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FINAL PROJECT REPORT

DEMONSTRATION OF ENERVAULT IRON-CHROMIUM REDOX FLOW BATTERY

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Prepared by: EnerVault Corperation

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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EnerVault Iron-Chromium Redox Flow Battery is the final report for the Flow Battery Solution to Smart Grid Renewable Energy Applications project (contract number PIR-10-066) conducted by EnerVault Corporation. The information from this project contributes to Energy Research and Development Division's Energy Technology Systems Integration 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

This project developed, deployed and tested a 250kW, 1MW per hour Iron-Chromium Redox Flow Battery by EnerVault Corporation and demonstrated the capability of the battery system to integrate solar and peak demand management. The final system is the only MW-hr scale Iron-Chromium Redox Flow Battery in the world.

Keywords: EnerVault, Energy Storage, Redox Flow Battery, Iron-Chromium

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EXECUTIVE SUMMARY

Introduction

In 2009, a U.S. Department of Energy American Recovery and Reinvestment Act - Energy Storage Demonstration program was launched. The goal of this program was to commercialize promising technologies required for stronger and more renewable-intensive grids. The integration of energy storage systems is necessary for increasing the amount of intermittent renewable generation such as solar and wind. In the energy storage market there is a gap between small power, short duration systems and large power, long duration systems. A safe, highly configurable, storage technology is needed that is easily sited and can cost-effectively address the critical needs of a future, clean, resilient grid. To meet this need, the storage system should be capable of rapidly absorbing excess energy and shaving peaks, shift load to off-peak, and store renewable energy for use during high demand.

Project Purpose and Results

EnerVault, a Sunnyvale, California company, received grant funding from the U.S. Department of Energy with matching funds from the California Energy Commission to develop energy storage systems based on its iron-chromium redox flow battery technology that would work for grid-scale storage.

Redox flow batteries are a type of electrochemical energy storage devices called flow batteries. Flow batteries are batteries where at least one or both of the active materials are in solution in the electrolyte at all times (substances consumed by a chemical reaction) moves through the system rather than being contained in a cell. Redox refers to the chemical reduction and oxidation reactions taking place in the battery to store energy in liquid electrolyte solutions that flow through a stack of electrochemical cells during charge and discharge. The liquid electrolyte solutions consist of reactants that carry the charge dissolved in water or other solvent. Reactants are typically metal salts.

EnerVault successfully designed, built, installed, permitted, and interconnected the world's first, megawatt-hour scale iron-chromium redox flow battery. Initially the team installed and tested two 7.5-kilowatt (kW) systems and a 30 kW system with more than 80 percent efficiency. EnerVault also permitted and demonstrated a full rated power 250 kW system delivering 1 MW- hour of energy at constant power during four-hour duration, over multiple cycles. Finally, a 15-megawatt (MW)/50 MW- hour pilot manufacturing and test operations process was started.

While the project was successful in scaling up and commercializing the technology, EnerVault sees a need for pilot programs to learn the operational and market optimal requirements of a grid-connected energy storage system, and has identified particular applications where the future need is high and the fit for long duration energy storage systems like EnerVault's is optimal.

Benefits to California

EnerVault's iron-chromium redox flow battery technology provides significant benefits to California by using plentiful, low cost, environmentally safe, and low hazard electrolytes with low production costs and low mitigation costs. The system provides peak electricity demand management to use more effectively the existing generation and transmission lines. This helps avoid costly transmission and distribution projects over sensitive areas. Since the power and energy can be separately sized, the technology provides a high degree of flexibility to tailor the set-up to the needs of the application. Adding more energy storage involves only increased tank sizes and a larger volume of low cost electrolytes so the marginal installed cost of an additional kW-hr of energy can be under $100/ kW-hr, making long duration applications cost effective. Finally, the iron-chromium redox battery helps leverage cost effectiveness of photovoltaic and wind resources, increasing the amount of renewables generation allowed on the grid.

CHAPTER 1
Background

1.1 Problem Statement, Goals & Objectives

1.1.1 Problem Statement

In the energy storage market there is a gap between small power, short duration systems and large power, long duration systems. Technologies such as flywheels and super capacitors work well for short duration such as power conditioning applications. Integrated cell batteries work well for low power, medium duration applications such as uninterrupted power systems. However, the scaling of power and duration for these technologies can be costly and dangerous. Technologies such as pumped hydro and compressed air are efficient at the large power, long duration end of the spectrum, but require long planning horizons, have limited siting and are only cost effective when very large. These systems address ancillary services and system balance needs, but a market gap exists with the increasing use of intermittent renewables, the desire to more efficiently use fossil fuels to reduce greenhouse gasses, and the need for more resilient systems. What is needed is a safe, highly configurable, storage technology that is easily sited and can cost-effectively address the critical needs of a future, clean, resilient grid. To meet these needs, the storage system should be capable of delivering flexible capacity (rapidly absorbing excess energy and shaving peaks), enable more efficient use of grid generation and transmission assets, shifting load to off-peak, and storing renewable energy for use during high demand.

1.2 Iron Chromium Redox Flow Batteries and EnerVault Technology

1.2.1 Redox Flow Batteries

1.2.1.1 Introduction to Redox Flow Batteries

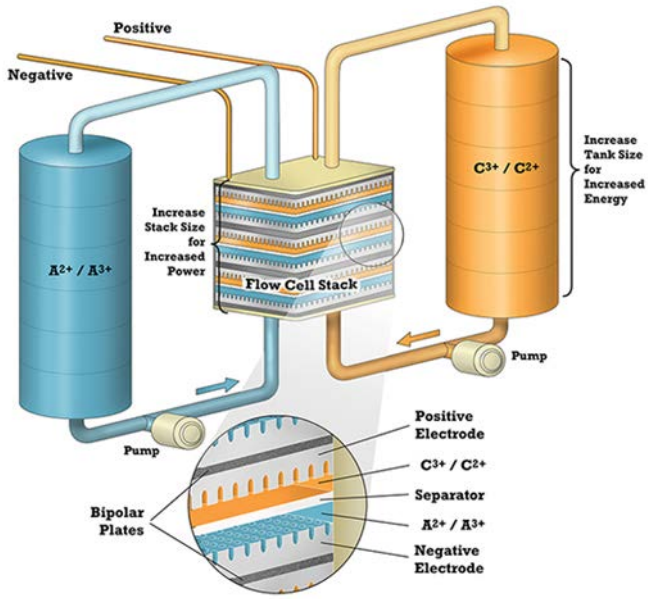
Redox flow batteries (RFB) are a subclass of electrochemical energy storage devices called flow batteries. Flow batteries are batteries where at least one of the reactants flows through the

system rather than being contained in a cell. In RFBs, both positive electrode and negative electrode reactants flow through the system and stay in solution during charging and discharging as shown in Figure 1: Simplified diagram of a redox flow battery (RFB)'s architecture. Positive (C) and negative (A) reactants. Examples of RFB reactant couple chemistries include the vanadium-vanadium and iron-chromium systems. Another subclass of flow batteries is hybrid flow batteries (HFB) where, although reactants flow through the system, at least one of the reactant is plated as a solid in the electrochemical cells during charge. Examples of HFBs include the zinc-bromine, zinc-ferricyanide, and all-iron systems.

The term "redox" refers to chemical reduction and oxidation reactions employed in the RFB to store energy in liquid electrolyte solutions that flow through a stack of electrochemical cells during charge and discharge. The liquid electrolyte solutions consist of reactants that carry the charge dissolved in water or other solvent. Reactants are typically metal salts. Several groups are evaluating other types of molecules.

Electrolytes containing the negative and positive reactants are flowed through the electrochemical cell and reduction-oxidation reactions proceed as shown in Figure 1. During discharge, an electron is released via an oxidation reaction from a high chemical potential state on the negative or anode side of the cell stacks. The electron moves through an external circuit to do useful work. Finally, the electron is accepted via a reduction reaction at a lower chemical potential state on the positive or cathode side of the cell stacks. The direction of the current and the chemical reactions are reversed during charging.

Figure 1: Simplified diagram of a redox flow battery (RFB)'s architecture. Positive (C) and negative (A) reactants



1.2.1.2 Advantages of Redox Flow Batteries

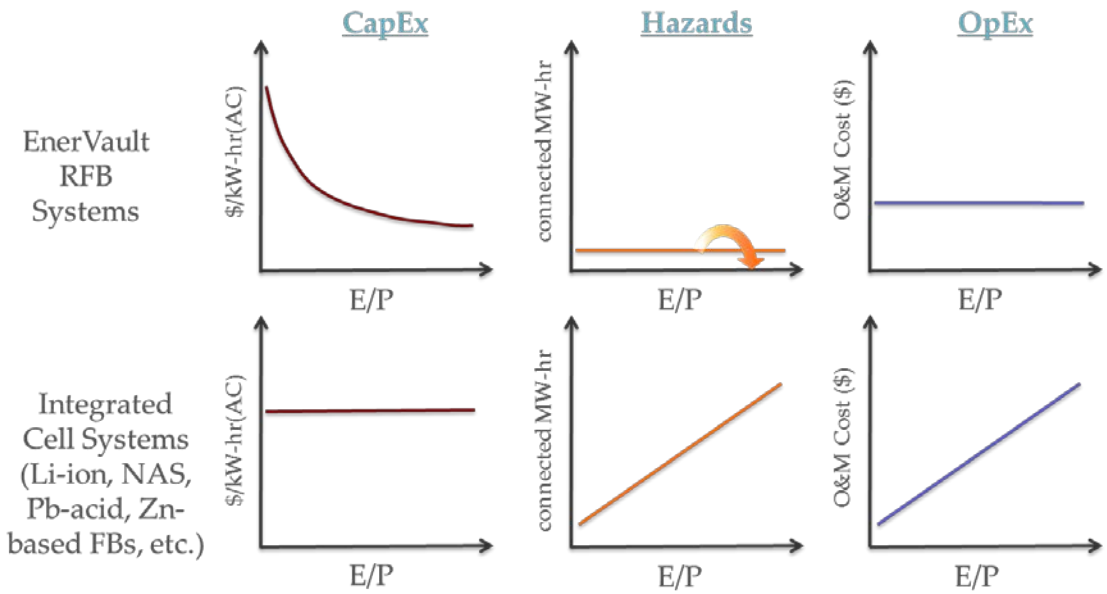
The separation of power and energy is a key distinction of RFBs compared to other electrochemical storage systems. The system energy storage capacity is based on the volume of

electrolyte solution. The power capacity of the system is determined by the size of the stack of electrochemical cells. Only the electrolyte present in the cell stacks at any given time is available to be charged or discharged. Since the positive and negative electrolyte solutions are stored separately, very little, if any, stored energy is lost to self-discharge over time.

