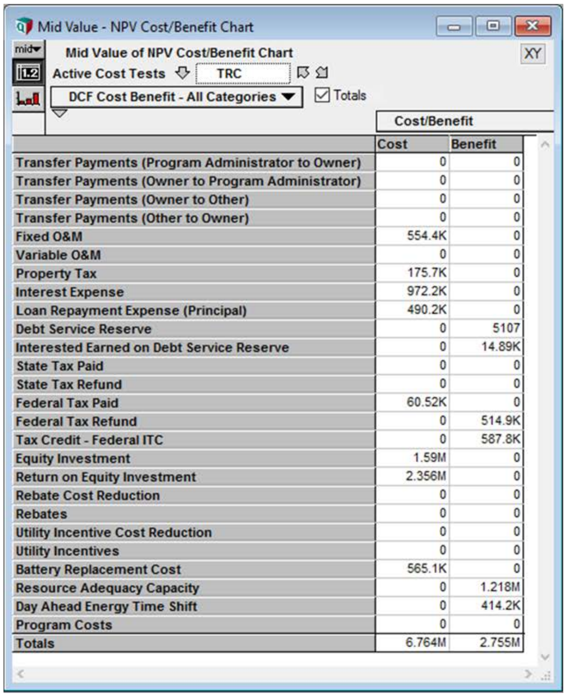


This scenario highlights StorageVET™'s ability to dispatch storage over multiple years with multiple price streams, thereby capturing changing market conditions over time. The model interpolates the costs and revenues between these dispatch years.

The resulting NPV TRC costs are $7.2 million, and the revenues are $4.1 million (Figure 21). The resource adequacy benefits are the same as those of Case #1 with current market prices, but the day-ahead energy benefits are higher ($1.9 million, relative to $414 thousand) due to the negative energy prices driven by excess generation with increasing renewable penetration. The system costs are the same as those of the Current Price Scenario, but higher revenues increase taxes paid, leading to higher NPV costs.

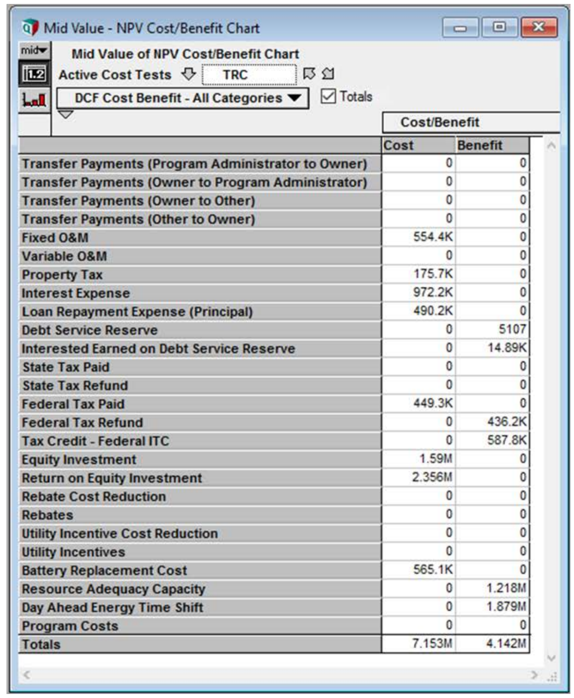
Figure 21: NPV Total Resource Cost Test Costs and Benefits

Current Scenario



Cost/Benefit	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	60.52K	0
Federal Tax Refund	0	514.9K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	414.2K
Program Costs	0	0
Totals	6.764M	2.755M

50% RPS Scenario



Cost/Benefit	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	449.3K	0
Federal Tax Refund	0	436.2K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	1.879M
Program Costs	0	0
Totals	7.153M	4.142M

The dispatch on September 7th (Figure 22) is the same as that of the previous scenario

Figure 22: Illustrative Dispatch for September 7, 2030

	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0
06:00	0	0	0	0	0	0	0
07:00	-2,000	-2,000	0	0	0	0	0
08:00	-410	-410	0	0	0	0	0
09:00	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0
17:00	2,000	0	2,000	0	0	0	0
18:00	2,000	0	2,000	0	0	0	0
19:00	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0
22:00	-410	-410	0	0	0	0	0
23:00	-2,000	-2,000	0	0	0	0	0

On a spring day, however, storage is dispatched more frequently to take advantage of negative energy prices (Figure 23).

Figure 23: Illustrative Dispatch for April 13, 2030

Mid Value - Storage Activity Detail

Mid Value of Storage Activity Detail

Sample Days: 4/13

Summary Column: Dispatch [kW]

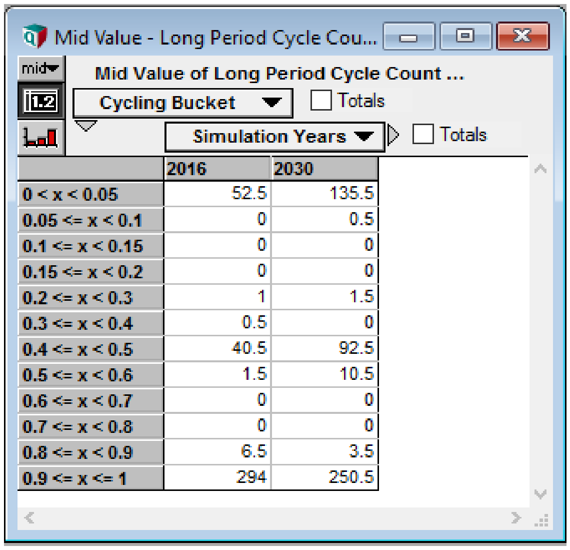
Daily Dispatch Index ☐ Totals

Dispatch Component ☐ Totals

	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0
06:00	2,000	0	2,000	0	0	0	0
07:00	0	0	0	0	0	0	0
08:00	-2,000	-2,000	0	0	0	0	0
09:00	-2,000	-2,000	0	0	0	0	0
10:00	-1,020	-1,020	0	0	0	0	0
11:00	-340	-340	0	0	0	0	0
12:00	-340	-340	0	0	0	0	0
13:00	-340	-340	0	0	0	0	0
14:00	-340	-340	0	0	0	0	0
15:00	-340	-340	0	0	0	0	0
16:00	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0
18:00	2,000	0	2,000	0	0	0	0
19:00	2,000	0	2,000	0	0	0	0
20:00	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0
22:00	-2,000	-2,000	0	0	0	0	0
23:00	-410	-410	0	0	0	0	0

Looking at the Long Period Cycle Count table, the cycle counts for several bins have increased in 2030 relative to 2015 (Figure 24). This shows how increased arbitrage opportunity with negative energy prices increases opportunities for the battery to earn revenues with charge and discharge cycles. The increased revenues with increased cycling may come at a cost of a shorter battery life. StorageVET™ provides the cycle counts for battery dispatch, so users can compare the number of cycles at different depths across cases.

Figure 24: Cycle Counts for Storage Dispatch



	2016	2030
0 < x < 0.05	52.5	135.5
0.05 <= x < 0.1	0	0.5
0.1 <= x < 0.15	0	0
0.15 <= x < 0.2	0	0
0.2 <= x < 0.3	1	1.5
0.3 <= x < 0.4	0.5	0
0.4 <= x < 0.5	40.5	92.5
0.5 <= x < 0.6	1.5	10.5
0.6 <= x < 0.7	0	0
0.7 <= x < 0.8	0	0
0.8 <= x < 0.9	6.5	3.5
0.9 <= x <= 1	294	250.5

Two-Hour Duration: Resource Adequacy, Day-Ahead Energy, and Frequency Regulation – 50% RPS Scenario

For the third case, the same inputs are used as in Case #2, but adding the provision of ancillary services, including frequency regulation, spinning reserve and non-spinning reserve. The day-ahead energy revenues are somewhat lower ($1.5 vs $1.9 million above), but frequency regulation adds $1.7 million in revenue. Total costs are marginally higher than before ($7.6, compared to $7.2 million above) due to increased taxes with higher revenues. Total benefits are $5.4 million, as compared to $4.3 million without ancillary services.

