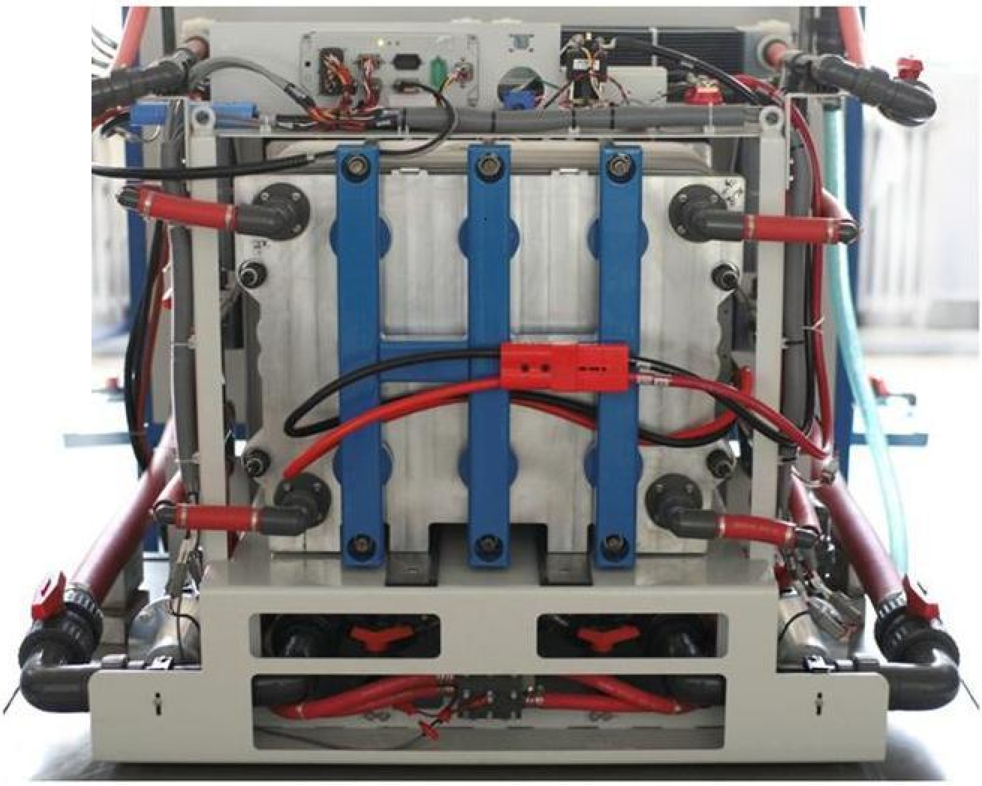
Advanced Battery Storage Systems Testing at ACEP

THE PRUDENT ENERGY VRB-ESS



Characterization and Assessment of the Flow Battery Concept for Energy Storage and Ancillary Services in Isolated Wind-Diesel Power Networks in Alaska

March 2012

UNIVERSITY of ALASKA
Many Traditions One Alaska

ACEP
Alaska Center for Energy and Power

Denali Commission
10 Years Of Progress 1998-2008
Alaska

Cover photo: The power conversion system of the 5 kw, 20 kWh Vanadium Redox Flow Battery courtesy of Prudent Energy.

Any comments or suggestions may be directed to the authors at the respective addresses below.

Billy Muhando
Asst Research Prof
Alaska Center for Energy and Power (ACEP)
University of Alaska Fairbanks
bemuhando@alaska.edu
1 907 474 7082

Tom Johnson
Research Engineer
Alaska Center for Energy and Power (ACEP)
University of Alaska Fairbanks
thjohnson@alaska.edu
1 907 474 5564

Further information may be obtained by contacting:

Gwen Holdmann
Director
Alaska Center for Energy and Power (ACEP)
University of Alaska
gwen.holmann@alaska.edu
1 907 474 5402
www.uaf.edu/acep

Abstract

With the implementation of state and possibly federal renewable portfolio standards, there is a significant increase in the penetration of intermittent, non-dispatchable energy sources, as evidenced by the upsurge in the deployment of wind-diesel systems in the electricity generation infrastructure in various off-grid rural or village power applications in Alaska. The variability associated with these energy sources has a substantial impact on the respective power networks, and energy storage provides one approach for addressing some of the impacts. Ancillary services have traditionally been provided by central power plants, but emerging business models are harnessing energy storage to fulfill these roles, including frequency regulation, synchronous reserve, reactive power, and renewables integration.

High wind penetration systems can be enabled significantly by developing managed, efficient, reliable, and economical energy storage technologies that eliminate the need for back-up utility baseload capacity to offset impacts of the intermittent resource. Large-scale energy storage signifies there is 'energy on demand' that enhances the reliability of the power system, can defer or reduce transmission system investments, and can capture alternative energy generated off-hours for use during peak load periods. Optimally, the energy storage solution should be a low-maintenance, environmentally-friendly and modular construction to provide maximum benefit. Flow batteries show potential for utility-scale electric energy storage that can improve the reliability and efficiency of the energy delivery network, and in turn, aid in the steady reduction of diesel usage and associated carbon emissions. Peak load shifting and energy arbitrage are other benefits that can be provided by these advanced energy storage systems.

The Alaska center for Energy and Power (ACEP) has been involved in advanced battery research by testing and evaluating battery systems for integration with renewable energy projects on remote power grids in rural Alaska communities. This report documents the methodology, key assumptions, and results of a preliminary qualitative and quantitative analysis of a 5 kW, 20 kWh Prudent Energy flow battery system tested between September 2010 and December 2011. The primary goal of the report is to shift conventional thinking surrounding grid management and investment by initiating stakeholder discussion regarding: a) the deployment of flow battery energy storage in wind-diesel systems in Alaska, and b) the investment needed to upgrade the current power systems to the higher performance levels required to support continued economic growth and improve productivity.

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Executive Summary

Project Background

The use of alternative and renewable energy sources on a large scale requires new technologies such as advanced energy storage systems. Multiple integration studies have suggested that the challenge of integrating renewables increases in a non-linear fashion as penetration levels exceed 20%. Alaska is already home to several systems pairing wind turbines with diesel power plants, and one of the challenges for these systems is the unpredictable wind system dynamics. Bulk storage is one of the major limitations in today's "just in time" electricity delivery system and one of the great opportunities for Smart Grid development in the future. In perspective and for Alaska in particular, storage—as both an end user and electric utility energy management resource —will become possible due to a confluence of high penetration wind-diesel systems deployment, dynamic pricing, and lower cost energy storage systems.

The genesis of this project was a proposal for the Alaska Center for Energy and Power (ACEP), partnering with the UAF Chukchi Campus, to assess small-scale advanced storage systems in support of the Kotzebue Electric Association (KEA) Premium Power Battery Project. Funding was provided through the Denali Commission Emerging Technologies Grant Fund for obtaining and testing the flow battery system. The funding for this project was intended as a sub-award to KEA's larger grant in recognition of the need to support ACEP's research program in assessing other battery storage options appropriate for the Alaska market. The research project involved characterization of a 5 kW, 20 kWh vanadium redox flow battery (VRB) system supplied by Prudent Energy Systems. The project has been conducted at the ACEP facilities in collaboration with the UAF Chukchi Campus, who purchased the battery for testing and will use data generated from this work as part of their sustainability curriculum. The project begun in September 2010 and the first phase involved verifying manufacturer specifications.

The program goals are twofold: 1) to provide early access of performance and durability data for utilities that manage isolated grid systems to make informed decisions about future deployment of large-scale energy storage systems in Alaska, and 2) to improve the academic research infrastructure at the University of Alaska Fairbanks related to distributed energy technologies. The overall analysis is based on testing and evaluation of the VRB unit to characterize the performance and durability of the technology by considering the duty cycle, discharge rate, dynamic voltage control on a distribution line, round-trip efficiency, cold climate operation, and other functioning issues. Initial results have been encouraging – there is strong indication that vanadium redox flow battery systems are potentially suitable for distribution grid support applications.

The VRB System

Prudent Energy's VRB storage system is an advanced flow battery technology designed to store and supply large amounts of electricity on demand. The VRB contains two different electrolyte solutions of vanadium and sulfuric acid, each in a separate tank (positive and negatively charged, respectively). To provide power, the VRB electrolytes flow through a fuel cell stack on opposite sides of an ionic exchange membrane, where their opposite charges create a gradient that powers an external current.

Scalability: unlike conventional batteries, power output is independent from energy storage capacity—output depends on the size of the fuel cell stack, while the energy storage capacity depends on the size of the electrolyte tanks. This unique characteristic enables flow battery systems to sustain utility-scale storage and power at potentially competitive prices. Note, however, that the ratio of storage to power determines how long the batteries can run without recharging (power can flow undiminished as long as there is fresh electrolyte to circulate through the stack).

Research Findings and Pertinent Issues

The experimental plan included running the battery to measure energy in and energy out as well as log any failures and performance issues. The focus has mostly been on the DC performance of the battery. Performance testing was limited to the scope of work as per the Award document, thus deep cycles to test degradation under chemically aggressive conditions was not carried out.

Features of the Battery

1. Spec sheet characteristics
    - Power rating: 5 kW (designed energy charge/discharge rate)
    - Energy storage capacity: 20 kWh (determined by tank size)
    - Life: >10,000 cycles
    - Operating temperature range: 10 degC to 35 degC
    - Allowable storage temperature: -25 degC to 75 degC
    - Weight: 510 kg (~3,000 kg with electrolyte)
    - Dimensions (power module only): 1m x 1.2 m x 1.1m
2. Operational Performance
    - The VRB unit has had a run time of 830 hours (this is the period covered under this report, and excludes initial commissioning and troubleshooting log times).
    - No. of complete cycles: 50 (average of 16 hrs charge/discharge cycles)
    - Efficiency: between 70-78% (the base case state of charge was 10%-90%).