There is an inherent safety advantage to the separation of power and energy. The amount of electrolyte flowing in the cell stacks at any moment is rarely more than a few percent of the total amount of electrolyte present (for energy ratings corresponding to discharge at rated power for 4 hours or longer). Flow can easily be stopped during a fault condition. As a result, system vulnerability to uncontrolled energy release in the case of RFB's is limited by system architecture to a few percent of the total stored energy. This feature is in contrast with packaged, integrated cell storage architectures (lead-acid, NAS, Li Ion), where the total amount of stored energy in the system is connected at all times and available for discharge. Consequently, complex controls and fault-protection devices are required in integrated cell systems to limit uncontrolled energy release. Such systems are not needed with RFBs.

The separation of power and energy also provides design flexibility in the application of RFBs, see Figure 2. The power capacity (stack size) can be specifically tailored to the application's load or generation profile. The energy storage capacity (electrolyte volume and size of storage tanks) can be independently tailored to the energy storage need of the specific application. Consequently, RFBs can provide an economically optimized storage system for each application. In contrast, the ratio of power capacity to energy storage capacity is fixed for integrated cells at the time of design and manufacture of the cells. Economies of scale in cell production limit the practical number of different integrated cell designs that are available. Because of this fixed coupling of power and energy, storage systems with integrated cells typically have an excess of either power capacity or energy storage capacity for a given application.

Figure 2: EnerVault Systems vs. Integrated Cell Systems



In hybrid flow batteries (HFBs), complete separation of power and energy is not achieved because energy is stored in the metal that is plated in the electrochemical stack during charge. Larger energy storage capacity requires a larger stack, so the distinction of these from integrated cell architectures is only partly achieved.

RFBs are well suited for applications with power requirements in the range of 100's of kW to 10's of MW, and energy storage requirements in the range of 500 kW-hr to 100's of MW-hr. RFBs can be the most cost effective choice in this range because storage tanks and flow controls are readily and economically scaled, and electrochemical stacks can have repeat units with power ratings in the 10's to 100's of kW.

1.2.1.3 Redox Flow Battery Configuration

The following lists the components of redox flow batteries and Figure 3 shows the configuration:

A. Energy Block

Main components: tanks, electrolyte

Function: stores energy

B. Power Block

Main components: cell stacks (cascades), stack module, rebalance system, State-of Health (eSOH) monitors

Function: absorbs and releases power

C. Hydraulic Block

Main components: main hydraulics, flow meters, filtration

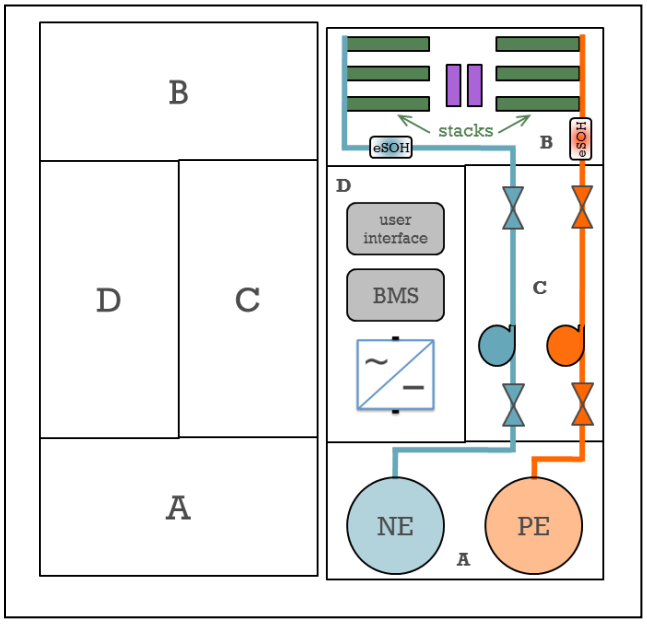
Function: distributes electrolyte from A to B

D. Controls Block

Main components: controls/user interface, battery management system, DC conditioning, AC/DC inverter

Function: controls system and monitors overall system State-of-Health; conditions power; grid interface

Figure 3: Redox Flow Battery Configuration



1.2.2 EnerVault's Iron-Chromium Redox Flow Batteries

1.2.2.1 Introduction to EnerVault's Iron Chromium Redox Flow Batteries

The iron-chromium chemistry is used in EnerVault's long-duration, grid-scale energy storage systems. The iron-chromium redox flow battery (Fe-Cr RFB) energy is stored by employing the Fe^{2+}- Fe^{3+} and Cr^{2+} - Cr^{3+} redox (reduction-oxidation) couples:

Discharging: $Fe^{3+} + e^- \Leftrightarrow Fe^{2+}$ (reduction)

$Cr^{2+} \Leftrightarrow Cr^{3+} + e^-$ (oxidation)

Charging: $Fe^{3+} \Leftrightarrow Fe^{2+} + e^-$ (oxidation)

$Cr^{3+} + e^- \Leftrightarrow Cr^{2+}$ (reduction)

The active chemical species are fully dissolved in the aqueous electrolyte at all times. Like other RFBs, the power capacity and energy storage capacity ratings of the iron-chromium system are completely independent of each other, and each may be optimized separately for each application.

The iron-chromium chemistry was pioneered and studied extensively by NASA in the 1970s and 1980s, as well as by Mitsui in Japan in the 1980s. Chromium's use in stainless steel makes it widely abundant and low-cost. All the other benefits and distinctions of RFBs compared to other energy storage systems are realized by iron-chromium RFBs.

1.2.2.2 Advantages of EnerVault's Iron-Chromium Redox Flow Batteries

In early implementations of the iron-chromium RFB, diffusion of the iron and chrome ions across the separator created an imbalance between the positive and negative electrolytes, resulting in an irreversible system capacity loss. Modern Fe/Cr electrolyte formulations using mixed iron and chromium on both sides of the cell have eliminated the irreversible loss and enabled the use of low cost, porous separator materials. These porous separators have also eliminated the "membrane fouling" failure mode that occurs with expensive ion exchange membranes used in early iron-chrome and some other current RFB technologies. Additionally, the most abundant source of chromium is chromite, $FeCr_2O_4$. The costs of chromite and iron ore as raw materials translate to approximately $4/kW-hr making the Fe/Cr couple one of the lowest cost elemental combinations for batteries.

EnerVault's combination of RFB system architecture and low-cost reactants translates to a marginal cost for an additional hour of discharge (at the system's nameplate power capacity) of less than $100/kW-hr on an installed basis.

The iron and chromium chemistry is environmentally benign compared to other electrochemical systems because the utilized iron and chromium species have very low toxicity, and the dilute water-based electrolyte has a low acid content and very low vapor pressure. Additionally, a unique feature from the presence of iron and chromium in both positive and negative electrolytes is that the electrolytes become chemically identical at zero state-of-charge (SOC) thereby making the cells, and stacks of cells, electrically neutral without damaging the

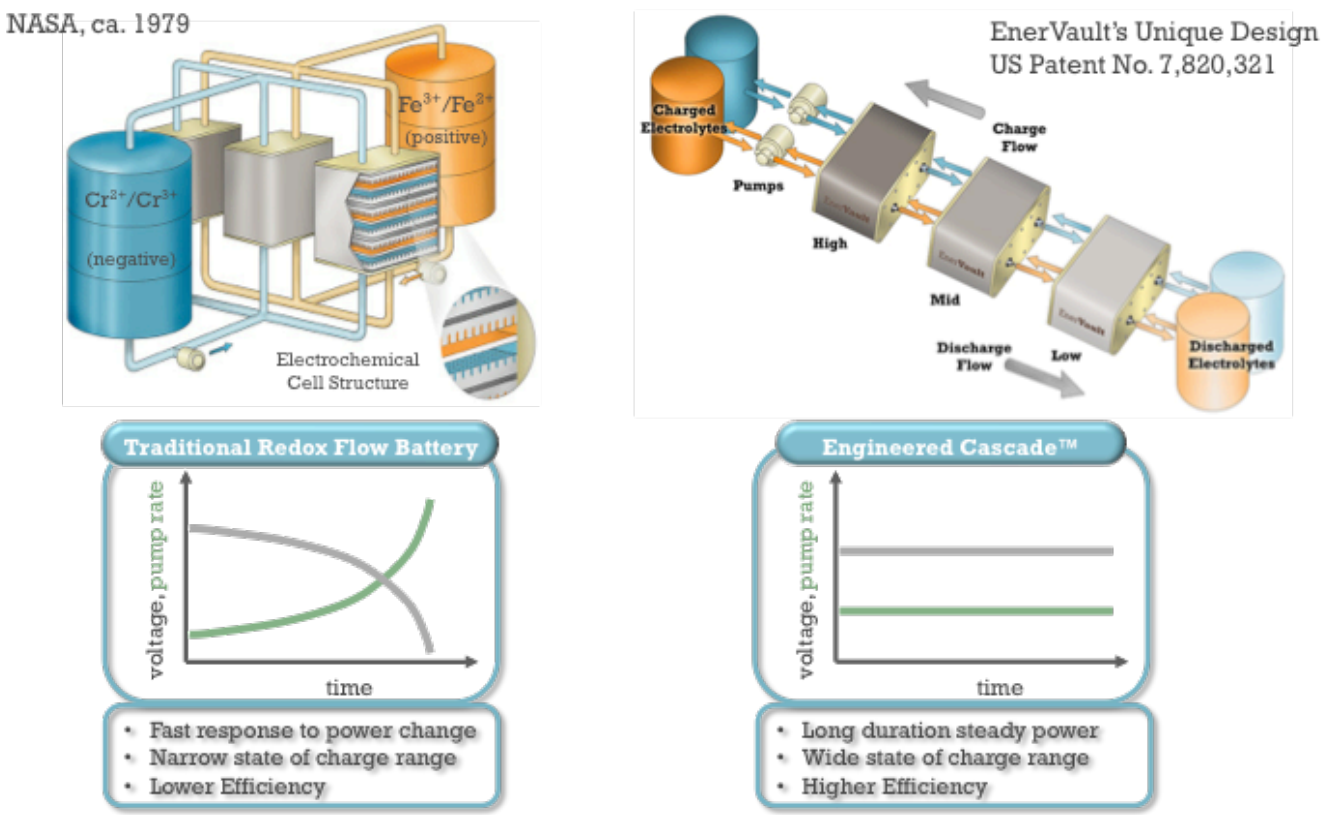
system's operability. In other words, electrical hazard can be eliminated in an EnerVault Fe/Cr RFB system by fully discharging it; then the system can be recharged safely and rapidly. These factors combine to make the iron-chromium RFB one of the safest systems for energy storage.