Figure 25: NPV Total Resource Cost Test Costs and Benefits

Without Ancillary Services

Mid Value - NPV Cost/Benefit Chart

Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

DCF Cost Benefit - All Categories; Totals

	Cost/Benefit	
	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	449.3K	0
Federal Tax Refund	0	436.2K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	1.879M
Program Costs	0	0
Totals	7.153M	4.142M

With Ancillary Services

Mid Value - NPV Cost/Benefit Chart

Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

DCF Cost Benefit - All Categories; Totals

	Cost/Benefit	
	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	718.1K	0
Federal Tax Refund	0	272.8K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	1.508M
Frequency Regulation	0	1.683M
Spinning Reserve	0	10.34K
Non-Spinning Reserve	0	52.72K
Program Costs	0	0
Totals	7.422M	5.353M

The *Storage Activity Detail* table shows the added activity with participation in the ancillary service markets. Between 10 am and 2 pm, the battery is offering regulation down, which charges the battery with 266 kW each hour given the mileage assumptions for offering frequency regulation (Figure 26). During the peak hour of 5 pm, the battery simultaneously discharges in the day-ahead energy market while offering regulation down to maximize revenue.

Figure 26: Illustrative Dispatch for April 14th

Mid Value - Storage Activity Detail

Mid Value of Storage Activity Detail

Sample Days: 4/14

Summary Column: Dispatch [kW]

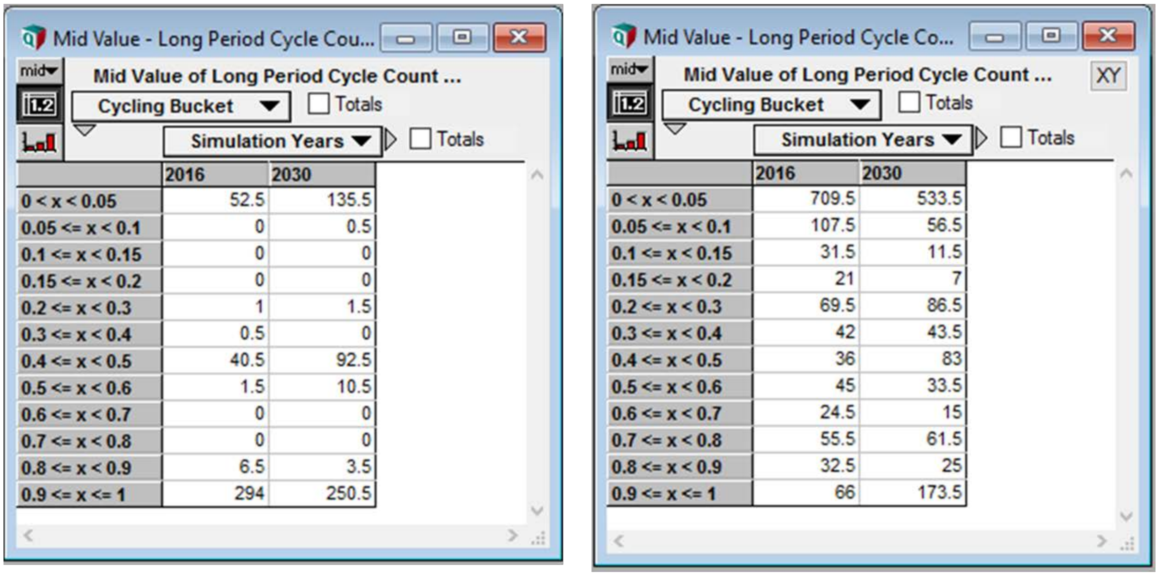
Daily Dispatch Index / Dispatch Component

	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	2,000	0	1,414	0	4,000	0	0
01:00	41	0	82	1,959	2,041	0	0
02:00	0	0	54	2,000	2,000	0	0
03:00	0	0	54	2,000	2,000	0	0
04:00	0	0	54	2,000	2,000	0	0
05:00	-2,000	-1,414	0	4,000	0	0	0
06:00	2,000	0	1,414	0	4,000	0	0
07:00	-96	-16	0	2,096	1,904	0	0
08:00	0	0	0	1,660	2,000	340	0
09:00	-2,000	-1,938	0	470	0	3,530	0
10:00	0	-266	0	0	2,000	2,000	0
11:00	0	-266	0	0	2,000	2,000	0
12:00	0	-266	0	0	2,000	2,000	0
13:00	0	-266	0	0	2,000	2,000	0
14:00	0	-266	0	0	2,000	0	2,000
15:00	-2,000	-1,414	0	4,000	0	0	0
16:00	-96	-16	0	2,096	1,904	0	0
17:00	1,680	0	1,197	320	3,680	0	0
18:00	0	0	320	2,000	0	0	0
19:00	0	0	320	2,000	0	0	0
20:00	0	0	320	2,000	0	0	0
21:00	0	0	54	2,000	2,000	0	0
22:00	0	0	54	2,000	2,000	0	0
23:00	0	-266	0	0	2,000	2,000	0

As demonstrated by the *Long Period Cycle Counts* output, this storage system favors shallow cycles to take advantage of frequency regulation revenue under current prices. Under reference 2030 prices, the storage system performs relatively more deep cycles to take advantage of large market day-ahead energy price discrepancies. In 2016, the battery cycles more frequently when providing ancillary services than when providing only resource adequacy and day-ahead energy arbitrage (Figure 27).

Figure 27: Cycle Counts for Storage Dispatch

Without Ancillary Services | **With Ancillary Services**



Without Ancillary Services:

	2016	2030
0 < x < 0.05	52.5	135.5
0.05 <= x < 0.1	0	0.5
0.1 <= x < 0.15	0	0
0.15 <= x < 0.2	0	0
0.2 <= x < 0.3	1	1.5
0.3 <= x < 0.4	0.5	0
0.4 <= x < 0.5	40.5	92.5
0.5 <= x < 0.6	1.5	10.5
0.6 <= x < 0.7	0	0
0.7 <= x < 0.8	0	0
0.8 <= x < 0.9	6.5	3.5
0.9 <= x <= 1	294	250.5

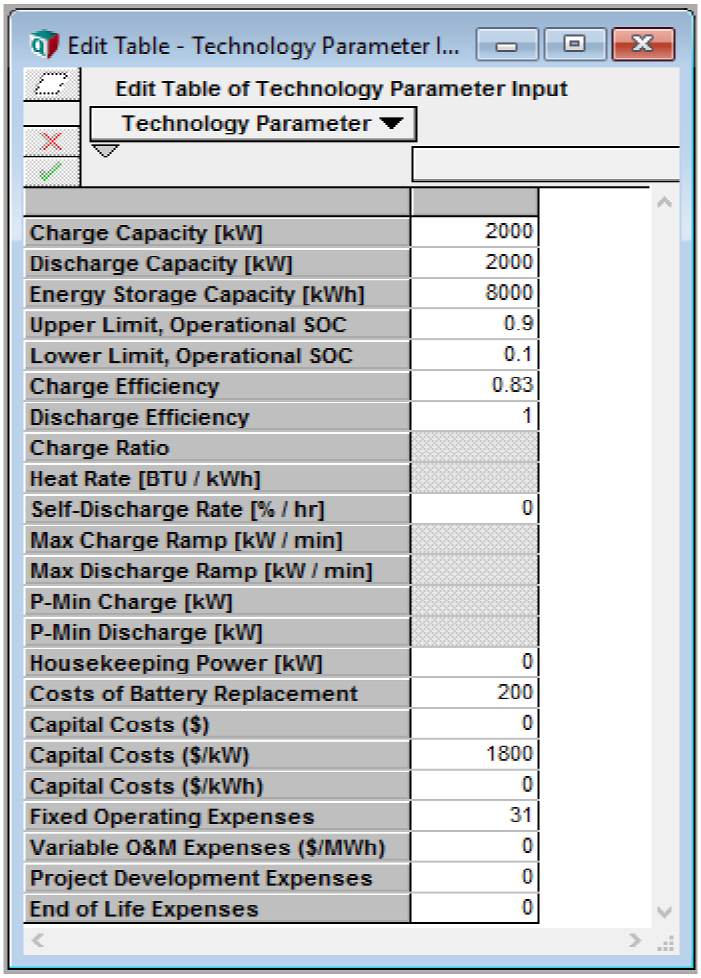
With Ancillary Services:

	2016	2030
0 < x < 0.05	709.5	533.5
0.05 <= x < 0.1	107.5	56.5
0.1 <= x < 0.15	31.5	11.5
0.15 <= x < 0.2	21	7
0.2 <= x < 0.3	69.5	86.5
0.3 <= x < 0.4	42	43.5
0.4 <= x < 0.5	36	83
0.5 <= x < 0.6	45	33.5
0.6 <= x < 0.7	24.5	15
0.7 <= x < 0.8	55.5	61.5
0.8 <= x < 0.9	32.5	25
0.9 <= x <= 1	66	173.5

Four-Hour Duration: Resource Adequacy, Day-Ahead Energy, and Frequency Regulation – 50% RPS Scenario

This case is the same as Case #3, but the battery analyzed in this case has lower capital costs per kWh and duration of four hours instead of two hours (Figure 28). Capital costs are $1,800/kW, or $225/kWh installed.

Figure 28: Technology Parameters



Technology Parameter	
Charge Capacity [kW]	2000
Discharge Capacity [kW]	2000
Energy Storage Capacity [kWh]	8000
Upper Limit, Operational SOC	0.9
Lower Limit, Operational SOC	0.1
Charge Efficiency	0.83
Discharge Efficiency	1
Charge Ratio	
Heat Rate [BTU / kWh]	
Self-Discharge Rate [% / hr]	0
Max Charge Ramp [kW / min]	
Max Discharge Ramp [kW / min]	
P-Min Charge [kW]	
P-Min Discharge [kW]	
Housekeeping Power [kW]	0
Costs of Battery Replacement	200
Capital Costs ($)	0
Capital Costs ($/kW)	1800
Capital Costs ($/kWh)	0
Fixed Operating Expenses	31
Variable O&M Expenses ($/MWh)	0
Project Development Expenses	0
End of Life Expenses	0

Relative to the previous case, the total costs have increased from $7.6 to $11.4 million (a 54 percent increase with a longer duration but a lower $/kWh installed cost), while the revenues have increased from $5.4 to $8.1 million, an increase of 52 percent (Figure 29). The benefit for resource adequacy, with a four-hour duration requirement, has doubled. Frequency regulation revenue has declined slightly, as the battery is maximizing revenues by participating more in the day-ahead energy market with a four-hour instead of two-hour duration.

Figure 29: NPV Total Resource Cost Test Costs and Benefits

Mid Value - NPV Cost/Benefit Chart

Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

DCF Cost Benefit - All Categories — Totals

	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	859.4K	0
Variable O&M	0	0
Property Tax	263.5K	0
Interest Expense	1.49M	0
Loan Repayment Expense (Principal)	751.5K	0
Debt Service Reserve	0	7661
Interested Earned on Debt Service Reserve	0	22.34K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	1.094M	0
Federal Tax Refund	0	432.8K
Tax Credit - Federal ITC	0	881.7K
Equity Investment	2.438M	0
Return on Equity Investment	3.611M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	904.1K	0
Resource Adequacy Capacity	0	2.437M
Day Ahead Energy Time Shift	0	2.647M
Frequency Regulation	0	1.566M
Spinning Reserve	0	19.73K
Non-Spinning Reserve	0	52.86K
Program Costs	0	0
Totals	11.41M	8.066M

The storage activity for April 14th (Figure 30) shows more charging and discharging, utilizing the larger kWh storage capacity, as compared to the prior case (Figure 26). Figure 31 shows that the four-hour battery tends to perform deeper cycles than the two-hour battery, reflecting the increased participation in energy arbitrage.

Figure 30: Illustrative Dispatch for April 14, 2015

Mid Value - Storage Activity Detail

Mid Value of Storage Activity Detail

Sample Days: 4/14

Summary Column: Dispatch [kW]

Daily Dispatch Index ☐ Totals

Dispatch Component ☐ Totals

	Energy Target	Net Charge	Net Discharge	Reg Up	Reg Down	Spinning Reserve	Non-Spinning Reserve
00:00	2,000	0	1,414	0	4,000	0	0
01:00	2,000	0	1,414	0	4,000	0	0
02:00	0	0	54	2,000	2,000	0	0
03:00	0	0	54	2,000	2,000	0	0
04:00	0	0	54	2,000	2,000	0	0
05:00	-816	-545	0	2,816	1,184	0	0
06:00	2,000	0	1,414	0	4,000	0	0
07:00	-96	-16	0	2,096	1,904	0	0
08:00	0	-266	0	0	2,000	2,000	0
09:00	-2,000	-2,000	0	0	0	4,000	0
10:00	0	-266	0	0	2,000	2,000	0
11:00	-1,565	-1,415	0	1,565	435	2,000	0
12:00	-2,000	-2,000	0	0	0	4,000	0
13:00	0	-266	0	0	2,000	2,000	0
14:00	-2,000	-2,000	0	0	0	0	4,000
15:00	-2,000	-1,414	0	4,000	0	0	0
16:00	-96	-16	0	2,096	1,904	0	0
17:00	2,000	0	1,414	0	4,000	0	0
18:00	0	0	320	2,000	0	0	0
19:00	0	0	320	2,000	0	0	0
20:00	151	0	422	1,849	151	0	0
21:00	2,000	0	1,414	0	4,000	0	0
22:00	0	0	54	2,000	2,000	0	0
23:00	0	0	54	2,000	2,000	0	0

Figure 31: Cycle Counts for Storage Dispatch

Two-Hour Duration

Mid Value - Long Period Cycle Co...

Mid Value of Long Period Cycle Count ...

Cycling Bucket / Simulation Years

	2016	2030
0 < x < 0.05	709.5	533.5
0.05 <= x < 0.1	107.5	56.5
0.1 <= x < 0.15	31.5	11.5
0.15 <= x < 0.2	21	7
0.2 <= x < 0.3	69.5	86.5
0.3 <= x < 0.4	42	43.5
0.4 <= x < 0.5	36	83
0.5 <= x < 0.6	45	33.5
0.6 <= x < 0.7	24.5	15
0.7 <= x < 0.8	55.5	61.5
0.8 <= x < 0.9	32.5	25
0.9 <= x <= 1	66	173.5

Four-Hour Duration

Mid Value - Long Period Cycle Co...

Mid Value of Long Period Cycle Count ...