3. Economics of storage: $0.29/kWh (a simple economic calculation based on 10,000 cycles at 20 kW-hr per cycle, or 200,000 kilowatt-hours total lifetime energy storage).
   Note, however, that the cost of VRB commercial units is currently placed at about $400/kW or $600/kWh.

Some observations:

1. Economic considerations – an assessment of the overall cost, in relation to other storage media and to other manufacturers/suppliers will determine whether the flow battery is justified in larger communities in conjunction with a wind turbine to stabilize delivered power.
2. Battery life and maintenance – during the testing period the battery has exhibited neither sign of degradation in performance nor balance of plant issues. Reliability of the battery relies on the maintenance of the system, while the maintenance schedule intervals (cycles or service life hours) determine the offline duration. The design life of the battery is pegged at slightly over 10,000 cycles (and/or a service life of 100,000 hrs). The electrolytes should in principle not get degraded, while it is expected that the cell stacks should be replaced every 10 years.
3. Cold climate and operational limits – with regard to suitability for Alaska, the electrolyte is fairly robust but is not to be exposed to extreme temperatures. Recommended electrolyte temperature range is 10 to 35 degC (during operation), while the allowable storage temperature range is -25 to 70 degC.

However, there are also a number of disadvantages:

- Space requirements – the energy density of the storage system is relatively low, rendering a large footprint of the vanadium battery. The main components of the VRB include the storage tanks, pumps and plumbing, cell stacks, and power conversion equipment. Footprint and volumetric space requirements scale with system ratings and can be very site-specific.
- The large quantity of vanadium electrolyte, which is ionic vanadium in sulfuric acid, is classified as corrosive.
- Containment – measures have to taken to avoid leakage to the environment.

The application of flow batteries offers many opportunities, especially in large-scale grid-connected applications. The first demonstration projects have demonstrated the technology on a large scale, but for characteristics like life time the technology first has to prove itself in the coming years. Based on the expected life time costs, it is a very attractive solution with both economical and technical benefits compared to the alternatives.

Future Perspectives of the Technology

Wind energy is a critical component of ACEP's larger energy storage program objectives, both because many of the issues addressed as part of the program are unique to Alaska, and because the existing need is greatest in the energy sector based on total installed and planned projects. Technology that improves the reliability of wind or other intermittent renewable energy resources fits with efforts to enhance Alaska's energy picture and improve energy security. The flow battery storage system can serve to minimize runtimes of diesel generators while improving the functionality of wind generation. The wind-diesel power system/flow battery integration, however, may still have room for improvement. The fundamental challenge is still the economics, and these batteries are still relatively expensive for their energy density, though this is expected to change as renewable energy becomes more common.

The technical viability of a wind-coupled energy storage system is set for demonstration by the Alaska Center for Energy and Power at the University of Alaska Fairbanks, where the 5 kW 20 kWh flow battery will be integrated with a 100 kW wind turbine simulator on a test bed platform[1]. The integrated approach will investigate benefits of such storage-coupled wind applications accrue in both directions: economic returns in specialized cases such as island systems, and providing ride-through and transient mitigation from the perspective of the wind plant during grid disturbances.

[1] This decision has been taken on the premise that it is highly unlikely facilities at the Chukchi campus would support the battery; part of the concern is the extra infrastructural cost for a dedicated structure that complies with EPA regulations. Additionally, KEA is not keen on hosting the battery at their wind farm as they have already acquired the flow battery unit from Premium Power.

Glossary

The following is a short explanation of some terminology and abbreviations used in this report for the Prudent Energy Storage System™ ("VRB").

A	Ampere – unit of current
AC	Alternating current – the standard form of electricity from the mains. Typically single phase for most domestic appliances; however three phases are used for higher power devices
BOD	Bottom of discharge – Reference to beginning of battery charge cycle
BOP	Balance of plant
Cell	The smallest unit of a battery. In the flow battery many cells are packaged together to form a stack
Charge efficiency	Ratio (%) between the energy removed from a battery during discharge compared with the energy used during charging to restore the original capacity. Also called the Coulombic Efficiency.
Converter	An electrical device for changing the voltage of an electrical supply; used when a DC load runs at a different voltage to the battery
Cycle	Process of charging followed by discharging (or *vice versa*), to bring the battery back to the same state-of-charge (typically completely discharged or charged). Battery life is often given as the no. of cycles to a certain depth-of-discharge
DC	Direct current – the standard form of electricity from a battery; may be used by some appliances but generally an inverter is used to convert it to AC
Depth-of discharge	How much capacity has been taken out of the battery in %; e.g., an 80% depth-of-discharge would leave 20% charge still in the battery
Electrolyte	(In the VRB), a solution of vanadium salts in sulphuric acid
ESS	Energy storage system – a device that can be used to store energy (especially electricity) until it is needed

Inverter	An electrical device for converting battery DC electricity into mains AC electricity
kW	Kilowatt (thousand watt) – unit of power. Mathematically it is equal to the current multiplied by the voltage
kWh	Kilowatt-hour – unit of energy (power multiplied by the usage time)
Load	The input impedance to the system circuit that takes electricity to work, and refers to any appliance connected to the flow battery
Oxidation state	A numerical measure of the degree of oxidation of an atom in a substance (how far the electrolyte has reacted). Vanadium in the VRB can have oxidation states +2 (little reacted), +3, +4 or +5 (fully reacted)
Redox	Reduction-oxidation chemical reaction
Smart controller	An essential device in the VRB that continuously monitors the state of the battery and power to the load(s). Controls the speed of the pumps, number of stages in operation, responds to alarm signals and can communicate with the user
SOC	State-of-charge – how much capacity (%) remains in the battery
Stack	A group of cells through which the electrolytes flow. At both ends of the stack are electrical connectors through which the battery may be charged and discharged
Stage	In the VRB not all of the stacks must be active at the same time, especially when the power is low. The controller can decide to activate or deactivate groups of stacks together, known as a stage
Thermal mass	A measure of how difficult it is to raise the temperature of an object. The VRB has a higher thermal mass than an equivalent amount of lead-acid batteries
TOC	Top of charge
V	Volt – unit of voltage (or potential difference)
Vanadium	A common metal that is widely distributed in nature. It reacts to form brightly colored salts that are used in solution in the VRB

Introduction and Theory of Operation

NEED FOR ENERGY STORAGE

Storage is essential for electricity consumers where power quality and reliability is critical, such as at airports, broadcasting operations, hospitals, financial services, data centers, telecommunications, and many finely tuned industrial processes. For grid systems that have a significant amount of renewable generation, a means to provide ancillary services is necessary to ensure power quality. Alaska has a number of isolated power systems that rely on diesel generators, wind turbines, or a combination of both. Hybrid wind-diesel systems, especially the high penetration types, require some spinning reserve component to ensure power quality. Generally speaking, it is relatively difficult for the conventional generator to keep good power quality in a closed grid because the generator output cannot follow the demand change quickly.

Developing the means to manage intermittent electricity generation from wind power has been a key challenge for grid operators. Whereas most power networks in the lower 48 have various solutions in dealing with grid imbalances caused by wind e.g., network interconnection and demand management, energy storage remains the most viable alternative for wind-diesel systems in Alaska. Storage also incurs energy losses, around 20-50% depending on the technology, which can put a dent in generating revenues. Energy loss during any of the conversion phases and during storage poses problems.

Energy storage technologies are not an alternative to any particular resource decision, but rather, a valuable adjunct to all resources, and they allow increased capacity to be derived from any given quantity of physical resources. The goal for energy storage technologies is to stockpile massive amounts of energy by transforming it into different but conveniently stored forms. Storage systems rely on three key components:

- An input energy-conversion module that receives energy from the grid and converts it to a storable form
- An energy-storage module that warehouses the energy, and
- An output-conversion module that turns the stored energy back into electricity.

Lead-acid batteries represent the most prevalent form of electric energy storage for residential, commercial and industrial customers wanting to maintain an uninterruptible power supply (UPS) system. However, storing massive amounts of energy from renewable resources requires rechargeable systems, like flow batteries.

FUNDAMENTALS OF VANADIUM REDOX FLOW BATTERY SYSTEMS

History of the Development of Flow Batteries

Flow batteries date back to the 19th century. They are best described as: '…a form of battery in which electrolyte containing one or more dissolved electro-active species flows through a power cell / reactor in which chemical energy is converted to electricity.

Full-scale development of the batteries started in the 1970s. The principle of the redox flow (RF) battery system was presented by L. H. Thaller of the National Aeronautics and Space Administration (NASA) in 1974[1]. NASA mainly conducted research on the Fe/Cr system, discontinuing it in 1984 with the publication of the Final Report[2]. At the same time in Japan, the Electrotechnical Lab. (ETL; currently the National Institute of Advanced Industrial Science and Technology) was conducting basic research, and the development of the Fe/Cr system made progress as a project of the New Energy and Industrial Technology Development Organization (NEDO).

Flow batteries suitable for large scale energy storage have currently been developed at various organizations around the world. The Vanadium type of flow battery has become a mature technology – this is a rechargeable flow battery that employs vanadium redox couples in both half-cells, thereby eliminating the problem of cross contamination by diffusion of ions across the membrane. Although the use of vanadium redox couples in flow batteries had been suggested earlier by Pissoort[3], by NASA researchers, and by Pellegri and Spaziante[4] in 1978, the first successful demonstration and commercial development was by Prof Maria Skyllas-Kazacos and co-workers at the University of New South Wales (UNSW) in Australia in the 1980's[5,6]. UNSW proceeded to develop the vanadium redox battery and patented it[7,8] – this resembled the present form (with sulfuric acid electrolytes). It is noteworthy that vanadium resources are abundantly available in Australia.