1.2.3 EnerVault Proprietary Technology

EnerVault has developed proprietary technology in two key areas of redox flow battery technology – the *Engineered Cascade*™ stack set design that is ideally suited for long-duration, grid-scale applications, and Fe/Cr chemistry, which provides an unparalleled combination of low cost and low hazard levels.

EnerVault's *Engineered Cascade*™-based RFB systems are unique in that the cells stacks are connected hydraulically in series. This arrangement lets the system charge and discharge at constant voltage. Therefore, the systems deliver constant power under steady-state operating conditions, and efficiency, for as long as charged electrolyte is pumped into the *Engineered Cascade*™ while power output or input is varied by a linear change in settings. This unique capability enables the system's charge and discharge duration at specified power level to be configured directly via the volume of electrolyte. This characteristic is in contrast to conventional RFB design invented by NASA where cells stacks are connected hydraulically in parallel. In this configuration, voltage varies during operation resulting in system output better matched to applications requiring fast response to varying power levels. Figure 4 compares and contrasts the two designs.

Figure 4: (LH) conventional and (RH) Engineered Cascade™ RFB design.



Conventional RFB designs and EnerVault's design have similar cell and cell stack design as well as other system attributes such as controls, state-of-health monitoring, operating algorithms, and hydraulic unit optimization.

EnerVault also has unique Intellectual Property around utilizing Fe/Cr chlorides as reactants, the manner in which the system operates with them, and the DRS™ (Dynamic Rebalancing Suite) unit that continuously detects and corrects reactant imbalance within the electrolytes during system operation. This suite of technologies creates the breakthrough unlocking the potential of Fe/Cr chemistry. The low cost and plentiful supply of Fe and Cr[1] enable EnerVault to offer customers a price for an extra hour of storage that is comparable to pumped hydro on an installed, AC basis.

1.3 Work Prior to Energy Commission Funding

1.3.1 EnerVault Installed Systems

EnerVault has to date, permitted 6 systems

- PTS Able 2.5 kW – Installed October 2010
- PTS Bravo 5.0 kW – Installed January 2011
- PTS Charlie 7.5 kW – Installed October 2011
- PTS Delta 7.5 kW (identical to PTS Charlie) – Installed December 2011
- PTS Echo 30 kW – Installed April 2012
- EnerVault Turlock 250 kW / 1 MW-hr – May 2014

1.3.2 Breadboard Design – PTS Able

PTS Able (Figure 5) was installed in October 2011 enabling EnerVault to begin bench scale testing. The sub-scale cells allowed EnerVault to build off the results published by NASA and successfully demonstrate its patented *Engineered Cascade*™ flow battery system with iron-chromium chemistry. Cell components such a separators, electrodes and end plates, as well as operating conditions, were easily re-configurable to different power sizes, using different materials, and different component designs. Cell surface area was scaled by a factor of 10 from bench scale to sub-scale, and stacks of up to 30 cells were arranged in multiple-stack cascades to demonstrate charge and discharge capacity at 2.5 kW.

[1] C. Wadia, P. Albertus, and V. Srinivasan, "Resource Constraints on Battery Storage Potential for Grid and Transportation Applications", J. Power Sources **196**(2011)1593-8.

Figure 5: - Breadboard Design - PTS Able

1.3.3 Sub-Scale System – PTS Bravo

The Sub-Scale Pilot Test System (PTS) Bravo was the redox flow battery system iteration achieved prior to receiving funding from the Energy commission. PTS Bravo is a 2.5 kW test system that ran on two hours cycles. System operation and control strategies learned from Able were incorporated into Bravo as the first, fully integrated storage system. The system demonstrated the constant power and stability of the battery throughout charge and discharge over multiple cycles, 57% DC-to DC roundtrip efficiency, response times less than 1.6 seconds from full discharge power to full charging power, and time-shifting capabilities. Further improvements were identified for subsequent systems in the areas of thermal controls, management of side-reactions, and switching modes from charge to discharge. Figure 6 shows PTS Bravo.

Figure 6: Sub-Scale System PTS Bravo

CHAPTER 2
Prototype Stack Development and Results

2.1 Prototype Flow Battery Stack Development and Fabrication

The product scale stacks, used as stages within EnerVault's *Engineered Cascade*™ design, were developed, manufacture and tested on the pilot manufacturing line. Components were optimized for performance, reliability, cost, and manufacturability. Product scale systems PTS Charlie and PTS Delta were designed and first implemented for use in development of product-scale stages. Once the stage design was fixed, PTS Charlie and PTS Delta were adapted for stage testing in EnerVault's pilot line manufacturing, becoming a key element in the factory-acceptance testing of all power stack racks used at EnerVault Turlock during the manufacturing process.

2.2 7.5 kW Battery Test Station Development and Fabrication – PTS Charlie & PTS Delta

Two systems, PTS Charlie and PTS Delta, were installed in October and December 2011 and used for prototype testing of the full-scale cell stack design. EnerVault's 7.5 kW Battery Test Station, Figure 7, was developed and fabricated using the standard redox flow battery design. Referring again to Figure 7, Label A shows the electrolyte tanks, label B shows the power block consisting of the test stack and the stack module, label C shows the hydraulics and flow meters, and label D is the control station.

Figure 7: One of EnerVault's 7.5kW Test Stations – PTS Charlie

2.3 7.5 kW Battery System Performance Testing

The 7.5 kW Prototype testing included the first multi-hour runs on multi-stack stages. Over 80% DC efficiency was achieved validating the substantial performance improvement forecasted with advanced cell designs as compared to sub-scale performance on PTS Bravo.

2.4 Pilot Line Manufacturing

EnerVault established pilot line manufacturing capability in May 2013 at its Sunnyvale, California headquarters. The serial fabrication line included the capacity to build and test more than 15 MW/50 MW-hr systems per year and included cell assembly, stage assembly, *Engineered Cascade*™ assembly, and acceptance testing. See Figure 8, Figure 9, Figure 10 and Figure 11.

Figure 8: Cell Assembly

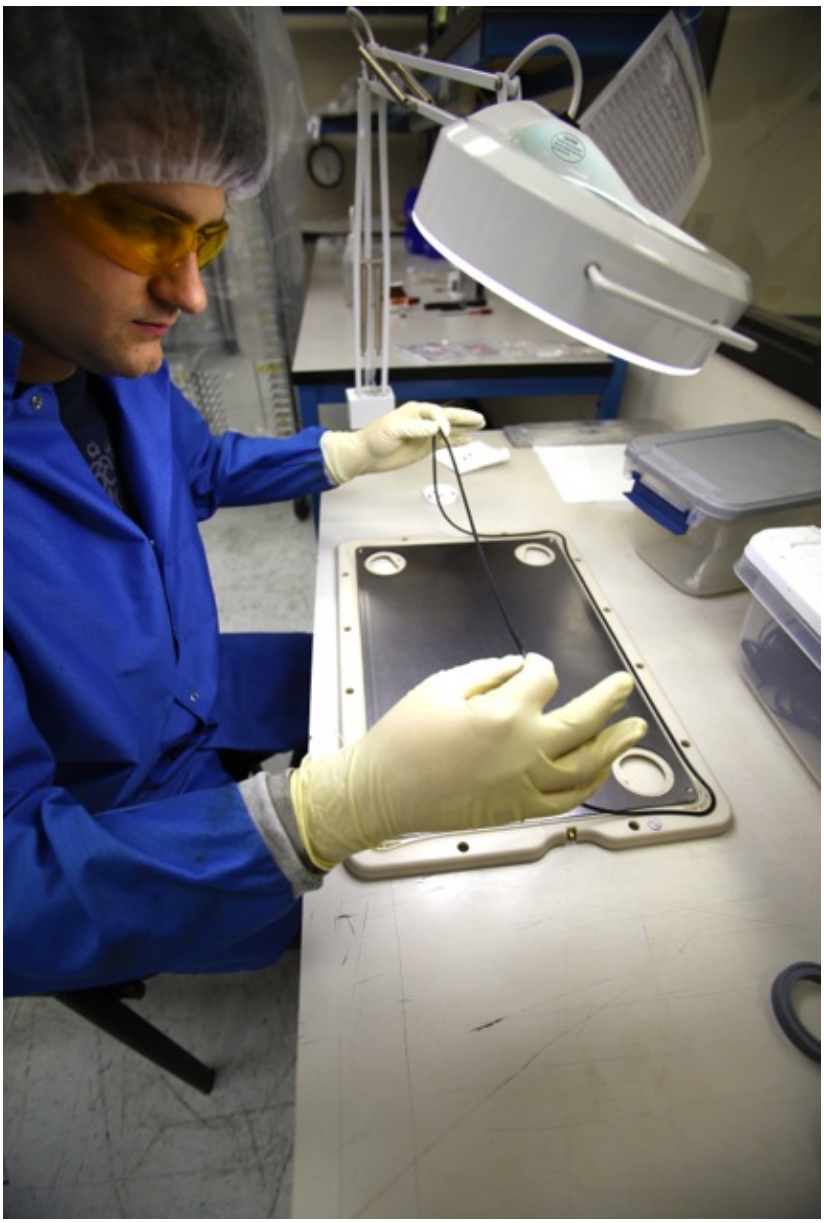


Figure 9: Stage Assembly

Figure 10: Cascade Assembly

Figure 11: Stage and Cascade Test

CHAPTER 3
Pilot System Development and Results

3.1 Prototype Cascade Development and Fabrication – PTS Echo

The prototype system was scaled up 10 times from the previous iteration to create a production scale, 30 kW test system, PTS Echo that was installed in April 2012. Figure 12Figure 12 shows the 30 kW test system.