Cycling Bucket / Simulation Years

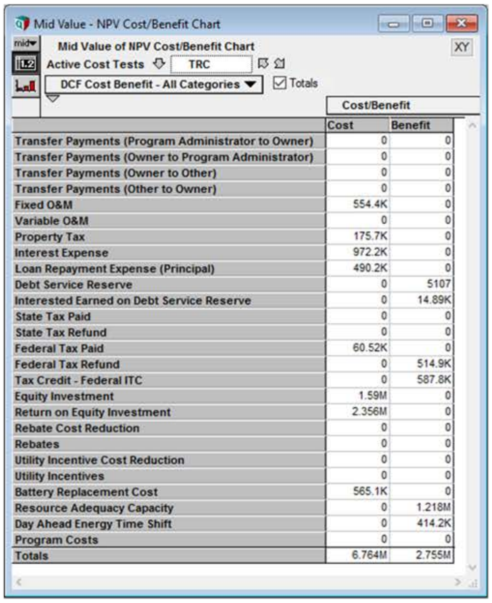
	2016	2030
0 < x < 0.05	486	321
0.05 <= x < 0.1	43	26
0.1 <= x < 0.15	55	71
0.15 <= x < 0.2	36.5	46.5
0.2 <= x < 0.3	32.5	72
0.3 <= x < 0.4	36.5	82
0.4 <= x < 0.5	38	33
0.5 <= x < 0.6	50	21.5
0.6 <= x < 0.7	58.5	19
0.7 <= x < 0.8	59	21.5
0.8 <= x < 0.9	35.5	53
0.9 <= x <= 1	22	204.5

Two-Hour Duration: Resource Adequacy, Day-Ahead Energy and Real-Time Energy - Current Scenario

Two new cases (Case #5 and #6) are now introduced to explore the impact of participating in the real-time market: one with hourly real-time dispatch and one with five-minutely real-time dispatch. StorageVET™ can perform storage dispatch at many different levels of time granularity (Figure 32) These cases are compared to Case #1, which is the same case without real-time market participation. The resource adequacy and day-ahead energy revenues in Case #5 are the same as those of Case #1, and the storage system earns revenues of $1.4 million in the real-time energy market, which is significantly higher than the $414 thousand in the day-ahead energy market. Dispatching every five minutes rather than each hour increases benefits from $1.4 to $1.9 million. This difference demonstrates the benefits of StorageVET™'s flexible dispatch granularity functionality.

Figure 32: NPV Total Resource Cost Test Costs and Benefits

Day-Ahead Energy Only



Mid Value - NPV Cost/Benefit Chart

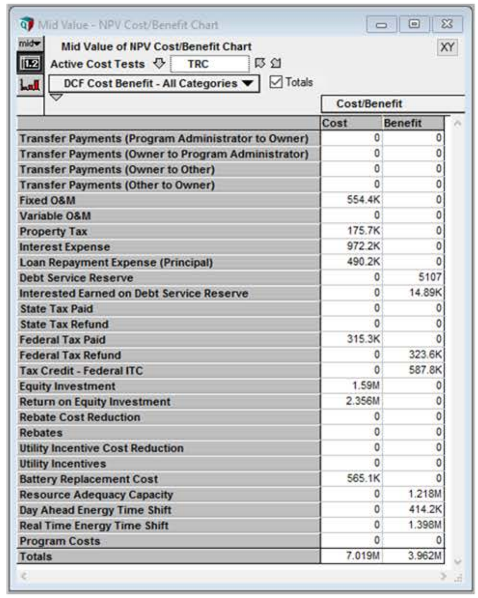
Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

DCF Cost Benefit - All Categories ☑ Totals

	Cost/Benefit	
	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	60.52K	0
Federal Tax Refund	0	514.9K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	414.2K
Program Costs	0	0
Totals	6.764M	2.755M

Day-Ahead and Real-Time Energy (1 Hour)



Mid Value - NPV Cost/Benefit Chart

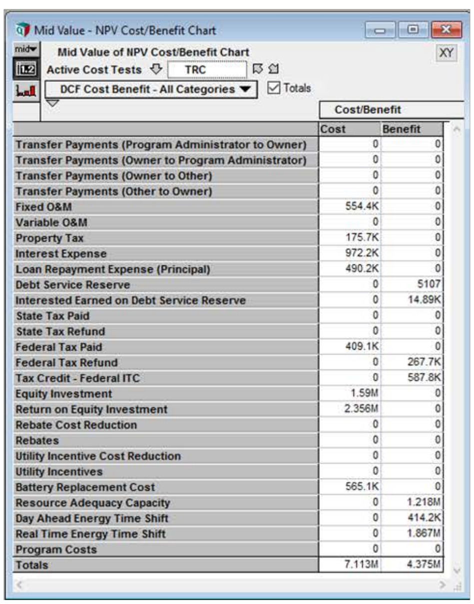
Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

DCF Cost Benefit - All Categories ☑ Totals

	Cost/Benefit	
	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	315.3K	0
Federal Tax Refund	0	323.6K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	414.2K
Real Time Energy Time Shift	0	1.398M
Program Costs	0	0
Totals	7.019M	3.962M

Day-Ahead and Real-Time Energy (5 Minute)



Mid Value - NPV Cost/Benefit Chart

Mid Value of NPV Cost/Benefit Chart

Active Cost Tests: TRC

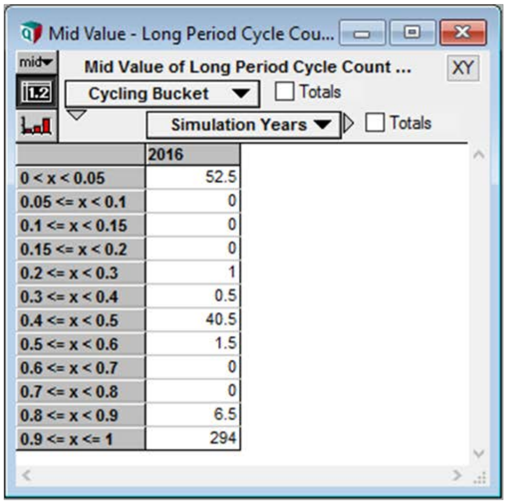
DCF Cost Benefit - All Categories ☑ Totals

	Cost/Benefit	
	Cost	Benefit
Transfer Payments (Program Administrator to Owner)	0	0
Transfer Payments (Owner to Program Administrator)	0	0
Transfer Payments (Owner to Other)	0	0
Transfer Payments (Other to Owner)	0	0
Fixed O&M	554.4K	0
Variable O&M	0	0
Property Tax	175.7K	0
Interest Expense	972.2K	0
Loan Repayment Expense (Principal)	490.2K	0
Debt Service Reserve	0	5107
Interested Earned on Debt Service Reserve	0	14.89K
State Tax Paid	0	0
State Tax Refund	0	0
Federal Tax Paid	409.1K	0
Federal Tax Refund	0	267.7K
Tax Credit - Federal ITC	0	587.8K
Equity Investment	1.59M	0
Return on Equity Investment	2.356M	0
Rebate Cost Reduction	0	0
Rebates	0	0
Utility Incentive Cost Reduction	0	0
Utility Incentives	0	0
Battery Replacement Cost	565.1K	0
Resource Adequacy Capacity	0	1.218M
Day Ahead Energy Time Shift	0	414.2K
Real Time Energy Time Shift	0	1.867M
Program Costs	0	0
Totals	7.113M	4.375M

Cycle counts are shown in Figure 33. With hourly real-time energy price dispatch, cycle counts with depths between 0.2 – 0.5 increase significantly. Moving to five-minute dispatch, there is a much wider range of cycling behavior. Cycles with depths below 5 percent increase by an order of magnitude.