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[1] L. H. Thaller, "Electrically Rechargeable Redox Flow Cells," Proc. Of the 9th IECEC, P.924 (1974).
[2] N. H. Hagedorn, "NASA Redox Storage System Development Project Final Report," DOE/NASA/12726-24, NASA TM-83677 (1984).
[3] P. A. Pissoort, in FR Patent 754065 (1933).
[4] A. Pelligri and P. M. Spaziante, in GB Patent 2030349 (1978), to Oronzio de Nori Impianti Elettrochimici S.p.A.
[5] B. Sun, M. Skyllas-Kazacos, "A Study of the $V^{(II)}/V^{(III)}$ Redox Couple for Redox Cell Application," J. of Power Sources, 15, P.179-190 (1985)
[6] M. Rychcik and M. Skyllas-Kazacos, "Characteristics of a new all-vanadium redox flow battery," Journal of Power Sources, 22, P.59-67, 1988.
[7] M. Skyllas-Kazacos, M. Rychcik, and R. Robins, in AU Patent 575247 (1986), to Unisearch Ltd.
[8] M. Skyllas-Kazacos, M. Rychick, R. Robins, All-vanadium redox battery, US Patent 4,786,567 (November 1988).

Vanadium Redox Flow Battery System

The word redox is a combination of, and thus stands for, *reduction* and *oxidation*. A redox battery refers to an electrochemical system that generates oxidation and reduction between two active materials, forming a redox system, on the surface of inactive electrodes. A redox flow battery has the electrolyte including these active materials in external containers, and charges and discharges electricity by supplying the electrolyte to the flow type cell by pumps or other means.

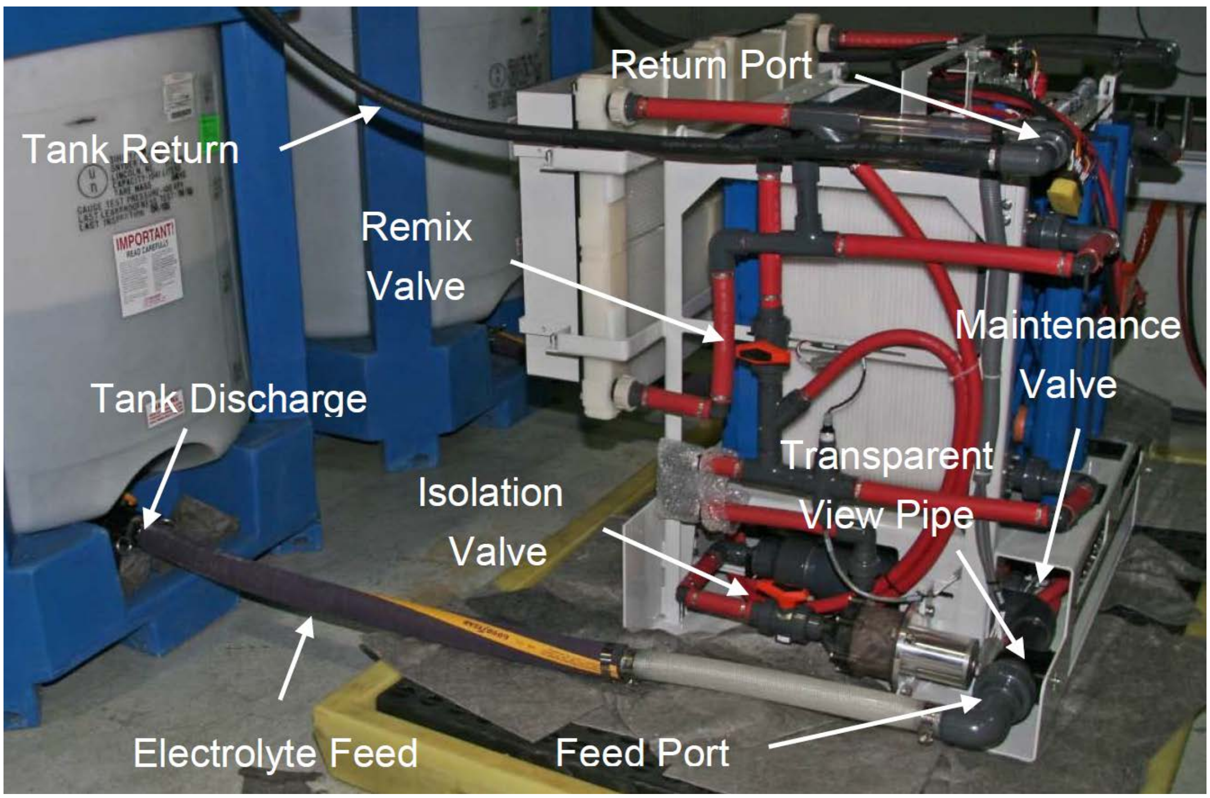


Fig. 1. VRB system

Fig. 1 shows Prudent Energy's VRB system. The three primary subsystems in the VRB are the converter, the power conversion module, and the electrolyte – the energy storage medium. The converter is the interface between the DC battery voltage and the 60 Hz AC network voltage. The converter transformers match the converter output to the grid system voltage. The VRB uses vanadium salts and sulfuric acid in the electrolytes to convert chemical energy into electrical energy. Vanadium is a relatively common metal, used to make vanadium steels and dietary supplements and is found in many common foods.

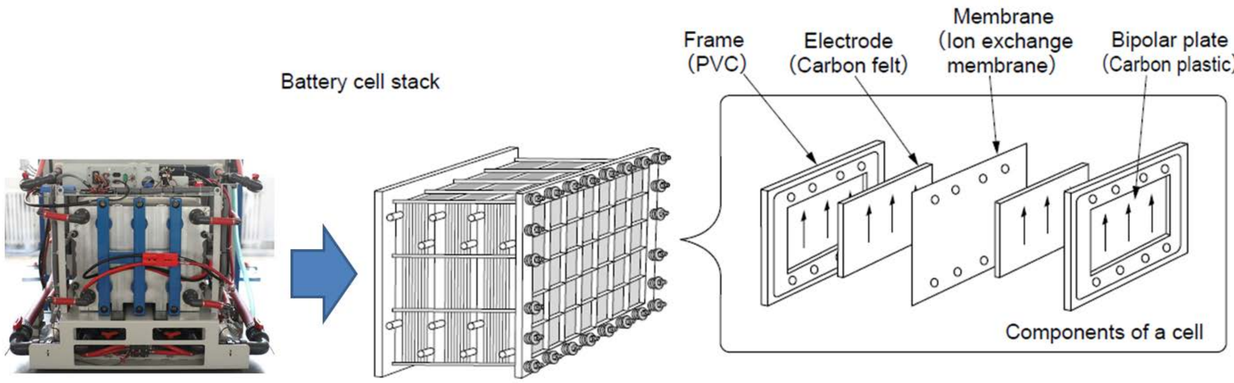
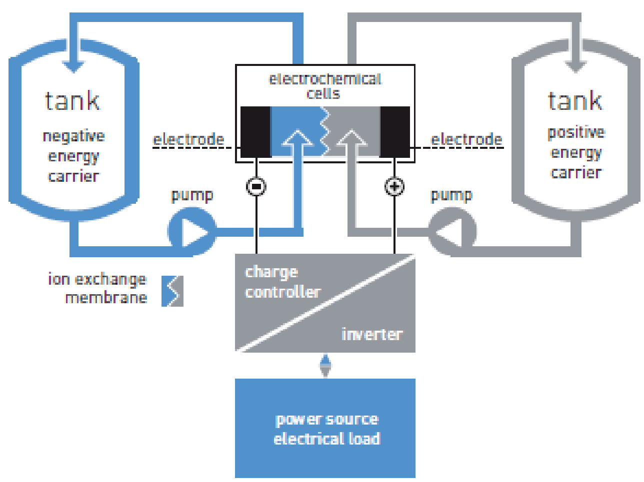


Fig. 2. Construction of the cell stack.

Generally the cells are grouped together in blocks known as stacks. In each stack the cells are connected electrically in series by bipolar plates, i.e. conducting plates that have positive electrolyte on one side and negative on the other. Each cell of a flow battery is practically identical, because they share the same electrolytes. Therefore, the stack voltage is the sum of the voltage of the individual cells. The main components of a cell stack are shown in Fig. 2.

Fig. 3 is a schematic of the operation of the VRB. The philosophy of operation is based on the fact that when connected to the electrical network, the battery cells store energy through charging; this energy is later released to the power system during the discharge cycles – ideal for storage of excess generation from distributed resources (wind turbines).



During charging, electrolyte flow is forced across both sides of an ionic exchange membrane as electrical current is applied to the VRB-ESS cell stack. This results in an electrochemical reaction forcing protons to pass through the membrane causing a change in the vanadium valence. This change in valence represents stored chemical energy that can be recovered by reversing the process through the VRB-ESS cell stack. Control of flow conditions and electrical performance is automatically maintained by the battery controller.

Oxidation States

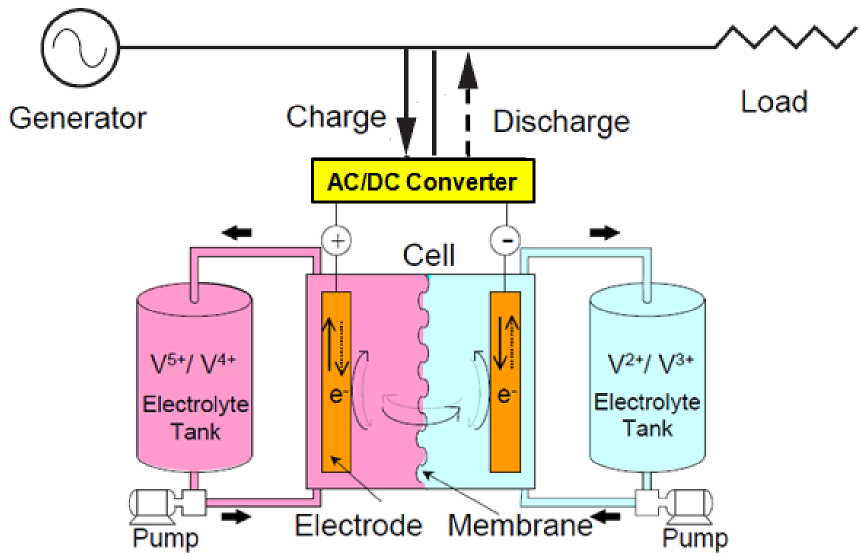


Fig. 4. Principle of the Vanadium Redox flow battery[9].