Figure 12: 30 kW PTS Echo System

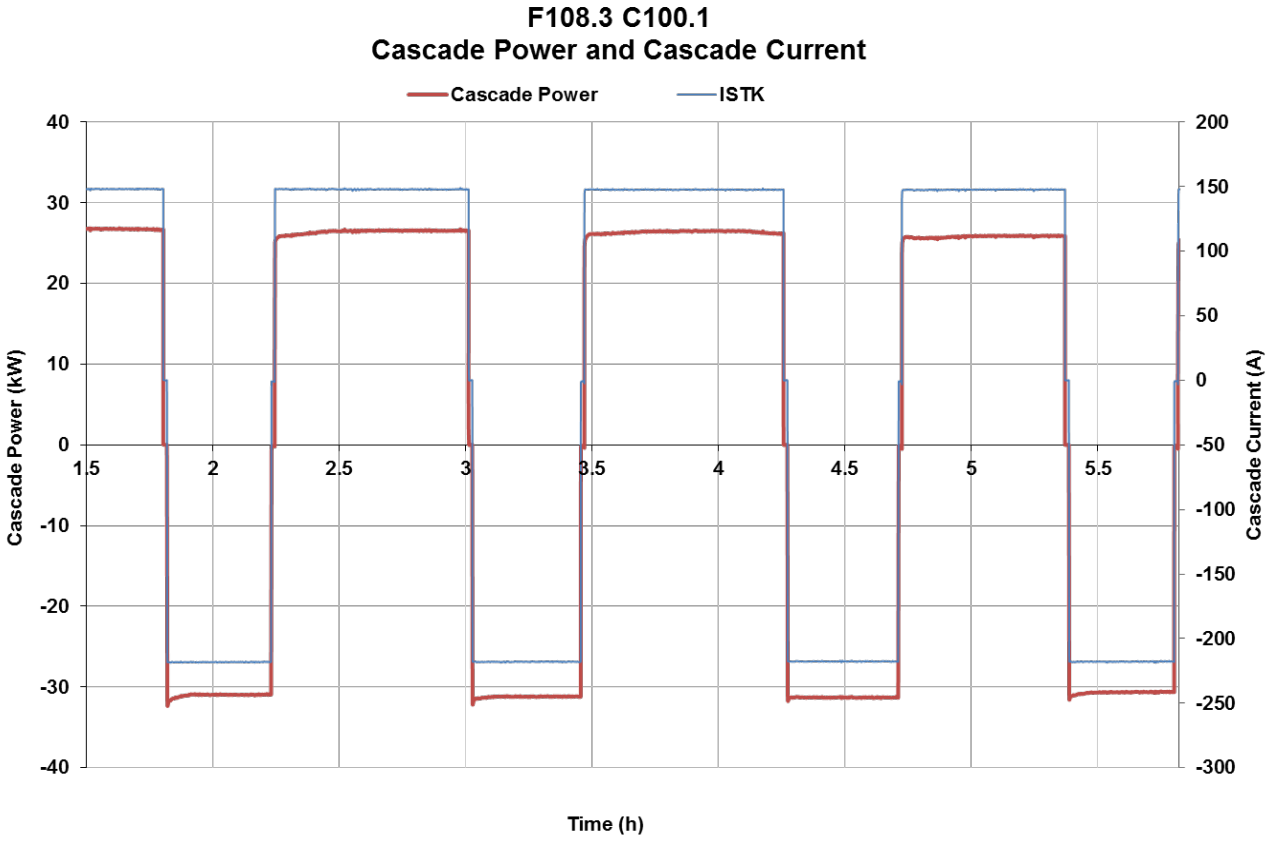
3.2 Pilot Cascade Test System Development and Fabrication

The 30 kW Echo test system was fabricated by Ascension Industries and the *Engineered Cascade*™ power modules were manufactured on EnerVault pilot manufacturing line in Sunnyvale, CA.

3.3 Pilot *Engineered Cascade*™ Performance Testing

The results from the sub-scale system Bravo were used to predict the results of the production scale model, systems Charlie, Delta, and Echo. When the actual test was conducted, results were as predicted by the design model. Figure 13 shows the cascade power compared to the cascade current.

Figure 13: Cascade Power Vs. Current



CHAPTER 4
250 kW Field System Development and Results – EnerVault Turlock

4.1 Results Summary:

- Demonstrated full system power rating of 250 kW net AC in charge and discharge modes
- Demonstrated full power, constant discharge of 250 kW net AC over 4 hours
- Demonstrated full system energy rating of 1 MW-hr
- Demonstrated cycling capability at full power and energy from the original set of cascades
- Demonstrated a high degree of cell voltage uniformity throughout the system
- Validated the ability to consistently manufacture precision, high quality stages due to a robust engineering of cells, stages, and cascades
- Validated thoroughness of factory acceptance testing protocols
- Demonstrated the ability to integrate system components including nine *Engineered Cascades*™ power unit

4.2 Overall Project Timeline

- Preliminary Engineering including project review with the county permitting authority – August to December 2012
- Detailed Engineering – December 2012 and August, 2013
- Procurement and Assembly – May to December 2013
- Installation and field work – November 2013 to March 2014
- Operating Permits Received – March 2014
- Electrical System start-up – March 2014
- Mechanical commissioning – March to April, 2014
- Water System Functionality Testing – April to May 2014
- Ramping Power – May to August 2014
- Ramping Energy – July to October 2014
- DOE protocol testing begin – November 2014

4.3 Integration of Multiple *Engineered Cascades™* Assemblies

In order to scale the system to 250 kW (1 MW-hr), nine 30 kW cascade flow batteries (Figure 14) were integrated into one unit. This was part of the assembly process that took place between November 2013 and March 2014.

Figure 14: 30 kWDC cascades in manufacturing

4.4 Balance of System

The 250 kW system included the first hydraulic and electrical integration of multiple cascades. The balance of system, including the hydraulic plant module and power unit enclosure, was designed by NORAM to EnerVault's specifications. This module included pumps, valves, filters, container modifications, ventilation, safety systems, sensors, software, and controls.

4.5 EnerVault Turlock Site

The EnerVault Turlock Site (Figure 15 and Figure 16) design consists of the EnerVault Fe-Cr RFB, an existing solar photovoltaic system, an irrigation pump, and connection to the power grid via a medium voltage - low voltage distribution transformer.

Figure 15: EnerVault Turlock Site

EnerVault System:

- Technology: Redox Flow Battery
- Chemistry: Iron Chromium
- Power: 250 kW_{AC}
- Energy: 1 MW-hr/ 4 hours duration at full rated power

Solar:

- 150 kW_{AC} PV
- 22 dual-axis trackers, 42 panels each
- 924 solar panels, 200 Wp each
- 2 DC to AC inverters, 75 kW_{AC} each
- Installed in 2008

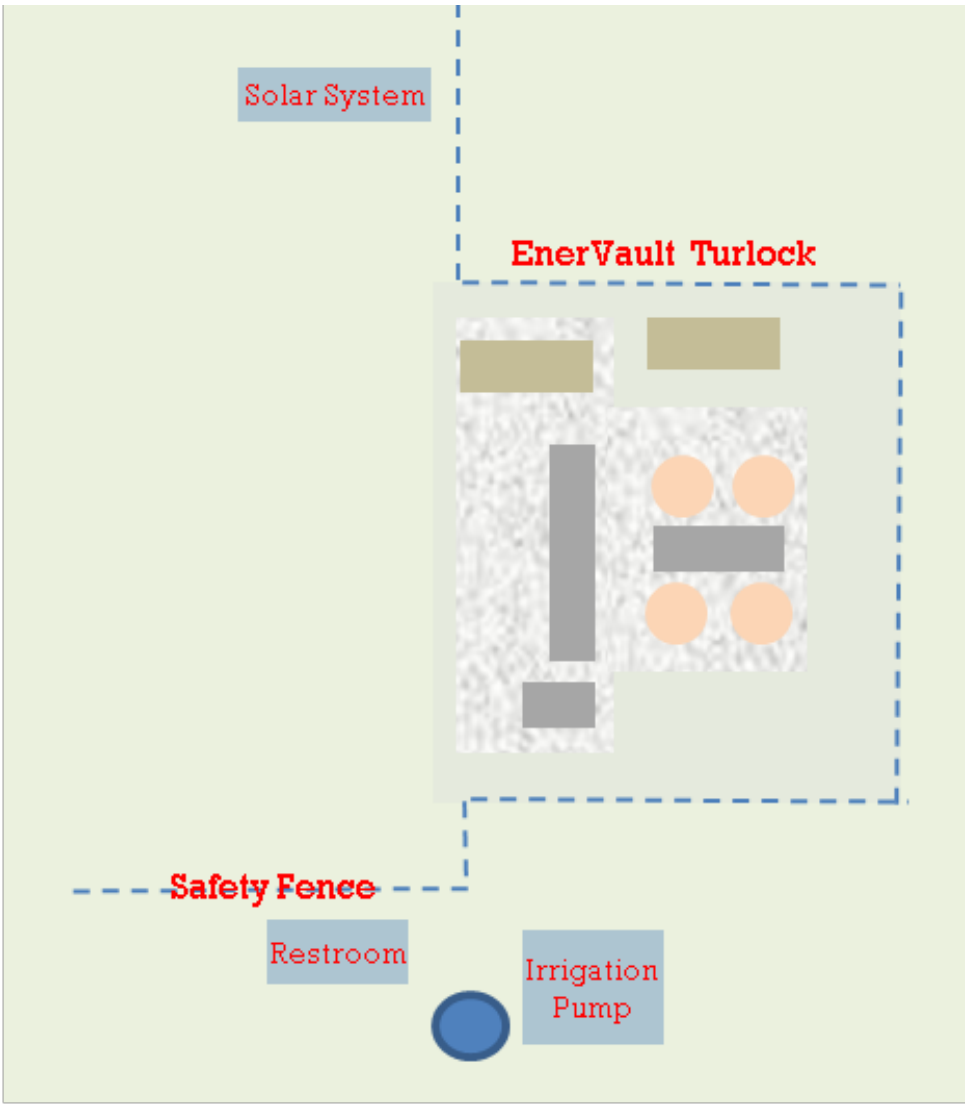
Load:

- 260 kW groundwater irrigation pump

Connection:

- Common 480 V AC bus
- 21 kV grid connection

Figure 16: Turlock Site Diagram



4.6 Installation of Megawatt-Hour Field System: EnerVault Turlock

After completing the installation of the 30 kW prototype system, PTS Echo in April 2011, the project focused on completing the system design, designing the site, beginning the permitting and interconnection process, and building the system. The timeline for these tasks is laid out in Figure 17.