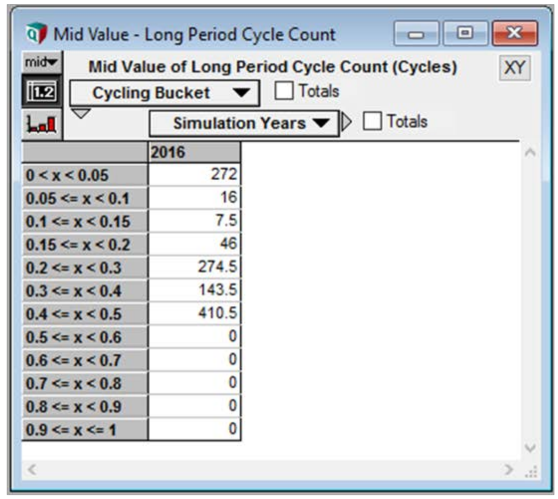
Figure 33: Cycle Counts for Storage Dispatch

Day-Ahead Energy Only



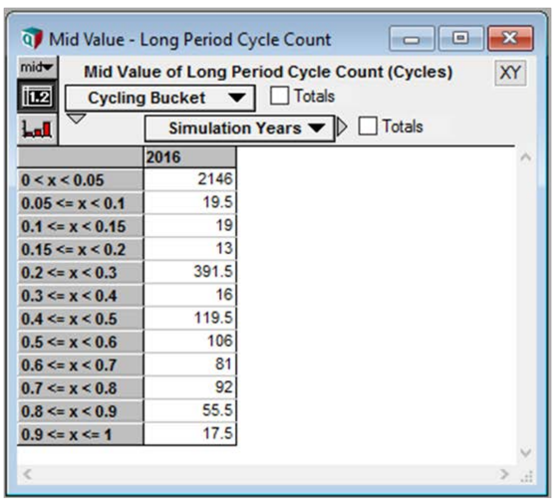
	2016
0 < x < 0.05	52.5
0.05 <= x < 0.1	0
0.1 <= x < 0.15	0
0.15 <= x < 0.2	0
0.2 <= x < 0.3	1
0.3 <= x < 0.4	0.5
0.4 <= x < 0.5	40.5
0.5 <= x < 0.6	1.5
0.6 <= x < 0.7	0
0.7 <= x < 0.8	0
0.8 <= x < 0.9	6.5
0.9 <= x <= 1	294

Day-Ahead and Real-Time Energy (1 Hour)



	2016
0 < x < 0.05	272
0.05 <= x < 0.1	16
0.1 <= x < 0.15	7.5
0.15 <= x < 0.2	46
0.2 <= x < 0.3	274.5
0.3 <= x < 0.4	143.5
0.4 <= x < 0.5	410.5
0.5 <= x < 0.6	0
0.6 <= x < 0.7	0
0.7 <= x < 0.8	0
0.8 <= x < 0.9	0
0.9 <= x <= 1	0

Day-Ahead and Real-Time Energy
(5 Minute)



	2016
0 < x < 0.05	2146
0.05 <= x < 0.1	19.5
0.1 <= x < 0.15	19
0.15 <= x < 0.2	13
0.2 <= x < 0.3	391.5
0.3 <= x < 0.4	16
0.4 <= x < 0.5	119.5
0.5 <= x < 0.6	106
0.6 <= x < 0.7	81
0.7 <= x < 0.8	92
0.8 <= x < 0.9	55.5
0.9 <= x <= 1	17.5

Reference Case Summary Findings

As demonstrated in the reference cases above, StorageVET™ has numerous features that may prove useful to policymakers, researchers, storage operators, storage owners, and storage developers. Among other use cases, the model facilitates comparison of storage system value across technologies, enables scenario analysis, and highlights potential market issues. While the focus of the reference cases depicted here was only six illustrative cases, users may glean many comparably important insights from using other StorageVET™ functionalities. Users may also obtain substantially different results, such as benefits that exceed costs, by using StorageVET™ to analyze other cases, such as lower-cost technologies providing additional or alternative services.

Discussion of Business-as-Usual vs. StorageVET™-Guided Planning Scenarios

The overall quantifiable benefit of StorageVET™ to ratepayers can be framed roughly by the magnitude of the improved project cost-effectiveness outcomes as a result of StorageVET™. This is challenging to measure as it is a counterfactual scenario. However, the following cases illustrate how the software may offer improved outcomes by incorporating refinements in requirements or the consideration of additional benefits, versus more rudimentary approaches to project specification. If it's assumed these cases are "typical" and the difference in outcome is multiplied by the size of the market and assumed StorageVET™ adoption rate, it can be estimated the magnitude of EPIC project value to improved storage-related decision-making in California.

To begin, the transmission-connected reference cases described above are used to illustrate quantifiable benefits. From there benefits for distribution-connected and customer-sited storage are explored qualitatively.

Case #1: Transmission-Connected Storage

Without a simulation tool, business as usual may be to overestimate or underestimate the market benefits.

1. Conservative, business as usual market value – simulate a case with a nominal annual growth rate of historical market prices
2. Evolving market conditions market value – simulate a case from the 50 percent RPS price outputs of the REFLEX model and interpolate the market conditions between historical prices and simulated future prices

First, net benefits are compared using the results from reference cases #1 and #2 from above:

Table 11: Transmission-Connected Reference Case Net Benefit Comparison

Business-as-Usual Reference Case #1 Historical Prices	StorageVET™-Guided Reference Case #2 50% RPS + Historical Prices	Difference in Outcome
-$3.86M	-$3.01M	$0.85M

To estimate California market impacts, the AB2514 transmission-connected procurement target of 700MW and an assumed StorageVET™ adoption rate of 50 percent per transmission-connected project are combined with the difference in net benefit outcome from the table above. This produces a total benefit of $297M for California ratepayers when comparing Business-as-Usual to StorageVET™-Guided valuation of projects.

Similar project benefit calculations can be conducted for distribution-connected and customer-sited storage.

Case #2: Distribution-Connected Storage
Without a simulation tool, utility business as usual would be to focus on the value of a distribution investment deferral or avoidance, as the distribution scope is focus.

Potential Scenarios to Investigate:

1. Conservative distribution upgrade deferral – utility may use a conservative peak day to size the storage system for a specified duration of deferral
    a. This could result in either an infeasibility, because it doesn't explicitly consider double peaks and potential time needed to charge
    b. Or this could result in oversizing the system
    c. Measure cost-effectiveness of this case
    d. Hypothesis: this will not result in cost-effectiveness
2. Right-sized distribution upgrade deferral – utility may use the software to analyze (net) load shape and growth rate to determine appropriate feasible size for storage to achieve target deferral
    a. Measure cost-effectiveness of this case
    b. Hypothesis: this will be better than the prior case, but will not result in cost-effectiveness
3. "Dual-use" stacked benefit distribution case
    a. By looking at the potential to incorporate CAISO market services, the net cost of equipment for a distribution investment deferral may be reduced
    b. Measure cost-effectiveness (TRC perspective)

Case #3: Customer-Sited Storage
Without a simulation tool, customer business as usual might be to think of cost-benefit in terms of a simple value proposition, for example, daily time-of-use (TOU) arbitrage and applicable incentives.

Key issues from the customer perspective:

- Customer potential to overestimate benefit: Customer may have insufficient load to shift, restricting TOU shift benefit.
- Customer potential to oversize/overpay for system: C&I customer may have challenge to size storage appropriately for demand charge management. However, a storage supplier may have a proprietary tool for guidance.
- Customer would have a significant challenge to understand the potential current benefits of bill management and the future benefits of service stacking which could involve day-ahead and/or real-time market participation

Key issues from the utility perspective:

1. Review total resource cost perspective of customer benefits, given a wholesale price environment (energy + RA value only), in each case

2. Develop a DR program framework to quantify whether TRC benefits can increase by addressing peak system load conditions

CHAPTER 7: Technology and Knowledge Transfer

Technology and Knowledge Transfer Plan

This chapter explains technology and knowledge transfer for this project. It includes goals and objectives pertaining to technology and knowledge transfer, metrics for success, the approach employed overview of successes and challenges, and plans for the future.