Fig. 4 illustrates the redox concept. The VRB consists of an assembly of power cells in which the two electrolyte solutions with a different redox potential are kept separated by an ion exchange membrane. This membrane allows one electrolyte to ionize the other by exchanging electrons while preventing the two solutions to physically mix.

Both electrolytes are vanadium based – the electrolyte in the positive half-cells contains VO_2^+ and VO^{2+} ions, the electrolyte in the negative half-cells, V^{3+} and V^{2+} ions. The electrolytes are typically prepared by a number of processes, including electrolytically dissolving vanadium pentoxide (V_2O_5) in sulfuric acid (H_2SO_4). The solution remains strongly acidic in use. Both half-cells are additionally connected to storage tanks and pumps so that very large volumes of the electrolytes can be circulated through the cell.

Generally, metal ions that change valence can be used in a redox system, and the vanadium (V^{2+}/V^{3+} – VO^{2+}/VO^{2+}) platform is among the best redox systems when such factors as energy density and economics are considered. The vanadium redox battery exploits the ability of vanadium to exist in 4 different oxidation states, and uses this property to make a battery that has just one electroactive element instead of two.

[9] Courtesy of Sumitomo Electric Industries, Ltd (SEI), Japan – Copyright 2009.

When the vanadium battery is charged, the VO^{2+} ions in the positive half-cell are converted to VO_2^+ ions when electrons are removed from the positive terminal of the battery. Similarly in the negative half-cell, electrons are introduced converting the V^{3+} ions into V^{2+}. The electrode reaction of the vanadium system can be expressed by:

- Positive electrode:
  VO^{2+} (tetravalent) + $H_2O \leftrightarrows VO_2^+$ (pentavalent) +2H^+ + e^-: $E^0 = 1.00$ V............ (1)

- Negative electrode:
  V^{3+} (trivalent) + $e^- \leftrightarrows V^{2+}$ (bivalent): $E^0 = -0.26$ V .... (2)

The reaction from left to right represents the reaction during charging in both equations. At the positive electrode, tetravalent V ions (VO^{2+}) are oxidized to pentavalent V ions (VO^{2+}) while at the negative electrode, trivalent V ions (V^{3+}) are reduced to bivalent V ions (V^{2+}). The hydrogen ions (H^+) generated at the positive electrode during charging move to the negative electrode through the membrane to maintain the electrical neutrality of the electrolyte. Supplied electric power is thus stored in the form of the transformation of V ions of differing valence.

During discharging, the stored power is delivered by the reverse reaction. The battery's electromotive force calculated based on the standard oxidation reduction potential (E^0) is 1.26 V. However, when the electrolytes and cells are prepared practically, the electromotive force is about 1.41 V (typical open-circuit voltage obtained at 25 °C).

- Overall reaction[10]:
  $V^{3+} + VO^{2+} + H_2O \leftrightarrows V^{2+} + VO_2^+ + 2H^+$ .... (3)

The discharged reactants are shown on the left and charged on the right. Because the electrolyte is returned to the same state at the end of every cycle it may be reused indefinitely (assuming it is not contaminated).

[10] **Oxidation States**: Vanadium is present in both the positive and negative electrolytes, but in different oxidation states. The oxidation state is a measure of how far a reaction has proceeded. For example unreacted vanadium has an oxidation state of zero, when it is fully reacted it has an oxidation state of +5. The oxidation state may also have values in between if the vanadium is only partially reacted, although not every value is possible. Vanadium is an unusual metal in that it forms stable, concentrated solutions with four different oxidation states, a property shared only by uranium and some other heavy, radioactive elements. Charging and discharging the battery changes the average oxidation state of the vanadium in the electrolytes.

THE ACEP PROPOSAL AND AWARD

Background and Context

One of ACEP's research objectives is to establish the efficient management of high penetration wind-diesel systems with integrated storage through advanced control. Advanced battery technologies is a field with considerable innovation and potential applicability in Alaska, and this research seeks to ascertain the performance and economic benefits of implementing such a system in isolated grids in communities.

In August 2009, the University of Alaska applied for funding from the Denali Commission Emerging Technologies Grant Fund to test advanced battery systems. The 5 kW, 20 kWh vanadium redox battery was purchased from Prudent Energy Systems for laboratory testing at ACEP for both performance data collection and assessment of validity of the claims made by the supplier with regard to performance. The project was carried out for joint research and educational purposes – a cooperative partnership between the Chukchi Campus, University of Alaska Fairbanks, and the Alaska Center for Energy and Power (ACEP), University of Alaska-Fairbanks.

The battery unit was commissioned in September 2010, and ACEP has performed the requisite tests as outlined in the grant proposal. Collection of clean performance data to assess the validity of the claims made by the supplier is still ongoing at the ACEP facility, and the next step is to integrate the flow battery into a wind turbine simulator test bed as part of the program to assess energy storage options appropriate for Alaskan markets.

This report documents the testing and analysis of the project.

Project Objectives/ Scope of Work

The Chukchi Campus and ACEP entered into a cooperative arrangement such that the Chukchi campus would purchase a Prudent Energy 5 kW system, and have it shipped to the ACEP laboratory in Fairbanks for performance testing. The specific responsibilities for ACEP were set out as follows:

1. Test the unit for up to 6 months. The purpose would be to verify manufacturer performance claims in a controlled environment with managed charge/discharge cycles, and to determine if any significant maintenance issues exist.
2. ACEP would work with the Chukchi Campus to integrate the battery testing into the classroom by a) sending a researcher to Kotzebue to present a lecture(s) on energy storage; and b) show the battery in testing configuration and give a 'tour' of it via distance education technologies.

3. ACEP researchers would assist the Chukchi Campus in selecting an appropriate location in Arctic Northwest Alaska served by the Chukchi Campus, where the system would be integrated with an existing renewable energy project. This decision would be made in consultation with local utilities, particularly the Kotzebue Electric Association, and take into account both future educational opportunities for working with the battery as well as the ability to continue long-term performance monitoring in the field. The Chukchi Campus, as the owner of the battery system, would have the final decision making authority in this matter.
4. ACEP would work to prepare and ship the unit as appropriate.
5. ACEP would install remote monitoring and data collection equipment on the system in the field (included in project budget). The goal was to have monitoring feeds installed at both Fairbanks and the Chukchi Campus via internet link.

Project Timeline

It was anticipated that the project would be undertaken over a period of 19 months, with the following specific milestones:

March 1st, 2010:	Project start date
March, 2010:	Procurement for the 5 kW Prudent Energy System initiated
July, 2010:	Delivery of Prudent Battery in Fairbanks
August, 2010:	Installation of battery at ACEP facility
September, 2011:	Commissioning by Prudent Energy Systems personnel
December, 2011:	Project closeout; final Report.

Progress reports were completed quarterly throughout the project.

Budget

The project operated under a budget of $175,000.
Major project costs were divided as follows:

1. Each organization (ACEP and Chukchi Campus) supported its own representatives working on the project in terms of time and travel. The majority of this cost was borne by ACEP, at a cost to the organization of $75,000.
2. The Chukchi Campus covered all equipment costs, including the battery and remote monitoring and data logging equipment that allow performance data to be transmitted from the battery location.

In the event that the system would be relocated from the ACEP facility (for, e.g., field testing), Chukchi Campus is obligated to cover shipping of the unit.

Delivery

The 5 kW Vanadium redox flow battery manufactured by Prudent Energy – the 4th generation[11] of this battery, advertised as having high energy conversion efficiencies and extremely long life – was delivered at the ACEP facility in Fairbanks in August 2010.

Fig. 5. Initial inspection of the crated stack after inception at ACEP's Bidwill Ave facility.

The weight of the power module alone is 510 kg, while the total weight (including electrolyte tanks) is 3,000 kg. The approximate power module physical specifications are: D = 1.0m, W =1.2m, H = 1.1m.

This VRB has been designed to provide energy for 2 hours to more than 8 hours depending on the application. Generally, the lifespan of flow batteries is not strongly affected by cycling. Suppliers of vanadium redox systems estimate lifespan of the cell stacks to be 15 or more years, while the balance of plant and electrolyte can have life-times of over 25 years. System suppliers also say they have achieved cycling capability of 10,000 or more cycles at 100% depth of discharge.

[11] ACEP tested a 3rd generation version to failure in 2009, and the lessons learned then have been incorporated in this model.

Commissioning

Commissioning of the system was undertaken by a representative of Prudent Energy from the Burnaby, BC, Canada office together with ACEP engineers on September 20~21, 2010. The flow battery system was connected to the mains via a Xantrex XW6048 inverter charger (6.0 kW 48V split phase) – this provides grid interface functionality via a control panel. The process of commissioning entailed running some charge and discharge cycles and verifying that there were no leaks.

Fig. 6. Commissioning: ACEP's Tom Johnson (L) and Aleks Velhner of Prudent Energy.

Commissioning involved setting the VRB system to an initialization state, where the battery controller first completes a series of diagnostic checks to ensure that the battery is functioning within allowable parameters. This check included ensuring that no critical event flags are active within the battery. The controller then executed a routine that circulated electrolyte through the cell stack to confirm that the sensors were functioning. After confirming that electrolyte flow had been established, the battery controller automatically shifted to the connected state (if there were major or critical events, the controller would have gone to the fault state).

The system was left to make one 8-hr full cycle for acceptance.