Figure 17: Design Build Timeline

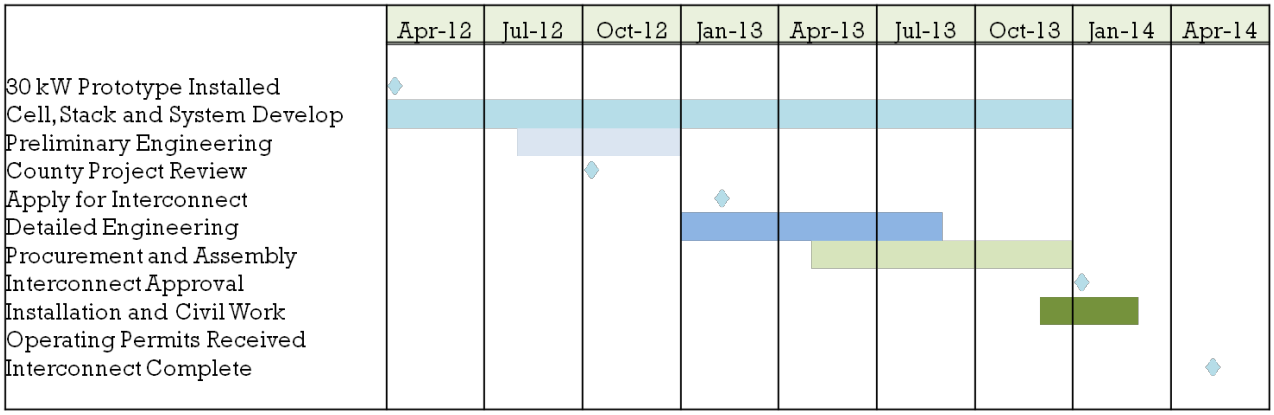


Figure 18 shows the line diagram for the installation of the field system. The original site installation is in blue, while green denotes new equipment for the EnerVault Turlock Redox Flow Battery operation. The BESS AC Loads are comprised of equipment AC loads directly related to optimal operation of the storage system (e.g., non-discretionary loads needed to deliver, store, and maintain readiness in idle states, which are part of the AC-to-AC roundtrip efficiency in charging and discharging the battery. These include pumps, flow sensors, pressure transducers, control computer, thermal controls, ventilation fans, safety systems, etc.). The AC Load Bank was installed due to voltage stability issues with the PG&E feeder line that were identified during the interconnect process. The AC load bank provides flexibility in the operation of the battery for testing purposes, without the constraint of irrigation pump operation (which is scheduled by the farmer based on the needs of the orchard). A reverse power relay currently prevents discharge of the EnerVault Turlock System into the grid.

Figure 18: Line Diagram

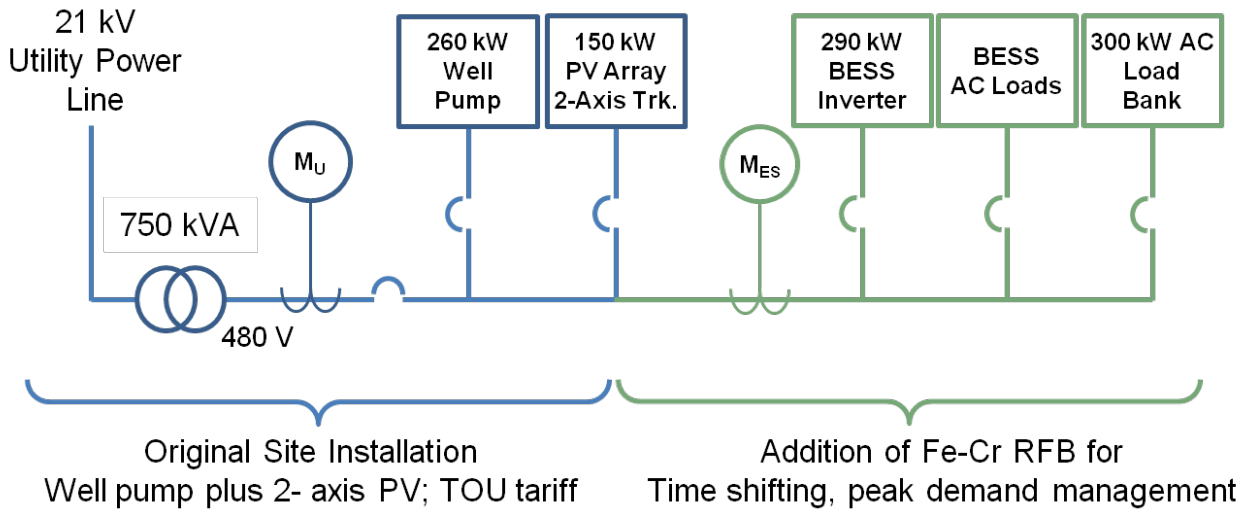


Figure 19, Figure 20, Figure 21, and Figure 22 show the main sub-systems of EnerVault Turlock. The Power Unit, Figure 19 was installed as nine 30kW cascades. Figure 20 shows the Hydraulic Plant Module being installed. Figure 21 shows the Energy Unit consisting of four electrolyte tanks. Figure 22 shows the inverter.

Figure 19: 30 kWDC cascades installed (9 in total)

Figure 20: Skid-mounted Hydraulic Plant Module

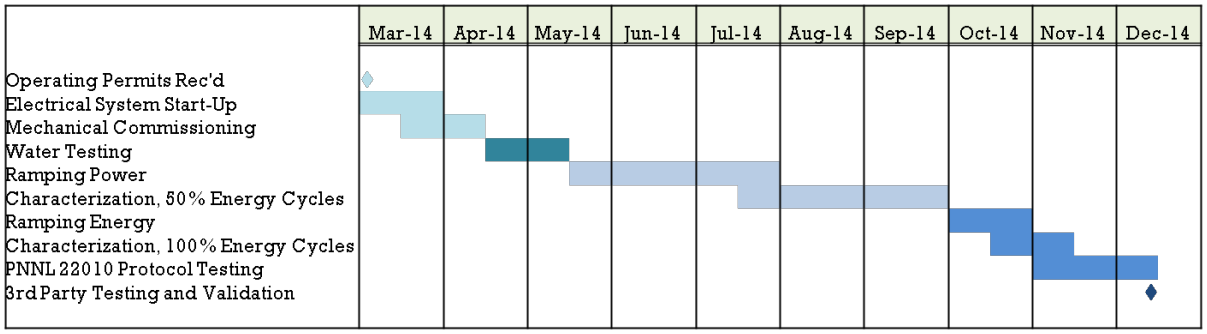
Figure 21: Electrolyte Tanks

Figure 22: Inverter

4.7 Field System Performance Testing

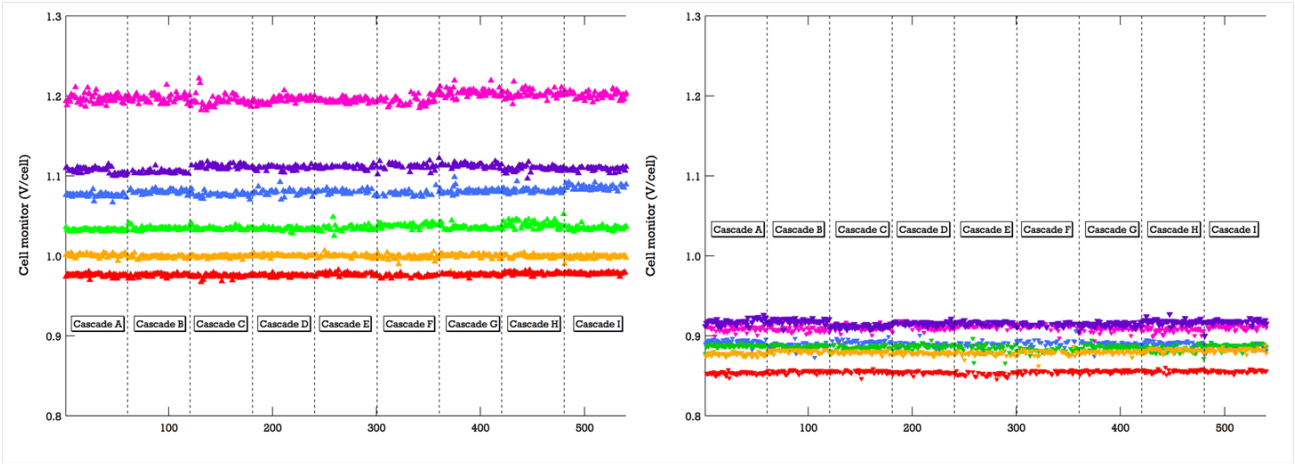
After completing the physical installation and receiving operating permits, The Turlock test system began performance testing in May 2014. Figure 23 shows the timeline for system commissioning and ramping the power and energy output. Initially the system was tested at 50% energy levels (i.e. up to 2 hour discharge) to generate more full cycle testing data. Power was ramped to the full 250 kW net AC and the remaining electrolyte added to bring the system to full capability in October 2014.