Goals and Objectives

The goal for technology and knowledge transfer activities of the StorageVET™ is to maximize the access and use of the software to people who may value from its functionality, particularly regulators, utilities, other energy storage investors, and energy storage suppliers

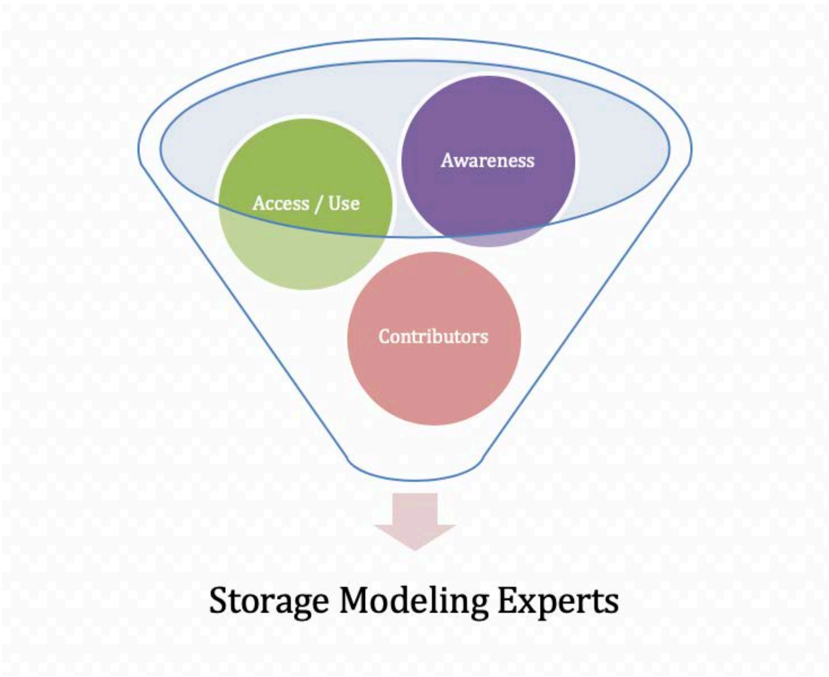
1. Increase awareness of the availability of publicly available storage valuation software and supporting resources
2. Support access and use of software
3. Engaging contributors for industry and research community for ongoing data and modeling enhancements

Transferring technology and knowledge ensures the project will be used and useful in the future by loading a funnel of prospects and supporting their deeper engagement with the modeling software to improve public understanding of energy storage value.

Planned Approach

This section summarizes the approach employed to support the goals and objectives of the project. At a high level, EPRI, with the support of project partners, provide a platform for continuous collaboration and improvement of the software and documentation. This can be visualized as a funnel, beginning with knowledge of the project, progressing to access and usage of the tool, deepening to collaboration and contribution to future enhancements of the model, and ending with the development of new experts who can support advancement of energy storage valuation methods and software (Figure 34).

Figure 34: StorageVET™ Engagement Funnel



Increasing Awareness

The initial technology and knowledge transfer goal is to support greater awareness of the project, including the software and the supporting research and documentation. To accomplish this, there will be multiple paths of outreach to the energy storage and electric power industries, regulatory organizations, and other potential users.

Technology transfer builds on prior engagements throughout the project development phases, beginning in 2015, with over 100 expressly interested users to date.

At the launch of the StorageVET™ software, EPRI plans a press release to support media redistribution of information for the project, as well as social media notifications. Additionally, EPRI seeks presentation opportunities at industry events, such as conferences, webcasts, and meetings.

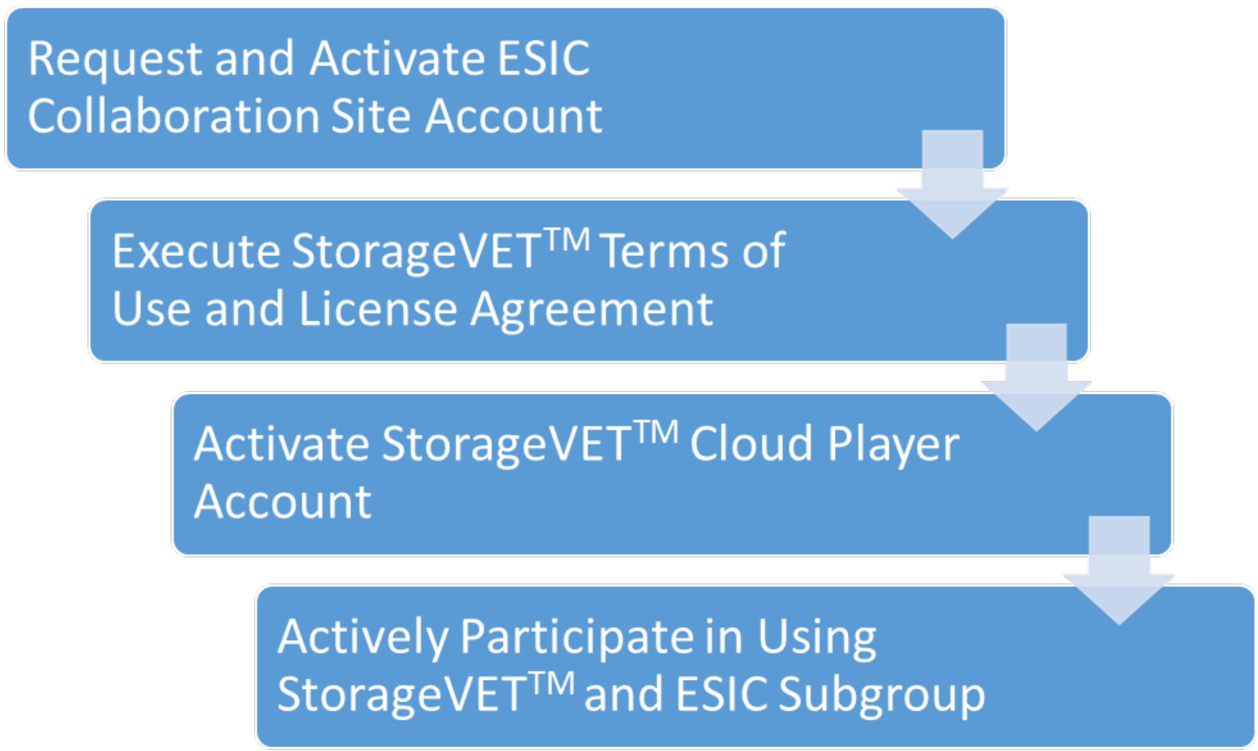
In addition to press release activity, EPRI will develop a website to host the StorageVET™ software and associated information and documentation. The URL www.storagevet.com and associated hosting services have been procured. All outreach and communications about the project intend to drive traffic to this website to facilitate deeper engagement.

Supporting Access and Use

After achieving awareness of the project by prospective users, the next level of deeper engagement is access and use of the StorageVET™ software and materials. Once users have been directed to the website, EPRI seeks to provide the necessary information for a prospective user to understand StorageVET™ capabilities and clear instructions on how to get access. Access instructions will be provided to users, which will entail enrollment in the ESIC forum, which will be used for EPRI to perform necessary export control screens and to verify the party. Then users will be provided a Terms of Use contract for execution. After execution, EPRI will set up a unique, password-protected account to enable users to access the Analytica™ Cloud Player and StorageVET™ model which resides on it.

To support skill development by users, EPRI provides regular demonstrations and training of the StorageVET™ model in different use cases. Additionally, frequently asked questions (FAQ) will be posted and other tools will be investigated to provide answers to new questions in a timely fashion (Figure 35).

Figure 35: StorageVET™ Access and Use Steps



Engaging Industry and Research Community

After users have access and essential information to get started with engaging the tool, the final phase of engagement is keep users engaged and contributing back to the community in the form of data or model improvement suggestions.

Using the StorageVET™ subgroup of the Energy Storage Integration Council as a platform, EPRI will host regular review meetings to review solutions to cases and solicit feedback for further augmentation. In addition, the StorageVET™ model is expected to be posted in the future as open-source software, so participants will have the opportunity to review and offer changes back to the model for subsequent releases.

Engagement Summary

Below are a summary of actions and approaches supporting each phase of user engagement toward the goal of developing experts in storage valuation:

- Increasing Awareness

- Develop press release
  - Drive website traffic
  - Hold outreach webcasts
- Supporting Access and Use
  - Execute terms of use
  - Support documentation access
  - Provide training
  - Post training and Frequently Asked Questions (FAQ)
- Engaging Industry and Research Community
  - Hold ESIC StorageVET™ subgroup meetings
  - Execute open source licenses

Metrics for Success

This section documents identified metrics for measuring success of the technology and knowledge transfer effort, and maps them to the key objectives. Table 12 provides a matrix for tracking the success of this effort.