Characterization: Performance Testing and Analysis

After commissioning, the battery system was instrumented and preliminary testing commenced – cycling with troubleshooting. The system did not come with data storage capability, thus it was necessary to have internet connectivity for data collection. ACEP developed the user interface program for analyzing data from the performance testing, as shown in Fig. 7. The VRB unit has several independent operating states that are automatically controlled through the battery controller's state logic. Transitions between states occur because of either an external command from the operator or internal parameter changes observed by the battery's process monitoring sensors.

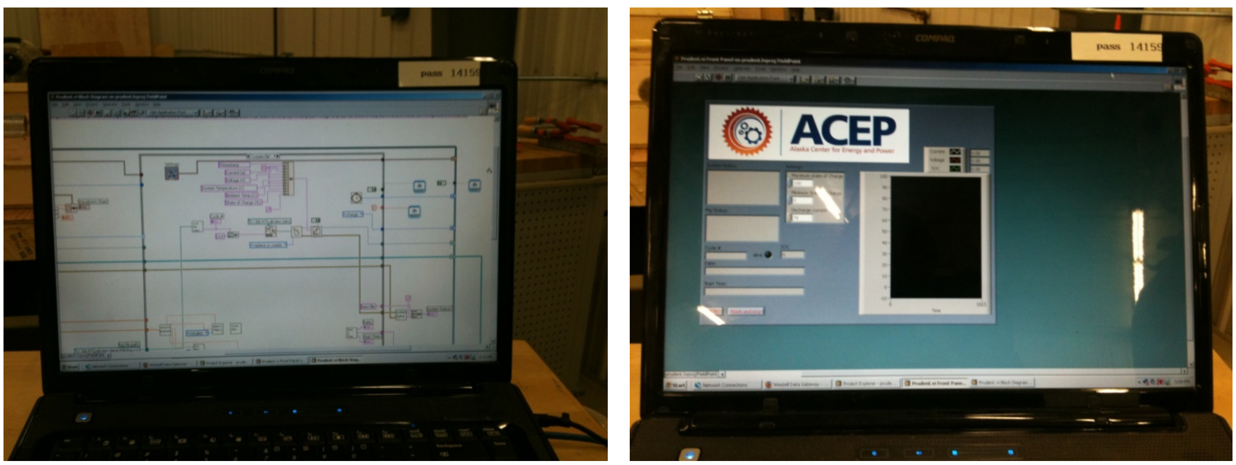


Fig. 7. User interface. Schematic represents the system circuit (L). Remote PC display (R).

ACEP performed custom performance and safety testing with full data acquisition and analysis. The data is streamed live via an ftp address to designated access computers. Performance analyses have included:

- Cycle life
- Discharge rate
- Duty cycle
- Environmental conditions (temperature).

Battery qualification is still an ongoing process that involves investigation of standby losses, capacity, etc. Some testing procedures e.g., accelerated life and storage analysis that typically involve deep cycling, have not been started. Overall, battery system performance specifications based on preliminary testing have shown very little deviation from the manufacturer specifications.

Previous Work

ACEP has been involved with flow battery testing for several years, including a performance test of a 10 kW vanadium redox flow battery (2006 – 2009). This unit was supplied by VRB, then a Canadian company.

Fig. 8. The 10 kW VRB battery that was tested at ACEP Lab between 2006 and 2009.

During the test period for the VRB battery, several issues were identified that were a cause for concern for this battery technology. A full report is available[12], but identified failure mechanisms were:

- "Balance of plant" failures. Two pumps, electrical contacts, computer hardware, leaky fittings and leaky tanks – all of which caused the unit to stop running. Some of these issues could be resolved with better selection of components.
- Stack failures. Though a fundamental flaw for this technology, these were not unexpected given the parent company's commitment to finding low cost materials for their manufacture (VRB announced that it intended to manufacture these units from commercially available off the shelf components, using materials of standard commercial purity.)

[12] Dennis Witmer, "VRB Vanadium redox battery testing at UAF," ACEP Report, June 2009. Available online: http://www.uaf.edu/acep/publications/

Characterization and Analysis

PERFORMANCE TESTING

Characteristics of the 5 Kw, 20 kWh Vanadium Redox Flow Battery

As per the project objectives, performance testing was undertaken to verify manufacturer performance *claims in a controlled environment with managed charge/discharge cycles*, and to determine if any significant maintenance issues exist. It is important to mention that the battery was not subjected to rigorous tests that would otherwise test the limits of performance.

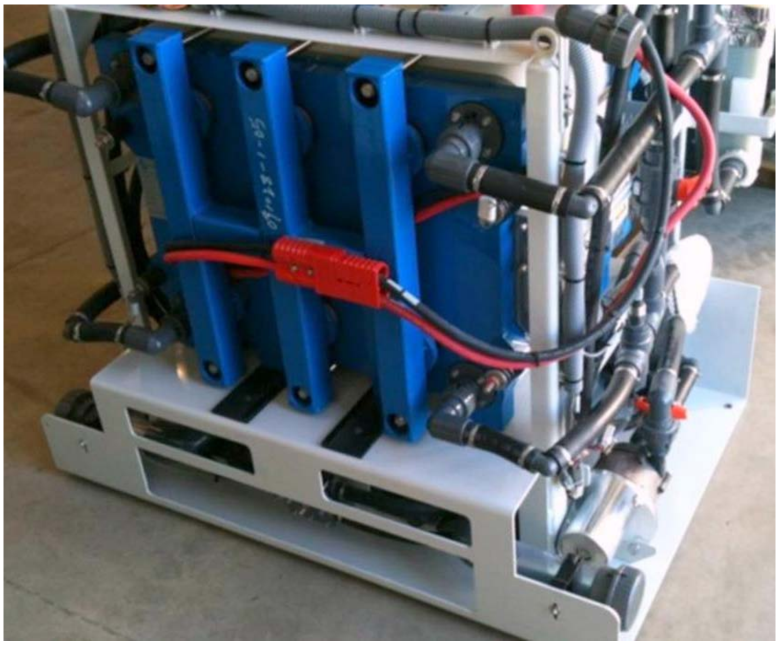


Fig. 9. The 5 kW Prudent Energy Battery (without electrolyte tanks).

The quantities used in validating the battery system include:

- Efficiency (power converter efficiency, cell stacks efficiency, overall efficiency)
- Auxiliary power consumption; other storage losses
- Storage capacity and State of Charge
- Starting and stopping ; response time and transients
- Degradation.

Table I. Performance characteristics and specifications: 5 Kw VRB

Power	5 kW
Energy storage capacity	20 kWh
Dimensions, power module	1m x 1.2m x 1.1 m
Weight, power module	510 kg
Weight, Total	3,000 kg
+ve Electrolyte	Vanadyl/Vanadium sulphate
-ve Electrolyte	Hypovanadous^{VII}/Vanadous^{VIII} sulphate
Electrolyte, operating temp. range	10 to 35 degC
Allowable storage temp.	-25 to 75 degC
Open circuit voltage at 0% and 100% capacity	50 VDC to 56 VDC
Max. charge voltage	58.9 VDC
Min. voltage on discharge	42 VDC
Max. charge current	140 ADC
Max. discharge current (continuous)	140 ADC
Max. discharge current (<300 s)	175 ADC
Continuous power at beginning of discharge	7.0 kW
Continuous power at end of discharge	5.25 kW
Duty cycle	100%

Table I gives the specifications and ideal performance characteristics for the VRB. The design life of the 5 kW, 20kWh battery is pegged at slightly over 10,000 cycles (and/or a service life of 100,000 hrs). Part of the performance and qualification testing is to establish the roundtrip efficiencies at various settings, the overall efficiency of the flow battery system, and cycle life.

The electrolyte is fairly robust but is not to be exposed to extreme temperatures. As regards operational limits and suitability for the cold Alaskan climate, the recommended electrolyte temperature range is 10 to 35 degC, at a non-condensing humidity of 0% to 95%. Altitude range is flexible: from 0 to 3,000 m. The allowable storage temperature range is -25 to 70 degC. Battery system performance specifications based on preliminary testing showed very little deviation from the manufacturer specs shown in the Table below.

The design life of the battery is pegged at slightly over 10,000 cycles (and/or a service life of 100,000 hrs). As expected, maintenance has to be scheduled at a predetermined interval, depending on the battery offline duration that may be tolerated. For an offline duration of less than 2 hrs, maintenance should be carried out every 9,000 hrs, while for a maintenance interval of every 27,000 hrs may be adopted if an 8 hr offline duration is possible.

Setting Up the Charge/Discharge Operation

The VRB-ESS is designed to be functionally identical to a conventional battery but with the ability to protect itself against abnormal conditions. Thus the charge and discharge characteristics are very similar to a conventional battery and no complex external control or charge management is required. Although the onboard control is comprehensive, the only control input to the battery is an on/off command signal from a relay or a switch installed in the auxiliary system. To activate the VRB-ESS, two conditions must be met:

- Electrical power must be available on the main DC bus either from an auxiliary system or the battery itself, and
- An external relay or switch is closed from an auxiliary system or operator to turn on the battery.

Before operating, the operator checks that electrolyte has entered the feed line. The cell stack isolation valves are opened slowly for the power module to flood with electrolyte, while ensuring that there are no electrolyte leaks. The power supply voltage is adjusted to 58.9 VDC, while the power supply is limited to 140 ADC. The battery controller is then turned-ON by closing the power on/off switch. Once started, the VRB-ESS initiates sensor functions, state handling, and process flow, and the system executes a series of diagnostic checks. Once the checks have confirmed that the system's operating parameters are within an acceptable range, the cell stack is then connected to the external DC bus to permit current flow. From that point, charge and discharge are governed by the state of that bus—a high electrical potential will charge the battery, and at a low electrical potential, the battery will deliver power to the load. The battery controller outputs data signals updating the capacity status of the battery.