Figure 23: Commissioning and Performance Ramp



Test results are displayed in the following figures. Figure 24 shows the cell voltage uniformity over charge and discharge cycles. Cell voltages are shown for each of the six stages, comprising each of the nine-30kW cascades. The flow and current distribution among stacks is purely passive balancing by design. All cells measured within a range of approximately 20 mV. This result indicates an excellent degree of electrical and reactant flow uniformity throughout the system.

Figure 24: Cell Voltage Uniformity



Charge Discharge

Figure 25 shows the system performance profile and uniformity over three shorter duration charge and discharge cycles at 250 kW AC net. The multi-colored lines shows voltage from each 120-cell stage, normalized to the cell count. Each color has nine plot points, one for each of the nine cascades that comprise the system. The narrow width of each plot is another indicator of the excellent electrical and hydraulic uniformity in the stages and cascades. The black line plots the cascade current for each of the nine cascades. The blue line shows the system flow rate as measured at multiple points within the hydraulic system.

Figure 25: Uniformity over Multiple Cycles

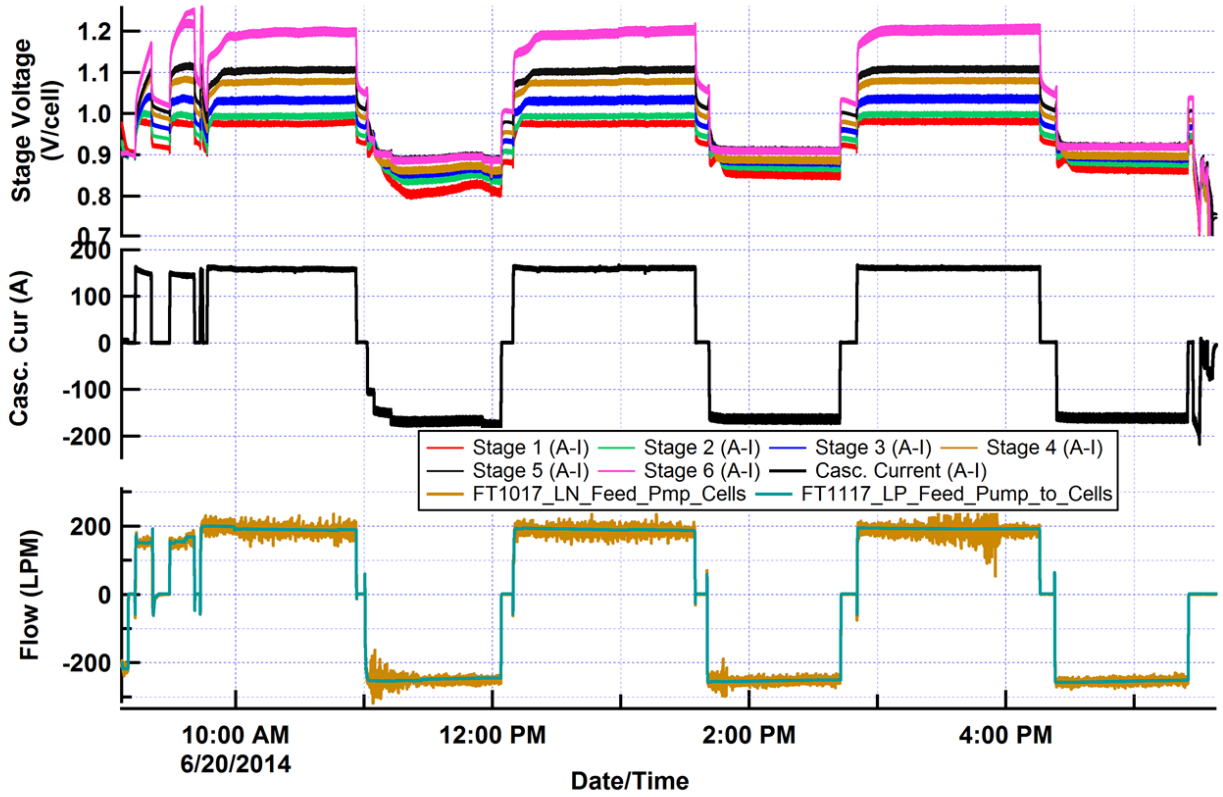
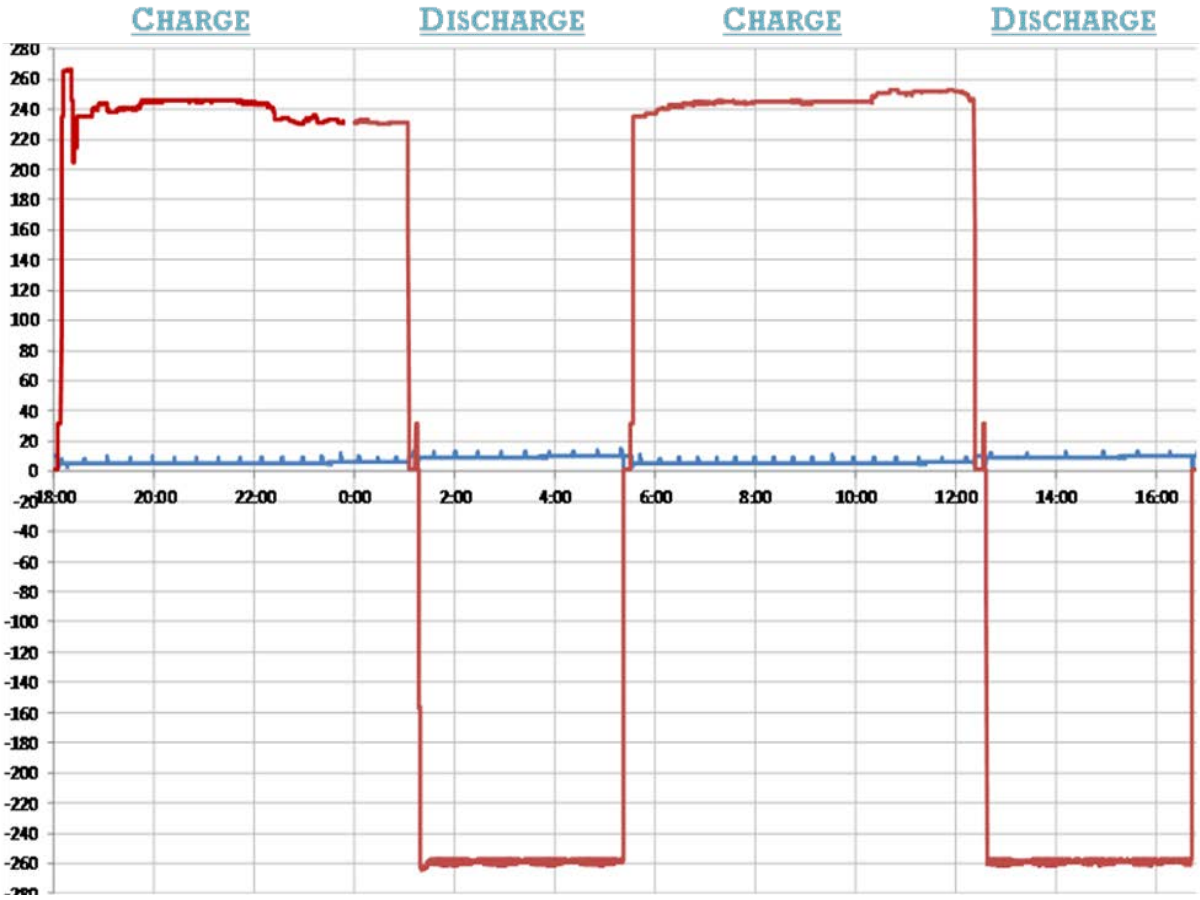


Figure 26 shows the full energy cycle performance from testing conducted over November 20-21, 2014. The charge power was adjusted to ensure adequate stored energy for subsequent steady discharge at 250 kW AC net for 4 hours, a goal that Figure 26 shows was achieved. The EnerVault Turlock system ramped from idle to full charge and to full discharge power (250 kW AC net) within 30 seconds.

Figure 26: Full Energy Performance Cycle



CHAPTER 5
Conclusions and Benefits to California

5.1 Conclusions

5.1.1 EnerVault Turlock

The world's first megawatt-hour class, Fe-Cr RFB system, "EnerVault Turlock" was successfully commissioned in May 2014 and initial performance testing was completed in December 2014. Milestones achievements include:

- 250 kW – as designed.
- 1 MW-hr delivered – as designed.
- Multiple full 4 hour discharge cycles demonstrated
- Underwent permitting and received operation permits
- Underwent Rule 21 interconnection process
- Co-located and connected in parallel to 480 V common AC bus with 150 kW_{AC} solar photovoltaic system driving 260 kW groundwater irrigation pump, connected to 21 kV PG&E distribution circuit.