Table 12: Technology and Knowledge Transfer Impact Metrics

Tech Transfer Objectives	Metrics	Value (as of 1/26/17)
Increasing Awareness	Press release media pickup	No press release
Increasing Awareness	Website visits	(not tracked)
Increasing Awareness	Outreach webcasts held	5 TAC, 14 ESIC
Increasing Awareness	Webcast attendance	30 per webcast
Supporting Access and Use	Active User accounts	250
Supporting Access and Use	Documentation downloads	(not tracked)
Supporting Access and Use	In-Person Training attendees	20
Engaging Contributors	ESIC StorageVET™ subgroup meetings	2
Engaging Contributors	ESIC subgroup average attendance	30
Engaging Contributors	Open source licenses executed	Open source licenses not yet available

Schedule and Description of Technology Transfer Activities

This section contains a brief description of technology transfer activities performed.

In-Person Training

For in-depth in-person trainings, the project team introduced participants to the following topics:

- The types of problems StorageVET™ is trying to address, including finding opportunities for storage, customizing and comparing projects, and optimizing storage project operations.
- Objectives for StorageVET™ as a web-based tool, free to the public, that is focused specifically on energy storage cost-benefit analysis, performs time-series dispatch optimization simulation, addresses stacked services, and can customize for location, sizing and use cases.
- Grid and customer services covered by StorageVET™
- Types of technologies covered by StorageVET™ and how they are modeled.
- StorageVET™ use cases
- StorageVET™ architecture and the optimization steps carried out
- StorageVET™ user interface
- How to import and export data with StorageVET™
- Participants running test cases with web interface

The first in-person training was held on October 3rd, 2016 in San Diego, preceding the Energy Storage North America conference. 19 participants attended a half-day StorageVET™ beta training with selected topics focusing on the StorageVET™ use cases and user interface.

The project team held a 2nd in-person training on December 6th, 2016 at EPRI's office in Palo Alto, CA that went through the full list of topics discussed above.

Webcast Training

The project team intends to cover the same topics from the in-person training in the webcast training, though web participation would limit the ability for participants to run test cases and troubleshoot in real-time.

- December 15

Other Presentations

The purpose of these presentations is to increase awareness of StorageVET™. The project team therefore focuses on the types of problems StorageVET™ is trying to address, the objectives, and a high-level overview of the use cases, the technologies, the model architecture, and the user interface. The project team also focuses on getting interested parties to start engaging with StorageVET™.

- December 6, 2016 - Greentech Media Executive Council Meeting in San Francisco

Press Releases

- TBD

Energy Storage Integration Council

- Insert list of StorageVET™ subgroup meetings

CHAPTER 8: Conclusions

Project Goals and Objectives

Under AB 2514 and other policies, California has taken a leadership position in the development and implementation of advanced energy storage projects. The experience with storage in the California power system will support the achievement of the state's policy goals, set precedents for similar public policies elsewhere, and provide critical information to the nascent storage market in the United States.

The Energy Commission provided the grant to support developing StorageVET™ to assist advancing storage modeling capabilities and provide a publicly accessible tool which could improve understanding of storage valuation and serve as a public benchmark. The tool incorporated advances which would support not just planning assessments but also operational and market simulation capabilities which provide results reasonably close to actual daily operations.

Based on the project team's survey of comparable tools, StorageVET™ is the most sophisticated commercial model of its type for the California market, as well as being both publicly available and easily accessible.

Software Review

Table 13 provides information on attainment of the different goals and objectives of this project. For a more detailed list of functional capabilities, refer to Appendix E.

Table 13: Summary of StorageVET™ Goals and Objectives Attainment

Goal or Objective Description	Level of Achievement	Details, Explanations as Needed
GOAL: Facilitate assessment and communication of the value for energy storage projects	Achieved	Provides the means to calculate and assess the value of storage projects from various perspectives. Excel input/output template to organize and compare assumptions of each case.
GOAL: Support optimization of energy storage project cost-effectiveness	Achieved	Scenario analysis allows for cost-benefit effectiveness optimization
OBJ: Obtain buy-in from key stakeholders on requirements and	Achievement is Imminent	Users expressed satisfaction with the modeling approaches and exhibited features. Buy-in will evolve with additional usage and discussion

Goal or Objective Description	Level of Achievement	Details, Explanations as Needed
approaches		about results.
OBJ: Leverage prior investments in models and analyses	Achieved	Leverages models and methodologies available in the Energy Storage Valuation Tool (ESVT).
OBJ: Create reference scenarios and data sets through coordination with relevant proceedings	Partially Achieved	Incorporates historical CAISO datasets and a year 2030 reference price set. Contains certain energy storage cost and performance characteristics, leveraging EPRI research projects. Completion of reference scenarios requires additional coordination and research to be completed. Complete datasets for such references are available within the tool. Refer to Chapter 4 of the document.
OBJ: Develop and deliver a public, transparent, and validated tool as cloud-hosted software	Achievement is Imminent	Tested and available to the public as a cloud-hosted software. Transparency of inputs and outputs Modeling approach well-documented through the published StorageVET™ User Guide More utilization and user experiences are necessary, along with real project benchmarking, to achieve validation of the tool
OBJ: Achieve broad adoption of software with robust technology transfer activities	Achievement is Imminent	Over 150 user accounts have been set by requests and 2 trainings (full day / half day) have been provided in December.

Understanding Industry Needs

The StorageVET™ project undertook an extensive set of stakeholder meetings and consultations to improve understanding of industry needs. This included engagement with target users through workshops and surveys to develop functional and technical requirements and background research of regulatory and technical information pertaining to storage to support model definition. The team also used the Energy Storage Integration Council (ESIC) for additional user engagement. The report reviews all of these processes and their outcomes. In particular, stakeholders were asked to prioritize use cases for inclusion, and the team then consolidated them based on whether they could utilize the same functionality.

The actual use cases implemented in StorageVET™ are summarized as:

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.

Software Development

StorageVET™ was developed from an earlier EPRI model, the Energy Storage Valuation Tool (ESVT), also developed in Analytica. While ESVT is itself a sophisticated tool developed over three years, it has certain limitations in how it represents storage operations and was restricted to an hourly time-step. StorageVET™ was completely redesigned using relevant formulations from ESVT and extending them. Notable improvements include the web-hosted capability, and include many changes to the representation of CAISO day-ahead and real-time market services. For example, StorageVET™ allows for several different representations of how storage resources will provide Regulation, depending on the market participation model. In addition, StorageVET™ includes a basic representation of real-time energy dispatch in the CAISO Fifteen Minute Market, including payments for the Flexible Ramping Product introduced in late 2016.

Another notable advance is in the architecture of StorageVET™, which contains four major modules: Pre-optimization configuration, Scheduling optimization, Post-optimization simulation, and Financial Calculations. This structure will enable flexibility, modularity, and specification of scenarios for evaluation.

Limitations of StorageVET™, and the general class of similar models, include that it takes market prices and/or operational requirements as inputs, and as such cannot determine the impact of storage operations on the wholesale market or power system. However, it can be used in tandem with different types of power system models – such as production cost models and power flow models – to fine-tune representation of storage operations. In addition, it can use simulated future prices from these models to evaluate changes in value from historical market periods.

Software Review

The StorageVET™ project followed standard software development and review procedures. Two user tests were organized to collect feedback on the user interface and modeling process. The alpha test was carried out under a controlled environment where the testers guided the users through specific test cases within designated time; the users only had access to the model within the sessions. The beta test was released to a broader group within ESIC over five weeks; the users were able to access the model on their own time and run their own cases with pre-loaded data sets, though the functionality to upload user-supplied time series data was not available in the beta model. In addition to the two external user tests, the project team carried out its own quality assurance and control processes to ensure the usability of the tool.