Charging the VRB-ESS

The fastest rate of charging the battery can be achieved by adjusting the power supply voltage to 58.9 VDC and current to 140 ADC. Once the battery is fully charged, the battery controller signals to the charging equipment that further charging is no longer required. The charging equipment is to be disabled when this signal is transmitted. Depending on the capacity rating of the battery there is an overvoltage buffer that provides time to react but once elapsed the VRB-ESS will disconnect from the external DC-bus to protect from damage. This will impact the ability of the battery to supply power to its load as time will be required for the battery controller to transition back to the connected state.

Discharging the VRB-ESS

Discharge can be done at a rate according to the load requirements being supported, subject to the battery's discharge current capacity.

At the bottom of discharge, the battery controller indicates that the battery is nearly depleted. However, the battery is not damaged by deeper discharges, so external loads may continue to draw voltage drops below a value that would not allow the continued circulation of electrolyte in the battery. Electrolyte circulation continues until there is no internal battery power available to the battery controller. At this point the battery will act as if it has been powered-OFF. However as long as the on/off switch remains engaged, the instant power source is applied the battery will power-ON and go through its initialization process.

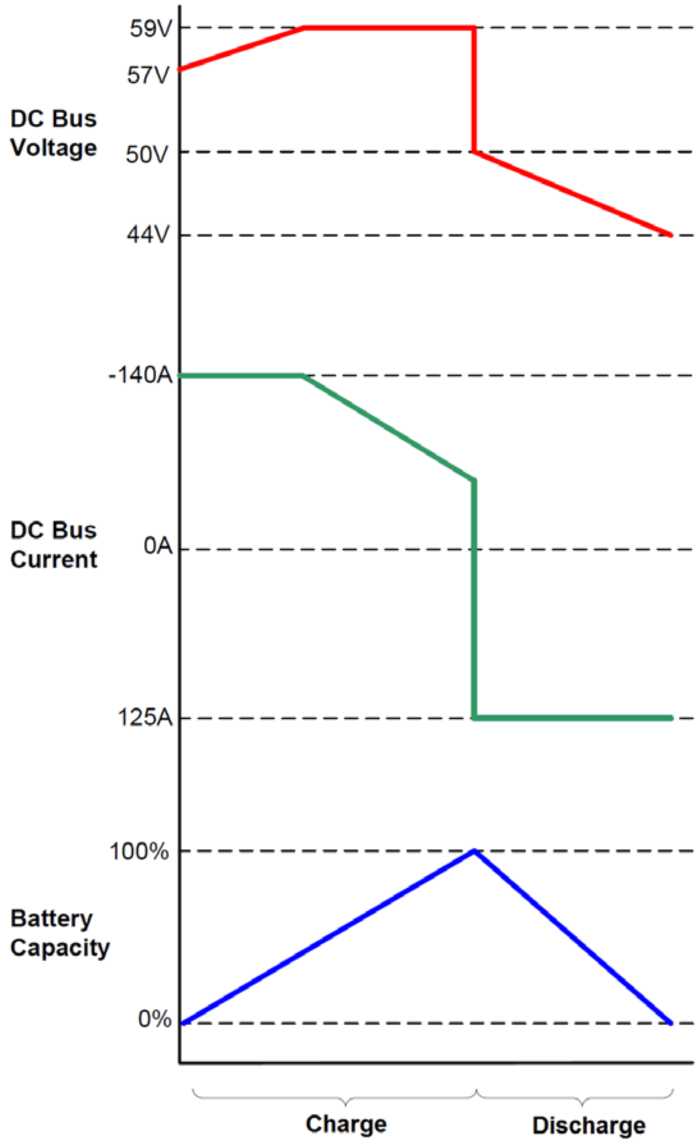


Fig. 10. Charge / discharge characteristics

Fig. 10 shows a typical charge-discharge characteristic for the 5 kW, 20 kWh VRB-ESS. To maximize battery performance and longevity the strategy of trickle charging is to be avoided. Auxiliary systems can be set up to respond to battery controller commands to request disabling charge current when TOC has been reached.

The advantage of the VRB technology is best demonstrated after repeated discharges below 0% capacity causes no harm. However, depending on the size of the load it may be disruptive to the user as power available is reduced at BOD.

OPERATIONAL PERFORMANCE

Sample Charge/Discharge Cycle Operations

Since its commissioning in September 2010, several different operating schedules and test sequences have been applied over the test period of the VRB-ESS, including:

- The battery was set to charge and discharge at fixed daily patterns, charging until maximum SOC and discharging thereafter with the maximum discharge power with simulated load, or exchange back to the grid.
- Over longer periods, the characteristic test pattern was to set the battery to subsequently charge fully and discharge fully at different power levels.
- At other times the battery has been set to charge and discharge to a random SOC with a random power.

These tests were carried out to verify manufacturer claims and ascertain conformance to the specs, notably the ones shown in the Table I.

Charge and Discharge Parameters for Test #51

Fig. 11 shows results for test no. 51 conducted for 16 hours continuously. When the battery is not in operation the cell stacks are drained to reduce self-discharge. The start and stop sequences of the battery take about 7 minutes. During startup the pumps are ramped up in speed to ensure that the stacks are completely flooded. The stop sequence stops the pumps and the electrolyte is drained (usually by gravity). The battery was on charge for about 8 hours, when it attained a peak voltage of 58.361 V. It was then left to discharge by feeding power to a resistive load bank.

The current and voltage plots give an indication of the changes that occur in stack performance, which changes over time, especially when the cycles are compared. During the initial 10,000 sec, the stack is charging at a rate determined by the output of the battery charger, thus the system is current limited. The current is sent to the power module at the maximum safe rate the stack will accept until voltage rises to near (80-90%) full charge level. There is no "correct" voltage for charging, but there are limits on the maximum current that the battery can take.

When the stack voltage rises to 58 V, the system becomes voltage limited, and the current starts to decrease. Voltage remains constant and current gradually tapers off; it is during this stage that maximum voltage is attained. This ensures complete charging. After the battery attains full charge, charging voltage is reduced to a lower level to prolong battery life. The battery then switches to the discharge mode, and discharges until the set point of 50 V is attained.

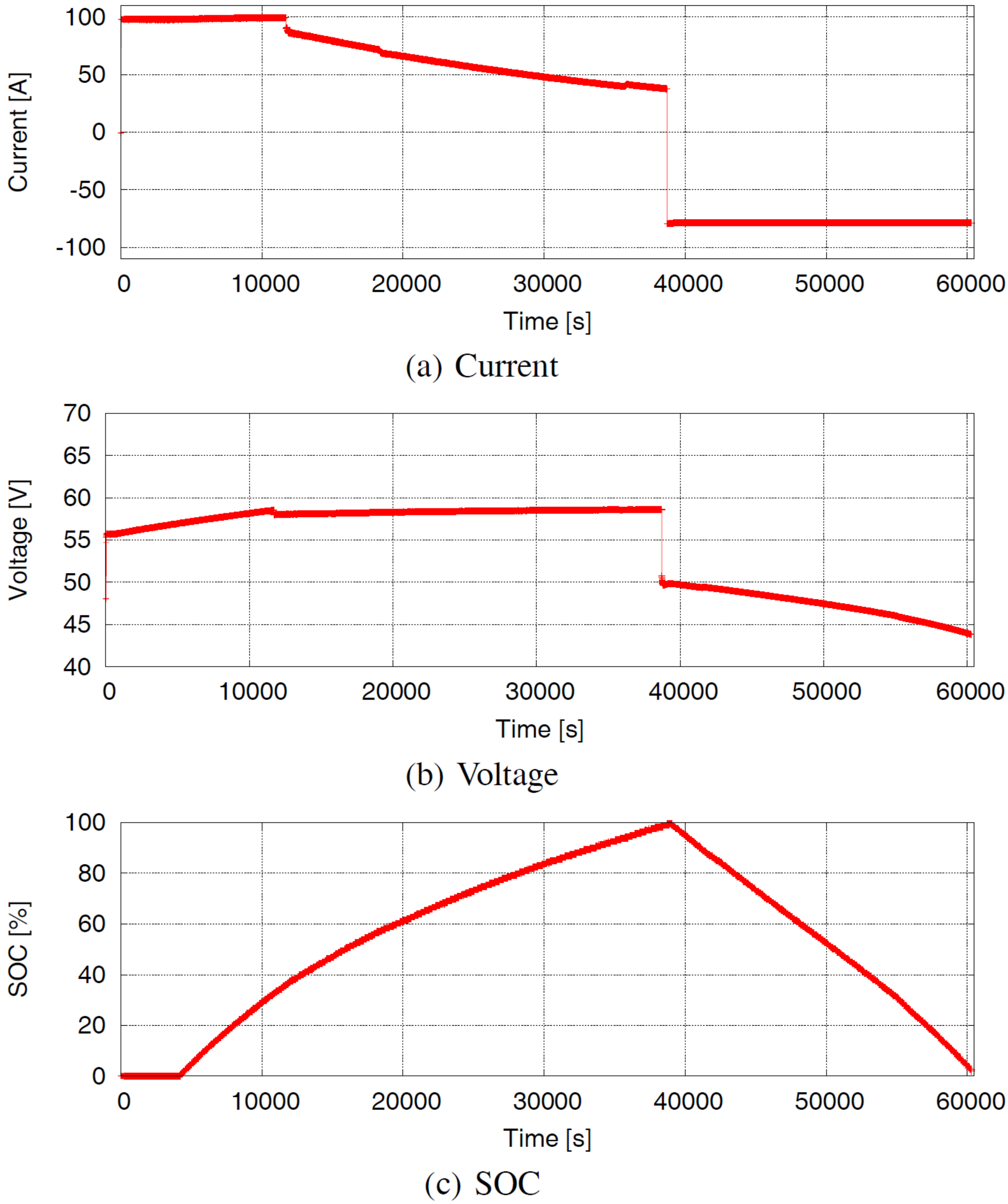


Fig. 11. Typical VRB charging sequence (Test #51).