5.1.2 EnerVault Systems

EnerVault has to date, permitted 6 systems, increasing scale 100X from the beginning of this project to present:

- PTS Able 2.5 kW – Installed October 2010 – (prior to project)
- PTS Bravo 5.0 kW – Installed January 2011– (prior to project)
- PTS Charlie 7.5 kW – Installed October 2011
- PTS Delta 7.5 kW (identical to PTS Charlie) – Installed December 2011
- PTS Echo 30 kW – Installed April 2012
- EnerVault Turlock 250 kW / 1 MW-hr – May 2014

5.1.3 EnerVault Innovations Demonstrated

- Engineered Cascade™ Architecture
- No de-rating, get what you pay for: full power delivered for the full duration delivers the full rated energy
- Fe-Cr Electrolytes
    - Readily available commodities iron and chromium mined broadly around the world

- Uses low cost, high reliability micro-porous separators – 1/100th of the cost of ionic membranes used in conventional flow batteries
- Low vulnerability - Due to the low hazard and environmental risks, the costs of mitigation and site preparation are significantly reduced
- Enables a lower cost system with fewer restrictions and additional site related costs
    - No thermal runaway
    - Only 6 minutes of total energy storage available for unintended release, can be grounded to zero in emergency event with no damage to battery
    - Can be located near factories, commercial buildings, and people
    - Non-volatile, benign chemistry requires only simple chemical containment

5.1.4 Cell Stack Development

- Product scale stacks were developed, manufacture, and tested on the pilot manufacturing line
- Two 7.5 kW systems were installed and used in development of the power stack design. These systems were later modified and used in the pilot line test operations
- One 30 kW test system was installed and used in development of full-scale, *Engineered Cascade*™ power modules
- Over 80% DC efficiency was achieved on stages on test systems

5.1.5 Pilot Line Manufacturing

- EnerVault established pilot line manufacturing operations in May 2013 at its Sunnyvale, CA headquarters
- Pilot line operations included cell assembly, stage assembly, *Engineered Cascade*™ assembly, and factory approval testing.
- The pilot line capacity is 15 MW/50 MW-hr per year

5.2 Benefits to California

Decarbonize Grid/ Increase Resiliency

EnerVault's technology mitigates the following:

- Rising fossil fuel costs
- Intolerable environmental impacts from fossil fuel
- Differences between peak and base load
- Transmission & distribution constraints

In addition, leverages:

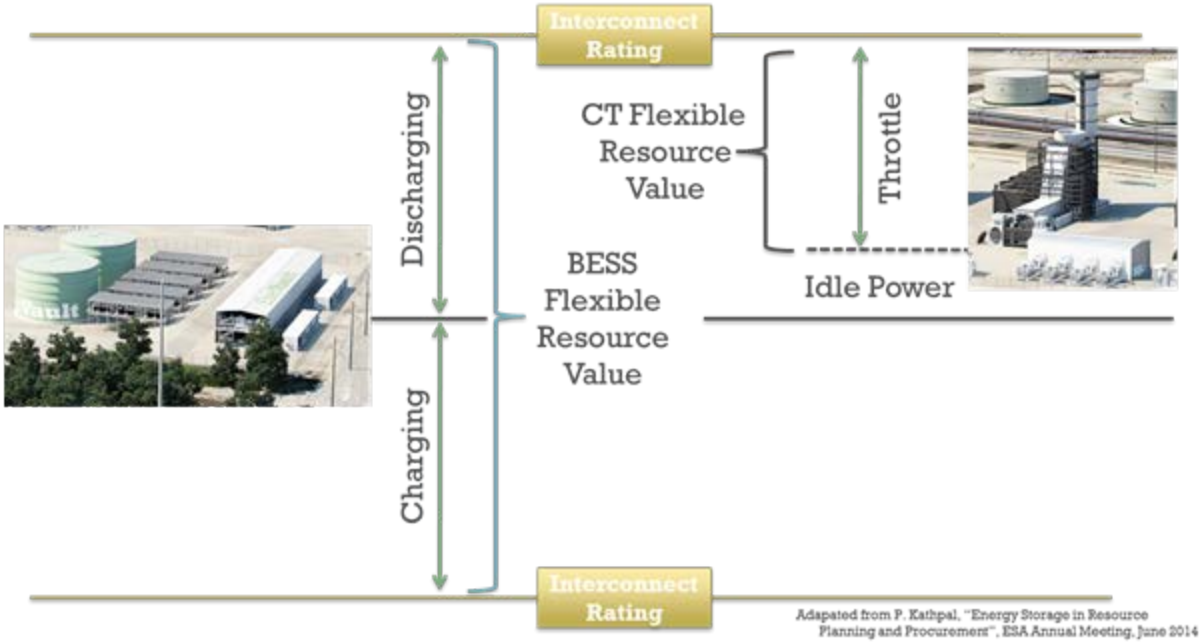
- Cost effectiveness of PV and wind
- Increase value of energy security

Lower Energy Costs/ Greater Reliability

- Enables peak demand management
- Avoids costly transmission and distribution projects over sensitive areas
- Provides backup
- Delivers clean peak electricity
- Improves grid efficiency
- Increases renewables penetration capacity
- Eliminates renewables curtailment

Finally, the EnerVault system provides over twice the flexible resource value as compared to a conventional peaker plant as shown in Figure 27.

Figure 27: Over 2X Flexible Resource Value vs. Conventional Peaker



CHAPTER 6
Lessons Learned and Recommendations

6.1 Lessons Learned

Several key lessons were learned throughout the completion of this project. For EnerVault technology to be beneficial, the market for energy storage and renewables must come as soon as possible. When working on a future project, early involvement of local authorities is a key part of smooth permitting. Local legislative bodies will have different requirements regarding permitting, and the requirements must be communicated openly. Another key to future projects is using shop-fabricated, modular construction. Fabricating modular units that are electrically and hydraulically connected on-site at standardized locations will reduce field time and cost. The final lesson learned from this project is the need for planning sufficient time in future projects for proposing, negotiating, and closing on utility interconnects. Acquiring a utility interconnect will be a new process for most emerging technologies and can be a difficult process. Energy storage technologies must apply for interconnect early during the execution of their project.

6.2 Recommendations

"Utility Pilot" projects are needed to move projects to full commercial readiness. The Energy Commission funding enabled EnerVault to attract investment to grow the knowledge of technology from a "Technology Readiness Level" TRL around 3 to 6. However, without utility pilots to use the energy storage system in real-world utility applications, the technology cannot achieve the TRL 9 currently needed to participate in most utility RFOs. In the current nascent state of utility storage even well-known technologies, already used elsewhere on utility grids require significant learning in operating the storage system, optimizing for market use, and integration on the system (e.g., such as PG&E's NAS batteries at Vaca-Dixon and SCE's Li-ion Tehachapi projects)

Example pilots needed for further maturing Fe-Cr RFB systems for utilities applications are given in Table 1

Table 1: Example utility pilot projects for grid-scale, long duration energy storage

Application	Demo Size	Full Scale	Comment
Flexible Peaker	2-10 MW / 3 hours	50 MW / 150 MW-hrs	100 MW of flexible range
Capacity Peaker	2-10 MW / 4 hours	25-50 MW / 200 MW-hrs	RA
Renewable Sited Storage	2-10 MW / 6 hours	25 MW / 150 MW-hrs	Wind and PV; Time-of-Delivery premium, dispatchable, curtailment avoidance
Hybrid (CT +ES)	2-10 MW / 6 hours	50 MW / 300 MW-hrs	
Transmission Peaker (Congestion Relief)	2-10 MW / 4 hours	50 MW / 200 MW-hrs	
Urban Resiliency	2-10 MW / 12 hours	25 MW / 300 MW-hrs	
Micro Grid	2-10 MW / 12 hours	20 MW / 120 MW-hrs	Islanding + greater renewable use

GLOSSARY

Cr	Chromium
DoD	Department of Defense
DRS™	Dynamic Rebalancing Suite
Fe	Iron
kV	Kilovolt
kW	Kilowatt
kW-hr	Kilowatt Hours storage capacity
HFB	Hybrid Flow Battery
mV	Millivolt
MW	Megawatts
MW-hr	Megawatt-Hours
NAS	Sodium Sulfur
NASA	National Aeronautics and Space Administration
PTS	Pilot Test System
PV	Photovoltaic
RFB	Redox Flow Battery
RFO	Request for Offer
SCE	Southern California Edison
SOC	State of Charge
eSOH	Electrolyte State of Health
TRL	Technology Readiness Level
Wp	Watt Peak

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Attachment 1:
Media Coverage of EnerVault Turlock

For Immediate Release: May 22, 2014

Media Contacts: Lori Sinsley, Energy Commission, 916. 539.8863 (mobile); 916.654.4989 (office)

Bret Adams, EnerVault, [351-201-9139]

California Energy Commission Joins U.S. Department of Energy to Dedicate EnerVault's Long-Duration Energy Storage System

First Grid-scale Iron-Chromium Redox Flow Battery in the World

TURLOCK, Calif. – Today, the California Energy Commission (Energy Commission) joins the U.S. Department of Energy (DOE) to dedicate EnerVault Turlock, the first grid-scale iron-chromium redox flow battery deployed in the world. EnerVault designed and manufactured the long-duration, grid-scale energy storage system in Silicon Valley with a combination of private funding and research and development grants from the DOE and the Energy Commission. Long-duration energy storage systems are emerging as the lynchpin to efficient operations for resilient grids as aging conventional power plants are replaced by higher levels of solar and wind. Interconnected to the distribution grid, EnerVault Turlock is co-located with a dual-axis tracking solar photovoltaic system in an almond orchard in California's Central Valley.

"With the support of DOE, the Energy Commission, our technical team and investors, EnerVault's long-duration, grid-scale energy storage systems are ready to participate in California's ground-breaking energy storage market in less than five years from our first round of funding," said Jim Pape, EnerVault CEO. "EnerVault Turlock will demonstrate that our proprietary technology is inherently safe, reliable and cost effective. Using commodity equipment and materials, EnerVault can manufacture large scale systems quickly: no gigafactory required."

"The EnerVault Turlock project solidifies California's position as an incubator of companies that attract investment, and demonstrates the value of public-sector investments in energy research and development," said Robert B. Weisenmiller, chair of the Energy Commission. "This storage technology will help integrate renewable energy and improve the reliability of California's evolving electricity system. Federal and State investments were critical to taking this project from laboratory prototypes to community-scale, energy storage system in less than five years."