Software Completion, Delivery, and Documentation

In addition to this report, the project team developed several documents to facilitate use of StorageVET™. These documents are available on the project website, and include:

- *StorageVET™ V1.0 User Guide.* This document is a starter guide on the objectives of StorageVET™, its use cases, user interface, along with example cases demonstrating the flow through its interface.
- *StorageVET™ Use Cases.* This document describes the different types of problems a user can utilize StorageVET™ to solve.
- *StorageVET™ Functional Requirement and Interface Specification.* This document describes the functionality of StorageVET™ software. It is derived mostly from the process section in the StorageVET™ use cases document.
- *Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model.* This document provides general descriptions and technical details about the California policy, program and market contexts for energy storage use cases and applications modeled in StorageVET™ and other storage valuation tools.

There are several other documents available for model developers as well as information embedded in StorageVET™.

EPRI has committed to providing support and maintenance for the web-hosted software for a period of two years after the project end date. StorageVET™ software will be hosted through the portal www.storagevet.com in 2017 and 2018 as part of a post-project commitment.

Project Benefits

The quantifiable benefit of StorageVET™ to ratepayers would be a result of improved project cost-effectiveness outcomes as a result of StorageVET™, leading to changes in the decision to undertake a project or in project specifications. While a baseline for the impact of one new modeling tool would clearly be difficult to determine, the outcomes are illustrated before and after results below as compared to prior, simpler models.

When comparing StorageVET™ results to earlier or more rudimentary models, researchers found that among other use cases, the model facilitates comparison of storage system value across technologies, enables scenario analysis, and highlights potential market issues. Six illustrative cases were described with examples given how users may glean many comparably important insights from using other StorageVET™ functionalities. Users may also obtain substantially different results, such as benefits that exceed costs, by using StorageVET™ to analyze other cases, such as lower-cost technologies providing additional or alternative services.

REFERENCES

California ISO (CAISO), "2015-2016 ISO Transmission Plan," March 28, 2016. [Online]. Available: http://www.caiso.com/Documents/Board-Approved2015-2016TransmissionPlan.pdf.

E3, Renewable Energy Flexibility (REFLEX) Model Energy and Environmental Economics, Inc. [Online]. Available: https://ethree.com/public_projects/reflex.php

Eichman, J., P. Denholm, J. Jorgenson and U. Helman, "Operational Benefits of California's Energy Storage Targets," December 2015 National Renewable Energy Laboratory, Technical Report NREL/TP-5400-65061. [Online]. Available: http://www.nrel.gov/docs/fy16osti/65061.pdf

EPRI. "Cost-Effective Energy Storage in California." *CPUC*. [Online]. Available: http://www.cpuc.ca.gov/General.aspx?id=3462.

EPRI. "Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model." 2016. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002009362.

The Electricity Advisory Committee. "2016 Storage Plan Assessment Recommendations for the U.S. Department of Energy." *Energy.gov*. [Online]. Available: http://energy.gov/oe/downloads/recommendations-and-report-approved-september-2016-meeting-eac.

Koritarov, V., T. Guo, E. Ela, B. Trouille, J. Feltes and M. Reed, "Modeling and Simulation of Advanced Pumped - Storage Hydropower Technologies and their Contributions to the Power System," Argonne National Laboratory, Energy Exemplar, LLC, National Renewable Energy Laboratory, MWH Americas, Inc., Siemens PTI, Inc., U.S. Department of Energy, 2013. [Online]. Available: http://energyexemplar.com/wp-content/uploads/2013/06/koritarov-et-al-2014_hv-paper_final2.pdf.

Liu, S., "A Bulk Energy Storage Resource Case Study updated from 40% to 50% RPS," California ISO, 2015-2016 Transmission Planning Process. [Online]. Available: http://www.caiso.com/Documents/BulkEnergyStorageResource-2015-2016SpecialStudyUpdatedfrom40to50Percent.pdf.

Pacific Gas and Electric. "EPIC Final Report - EPIC Project 1.01, Energy Storage End Uses: Energy Storage for Market Operations." September 13, 2016. [Online]. Available: https://www.pge.com/pge_global/common/pdfs/about-pge/environment/what-we-are-doing/electric-program-investment-charge/PGE-EPIC-Project-1.01.pdf.

Pacific Gas & Electric. "Supply-Side Pilot." n.d. [Online]. Available: http://olivineinc.com/ssp/.

Rawson, M, and E. Sanchez, Sacramento Municipal Utility District (SMUD). "2014 Sacramento Municipal Utility District – Photovoltaic and Smart Grid Pilot at Anatolia." California Energy Commission. Publication number: CEC-500-2015-047. [Online]. Available: http://www.energy.ca.gov/2015publications/CEC-500-2015-047/CEC-500-2015-047.pdf.

San Diego Gas & Electric (SDG&E). "Optimized Pricing and Resource Allocation (OPRA) Project, Presentation at CPUC/CAISO Workshop on Multi-Use Applications." May 3, 2016. [Online]. Available: http://www.cpuc.ca.gov/General.aspx?id=3462.

Southern California Edison (SCE). "Preferred Resources Pilot (PRP)." n.d. [Online]. Available: https://www.sce.com/.

GLOSSARY

A/S	ancillary services
ACP	Analytica Cloud Player™
CAES	compressed air energy storage
CAISO	California Independent System Operator
CAPEX	capital expenditure
Energy Commission	California Energy Commission
CEP	consistent evaluation protocol
CPUC	California Public Utilities Commission
DA	day ahead
DOE	U.S. Department of Energy
DR	demand response
EIM	energy imbalance market
EPRI	Electric Power Research Institute
ESIC	Energy Storage Integration Council
ESNA	Energy Storage North America
ESS	energy storage system
ESVT	Energy Storage Valuation Tool
FAQ	frequently asked question
FITC	federal investment tax credit
FMM	fifteen minute market
FRP	flexible ramping product
GHG	greenhouse gas
MIP	mixed integer programming
NGR	non-generator resource
NPV	net present value
NREL	National Renewable Energy Lab
O&M	operations and maintenances
PCM	production cost modeling

PHS	pumped hydro storage
P_{min}	minimum power output, usually refer to the minimum power output from a generator.
PV	photovoltaic
QA/QC	quality assurance/quality control
RA	resource adequacy
REM	CAISO Regulation Energy Management rules
ROE	return on equity
RT	real time
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SMUD	Sacramento Municipal Utility District
SOC	state of charge
StorageVET™	Storage Value Estimation Tool
TOU	time of use
TRC	total resource cost
UI	user interface
WACC	weighted average cost of capital

APPENDICES

The following appendices provide further documentation that supported the development and use of the Storage Value Estimation Tool (StorageVET™)

Appendix A: StorageVET™ Use Cases

Provided as separate publication, publication number:
CEC-500-2017-016-APA

Appendix B: Functional Requirements and Interface Specification

Provided as separate publication, publication number:
CEC-500-2017-016-APB

Appendix C: Energy Storage Valuation in California: Policy, Planning and Market Information Relevant to the StorageVET™ Model

Provided as separate publication, publication number:
CEC-500-2017-016-APC

Updated versions may be published over time. These can be found at:
http://www.storagevet.com/documentation

Appendix D: StorageVET™ V1.0 User Guide

Provided as separate publication, publication number:
CEC-500-2017-016-APD

Updated versions may be published over time. These can be found at
http://www.storagevet.com/documentation

Appendix E: StorageVET™ Software Review

Provided as separate publication, publication number:
CEC-500-2017-016-APE

Appendix F: StorageVET™ Technology & Knowledge Transfer Report

Provided as separate publication, publication number:
CEC-500-2017-016-APF

Appendix G: Final General and Technical Project Benefits Questionnaires

Provided as separate publication, publication number:
CEC-500-2017-016-APG