Charge and Discharge Parameters for Test #50

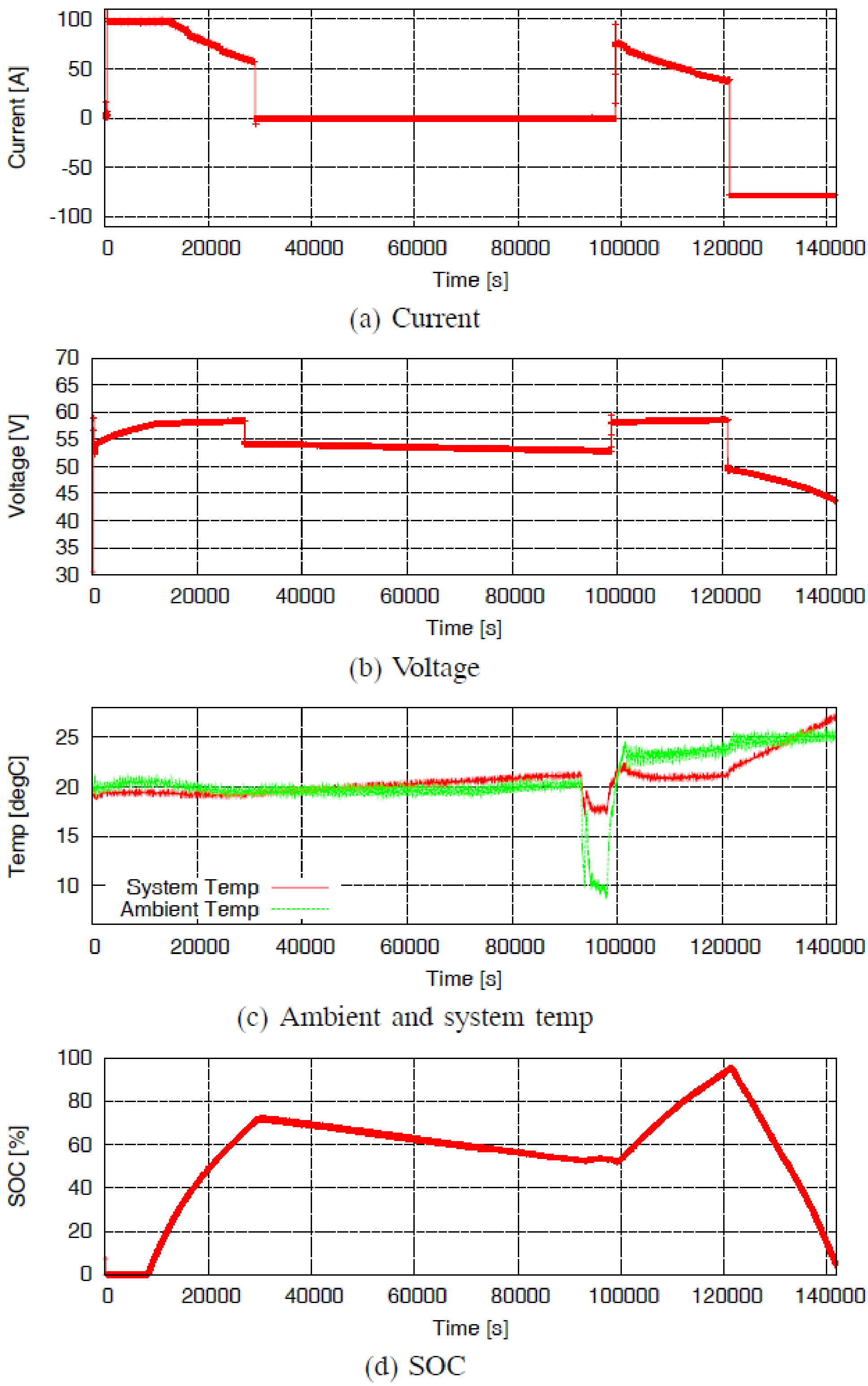
Fig. 12 shows results for test no. 50 conducted for about 40 hours continuously (between 3/24/2011 10:06:53 and 3/26/2011 01:27:21). The battery was on charge for about 8 hours, when it attained a peak voltage of 58.361 V. It was then left to discharge by feeding power back to the grid for another 19.4 hours, after which charging was resumed at the minimum set value for the state of charge (SOC) at 52% – this was arbitrarily set to monitor other parameters. It can be observed that under normal conditions the battery operates as per the specifications detailed in Table II.

A Note on Ambient and System Temperatures: Suitability for Cold Climate Operation

Fig. 12(c) shows the progression in the system temperature over the duration the operation. The experiments are carried out in a controlled facility, thus there is little deviation in the ambient temperature. It is seen that, as expected, the system temperature tends to rise with time, but more so with each successive discharge of the battery. The system has a self-regulatory power conditioning system that stabilizes this situation to ensure the limits of electrolyte operating temperature are respected.

By Arrhenius Law, the rate at which the chemical reaction proceeds increases exponentially as temperature rises, allowing more instantaneous power to be extracted from the battery — higher temperatures improve ion mobility reducing the cell's internal impedance and increasing its capacity. However, thermal management is necessary so that both charge capacity and cycle life can be optimized since high temperatures may also initiate irreversible chemical reactions that can cause permanent damage or complete failure of the battery.

Typically, the temperature of the electrolyte is managed internally by the VRB-ESS. There are two issues worth mention: at high temperatures (say above 40 degC which is NOT an Alaskan concern) and at low temperatures say below 10 degC which is an Alaskan concern. At low temperatures the electrolyte must be warmed, and this is accomplished automatically if the system is operating (cycling). The reason for this is not so much a case of freezing since the electrolyte does not freeze until below about -20 degC, but is more a case of viscosity. It is hard to pump the thicker electrolyte given the pump designs in use. Generally the capacity of the system is not affected by the cold. If it is extremely cold then the system has to be designed for it. Similarly, in very hot climates the system must be so designed as to cool the electrolyte to below 40 degC (105 degF).



(a) Current

(b) Voltage

(c) Ambient and system temp

(d) SOC

Fig. 12. Charge/discharge for the battery (Test #50).

Charge and Discharge Parameters for Tests #51 – #54

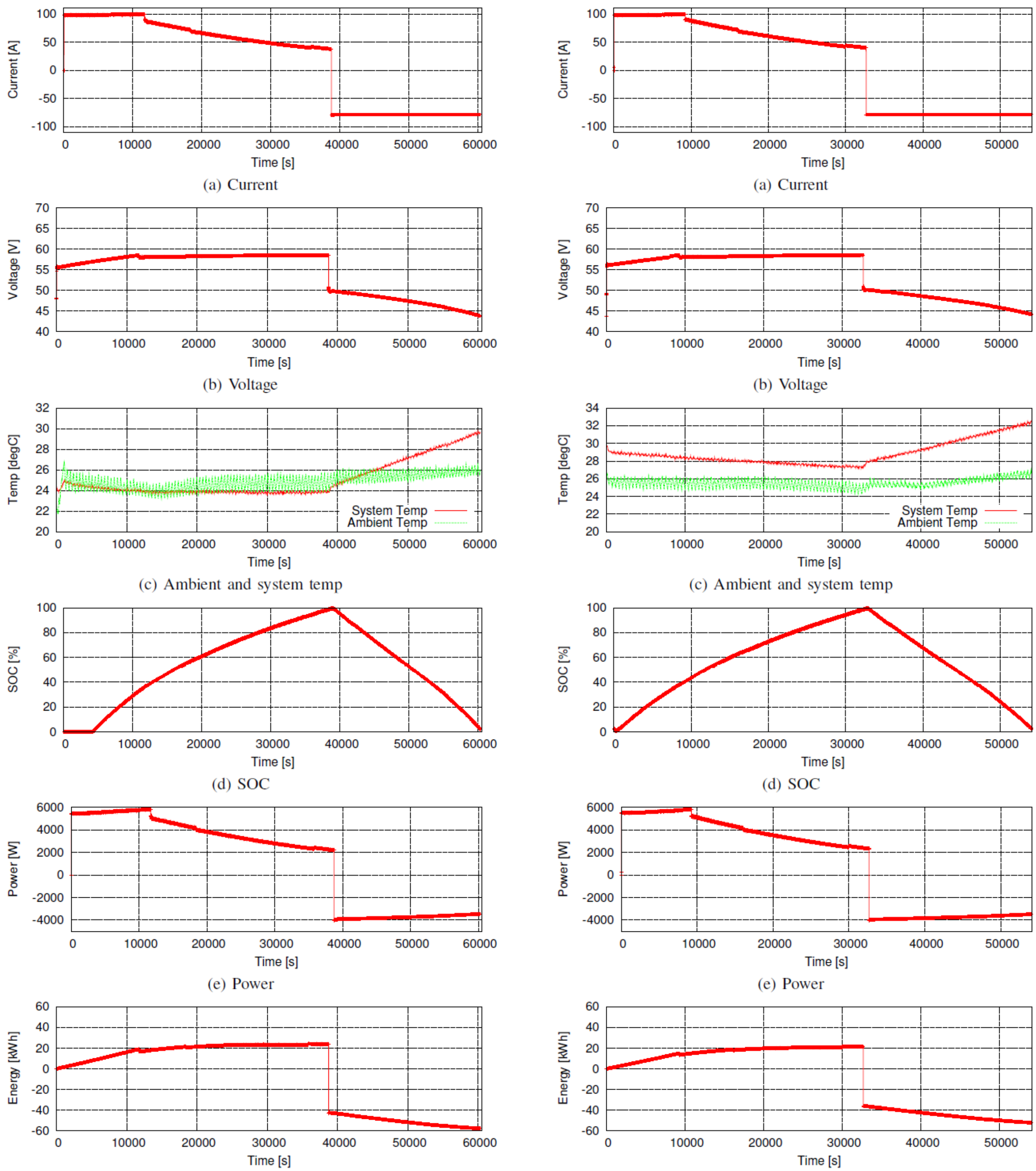
Generally the flow battery has been performing well since its commissioning. Figs. 13 and 14 show the charge and discharge sequence for four consecutive cycles (controlled settings that have the battery charging for 10 hours and then discharging on attainment of TOC). These results are just a synopsis of a few trial runs but are representative of the capability of the technology to charge and discharge appropriately when integrated with a power system. Other results are included in the Appendix to this report[1].