Forbes

Peter Kelly-Detwiler
Contributor

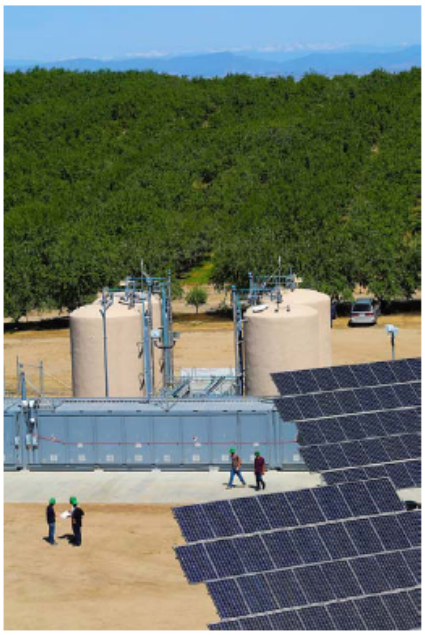
ENERGY 5/30/2014 @ 11:15AM | 19,108 views

EnerVault Unveils First Of Its Kind Iron-Chromium Megawatt-Scale Flow Battery

+ Comment Now + Follow Comments

This past week, EnerVault – a company which has developed a unique iron-chromium redox flow battery technology – dedicated its utility-scale Turlock demonstration storage project in California's Central Valley. This redox flow battery storage system can deliver one megawatt-hour of energy from a 250 kW battery that can perform at that rated level for four hours.

The Turlock project is particularly interesting, as it is located next to a 150 kW solar system and a 260 kW irrigation pump, helping to optimize the overall system, storing the sun's energy and releasing it when needed. Funded in part by over $4.7 million from the US Department of Energy and $476,000 from the California Energy Commission, the project is meant to demonstrate the feasibility of iron-chromium redox flow batteries as reliable utility-scale storage resources.



Redox flow batteries, a subset of the general class of battery architectures known as flow batteries, are intriguing beasts. Unlike their famous cousin, the lithium ion technology which is getting so much attention as part of Tesla's proposed $5 billion gigafactory, flow batteries are not light, and they are not designed to deliver power instantaneously. But they don't need to get you from zero to sixty in four to five seconds. Instead, they are designed to be the workhorses of the industry; to hold a significant charge indefinitely and to deliver kilowatt-hours as reliably and cheaply as possible.

MIT Technology Review

ENERGY NEWS

10 COMMENTS

A Battery Made of Iron Could Improve the Economics of Solar and Wind Power

A new type of flow battery could allow renewable-energy developers to store power until it's most valuable.

By Kevin Bullis on May 28, 2014

Batteries included: Large tanks containing energy storage materials made of iron, chromium, and water form a key element of a new, potentially low-cost battery.

At a small solar power plant near Modesto, in California's Central Valley, a startup called Enervault recently unveiled battery technology that could increase the amount of renewable energy utilities can use. The technology is based on inexpensive materials that researchers had largely given up on because batteries made from them didn't last long enough to be practical. But the company says it has figured out how to make the batteries last for decades.

The technology is being demonstrated in a large battery that stores one megawatt-hour of electricity, enough to run 10,000 100-watt light bulbs for an hour. Enervault says its batteries could compete with the cheapest form of electricity storage available today—pumping water up a hill so that it can spin turbines as it flows back down, which is feasible only in certain locations. The company has been testing a similar, though much smaller, version of the technology for about two years with good results. It has raised $30 million in funding, including a $5 million grant from the U.S. Department of Energy.

The batteries are particularly well suited to storing large amounts of energy, such as hours of output from a wind farm or solar plant. They could thereby help solve a big problem with renewables: sometimes they generate electricity when not much is needed, such as in the early morning hours or on cool, sunny weekend days.

The technology is a type of flow battery, so called because the energy storage materials are in liquid form. They are stored in big tanks until they're needed; then they're pumped through a relatively small device, called a stack, where they interact to generate electricity. Building bigger tanks is relatively cheap, so the more energy storage is needed, the better the economics become. That means the batteries are best suited for storing hours' or days' worth of electricity, not delivering quick bursts.

Enervault's particular version of the technology uses water, chromium, and iron—cheap, safe materials that had been tried in batteries in the 1970s. But unwanted chemical reactions such as the release of hydrogen caused them to degrade, decreasing the amount of energy they could store.

Big battery at Stanislaus-Merced line called a game changer in solar-energy storage

BY J.N. SBRANTI
jnsbranti@modbee.com May 22, 2014

DENAIR — In the middle of a remote almond orchard near the Stanislaus-Merced county border, a revolutionary "battery" was unveiled Thursday.

Energy experts are calling it a game changer that will help stabilize California's electrical grid.

It's the world's largest iron-chromium redox flow battery, and it can store the electrical power generated by the adjoining photovoltaic solar panel array.

That's apparently never been done before on such a large scale and for such a long duration, which is why energy industry bigwigs took the long drive out to see it.

"It's big, it matters, and it's going to be very, very important," assured Jim Pape, chief executive officer of EnerVault, the Silicon Valley startup that designed it.

That company invested $30 million in developing the technology, and taxpayers contributed $5.5 million toward the effort.

A chunk of that money ended up being spent in Stanislaus County because Turlock's JKB Energy built the facility in the orchard, hiring dozens of local construction workers to do the job.

Guests take a tour of EnerVault Turlock's megawatt-hour scale iron-chromium redox flow battery at their site in east Turlock on Thursday May 22, 2014. The battery provides long-duration storage of solar energy.
ANDY ALFARO — aalfaro@modbee.com | Buy Photo

May 21, 2014, 12:52pm PDT | **UPDATED:** May 21, 2014, 2:48pm PDT

If Tesla powers your future car, this water battery may power your future home

Jon Xavier
Technology Reporter-
Silicon Valley Business Journal
Email | Twitter | Google+

EnerVault

EnerVault will officially open a 1 Megawatt hour energy storage facility in Turlock on Thursday.

EnerVault, a Sunnyvale startup that makes battery technologies to support large-scale electrical utilities, on Thursday will unveil a system it's positioning as a superior alternative to lithium-ion systems.

The company's so-called flow battery, which stores chemical energy and generates electricity by passing charged liquid through a barrier, is the biggest test yet of the technology.

The 1-megawatt-hour setup in the Central Valley town of Turlock is a big deal for EnerVault. It might be an even bigger deal for the energy industry, which is faced with a problem that likely will either be solved by the kind of lithium-ion batteries that will be made by Tesla's planned Gigafactory or an emerging technology like EnerVault's.

Iron-Chromium Flow Battery Aims to Replace Gas Plants

By Martin LaMonica
Posted 21 May 2014 | 17:00 GMT

Photo: EnerVault

The four round structures pictured above may look like grain silos but they're actually giant flow batteries. They're part of a demonstration plant going online this week, and proponents say it could represent the future of long-duration energy storage on the electric grid.

Startup EnerVault will unveil tomorrow what it says is the largest iron-chromium flow battery ever made. Installed in Turlock, Calif., the four-hour, 250-kilowatt battery will be charged by a solar array and power an irrigation system. The project was funded by about US $5 million from Department of Energy through the stimulus program and the California Energy Commission.

If this technology demonstration performs well, it will be a step towards much larger flow batteries that could replace natural gas plants or provide round-the-clock power from wind and solar farms.

greentechgrid:

EnerVault Nears Completion of Its First Commercial-Scale Flow Battery

A storage tank is installed at EnerVault's first commercial site in Turlock, California. Image credit: EnerVault

The company says it's prepared to beat DOE's cost targets for redox flow batteries.

Stephen Lacey
January 9, 2014

Founded in 2008, California-based storage startup EnerVault has remained relatively quiet on its progress.

The flow battery market is, after all, defined more by grandiose claims from companies than by commercial projects in the ground.

But with $24.5 million in funding and an executive team hailing from SunPower, Tesla, and a range of battery, power plant engineering and fuel cell companies, EnerVault is now going public with its performance expectations.

"We've been particularly quiet about achievements," said Jim Pape, EnerVault's CEO and former president of residential and commercial solar at SunPower. "Part of that is our investors; part of that is that we don't want to put out statements we have to later jump over."

EnerVault and NORAM Announce Strategic Partnership

EnerVault Poised to Scale Production and Commercialize Long-duration, Grid-scale Energy Storage Systems

SUNNYVALE, Calif., Feb. 26, 2014 /PRNewswire/ -- EnerVault, designer and manufacturer of long-duration, grid-scale energy storage systems, and NORAM, a specialized engineering and process design firm, today announced a collaborative agreement to scale production and commercialize EnerVault's iron-chromium redox flow batteries.

"EnerVault welcomes NORAM's decades of industrial engineering design expertise to support the commercialization of our long-duration, grid-scale energy storage systems," said Jim Pape, EnerVault CEO. "With NORAM's expertise in system design for simplicity, reliability and safety, we expect EnerVault's long-duration, grid-scale energy storage systems to meet the capital cost and energy delivery cost targets established by the U.S. Department of Energy."

"EnerVault's technology represents the safest of the ready-to-scale chemistries for redox flow batteries, a primary attraction for us to work with Jim and his team," said Tony Boyd, NORAM's President and COO. "EnerVault's long-duration, grid-scale energy storage systems are built with components and processes that are fully scaled in other industries. With effective engineering, NORAM believes that EnerVault's energy storage systems will be very cost-competitive."

In January, 2014, EnerVault began commissioning the largest iron-chromium redox flow battery in the field anywhere in the world: a 250 kilowatt, 4-hour system capable of delivering 1 megawatt-hour of stored energy. Located in Turlock, Calif., and sited on agricultural land in combination with a ground-mounted solar system, the EnerVault redox flow battery system will begin operation in the spring of 2014.

About EnerVault:
EnerVault designs and manufactures long-duration, grid-scale energy storage systems based on iron-chromium redox flow battery technology first pioneered by NASA. EnerVault's energy storage systems offer grid operators the flexibility to both absorb and deliver energy to cost effectively manage system efficiency, increase reliability and integrate renewable resources. Based in Silicon Valley, EnerVault is the first company to deploy megawatt-hour scale iron-chromium redox flow battery systems in field operations. For more information, visit www.EnerVault.com

About NORAM:
Since 1988, NORAM has built a global reputation for innovation and excellence in the supply of proprietary engineering and equipment systems to the chemical and commodity sectors. NORAM's specialized business groups have completed large capital projects on five continents and is recognized as a leader in the fields of nitration, sulfuric acid and electrochemistry. In addition to carrying out large assignments for major multi-national clients and municipalities, NORAM selectively collaborates with early-stage technology companies to provide its experience in technology commercialization. For more information, visit www.noram-eng.com