The figures show, consecutively, the variation in current, voltage, ambient & system temperatures, state of charge, power and energy storage for each cycle. A battery "cycle" is one complete discharge and recharge cycle, typically considered to be discharging from 100% to 20%, and then back to 100%. However, the operator has the ability to vary the charge/discharge cycles based on either voltage or SOC levels (and hence the depth of discharge (DOD)). The charge controller (Xantrex type) is the regulator that goes between the grid network and the battery and serves to keep the battery charged at peak without overcharging.

The electrochemical performance of the battery stacks is of special interest — after an initial break-in period, the cycling of the system is very repeatable, with only minor differences noted in the electrical performance over a period longer than 48 hrs. Since performance also varies with ambient temperature, these differences may be overlooked; however, it is important to realize that each individual stack is unique and can degrade to the point where the system is no longer successfully taking a charge. Deep cycling is not performed in this cycle run, thus keeping temperatures low.

The various results show that when linked to the grid, the battery operates within specified limits in Table I, and more importantly, seamlessly draws power from, and discharges back to the network at the right frequency and with minimal losses.
The essence of the performance testing is to verify that aside from large installations that require storage (load shifting), cascaded use of this battery technology may be implemented. This involves utilizing the flow battery for more than one application, e.g., UPS, electric vehicle charging, laptop charging station, and efficient energy storage at minutes to hours duration to firm ramping balance.

[1] Note that a scan through all power levels from (-5kW to 5kW with reasonable step intervals) at different SOCs (from 0% to 100% with, e.g., 5% steps) is still being carried out in order to evaluate the battery performance and degradation over time. This requires more months (yrs?) and is not considered here.



(a) Current (a) Current

(b) Voltage (b) Voltage

(c) Ambient and system temp (c) Ambient and system temp

(d) SOC (d) SOC

(e) Power (e) Power

(f) Energy (f) Energy

Fig. 13. Charge/discharge for the battery (Tests #51 and #52 respectively).

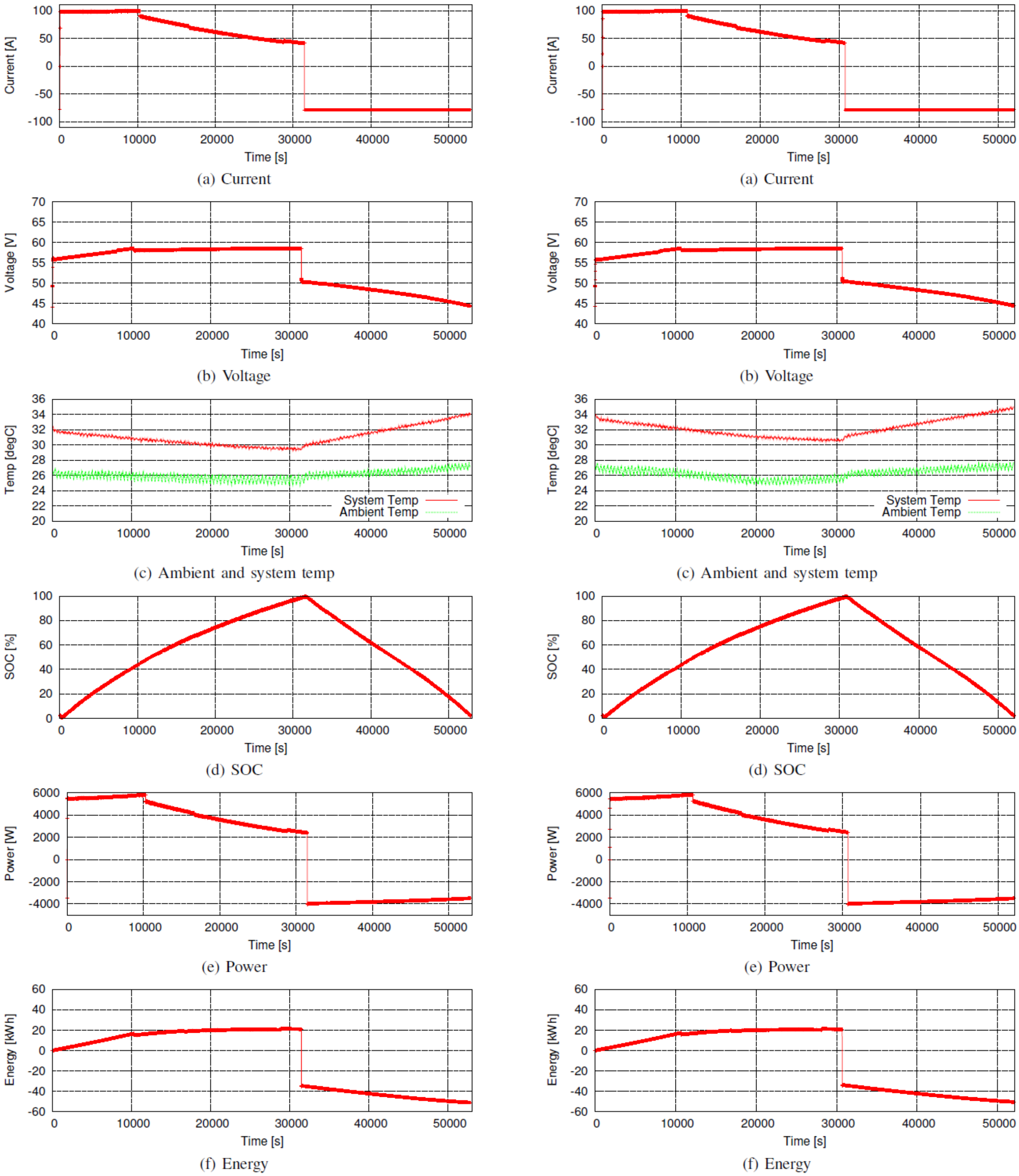


Fig. 14. Charge/discharge for the battery (Tests #53 and #54).

Efficiency

The performance testing showed that the efficiency of the battery was over 70% on a DC in DC out basis, a figure that sits well with the spec sheet values. The efficiency plots are in the Appendix. Efficiency is based on the total DC energy put into the battery versus the useful energy released on discharge in kW-hrs.

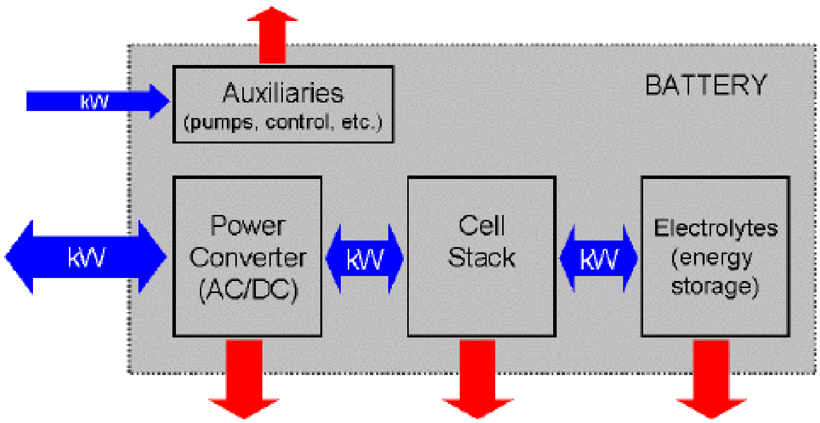


Fig. 15. Schematic of the battery system. The red arrows indicate losses from the different parts of the system.

As with all storage technologies, every charge/discharge cycle results in some loss of energy due to system inefficiencies. For stand-alone or typical grid-connected applications, this means that from a global perspective, several losses must be accounted for in characterizing the VRB performance:

- Power Conversion System (PCS) losses: Whether charging or discharging, power flow through the PCS is subject to losses related to voltage drops across the switching devices. PCS throughput efficiency depends somewhat on load and PCS design, but is typically about 95%.
- Battery DC losses: Actual DC losses depend on rate of charge and discharge. Internal battery losses include voltaic losses such as ionic flow resistance and coulombic losses such as cell-to-cell shunt currents. The energy to charge the battery is typically 20% greater than the energy delivered during discharge for a full power rated discharge interval.
- Transformer losses: To connect to utility distribution voltages, a transformer must be installed resulting in losses of a few percent.
- Pumping losses: Pumping power is an auxiliary load that is drawn whenever electrolyte must be supplied to the stacks. The actual efficiency penalty for pumping depends upon the frequency of cycling and the pump design.

Features and Advantages of the VRB

Most of the advantages of the vanadium battery are due to the use of the same element in both half-cells which avoids problems of cross-contamination of the two half-cell electrolytes during long-term use. This means that the electrolytes have an indefinite life so that waste disposal issues are minimized.
Other advantages of the VRB include:

- Cost – they have low cost for large storage capacities. Cost per kWh decreases as energy storage capacity increases, typical projected battery costs for 8 or more hours of storage being as low as US$150 per kWh (EPRI statistics).
- Easily upgradeable – existing systems can be readily upgraded and additional storage capacity can be easily installed by changing the tanks and volumes of electrolyte.
- Energy and power sizing is independent
- Scalable for large applications
- High energy and power density
- Long cycle life (more than 10,000 charge/discharge cycles)
- Easy maintenance. Also, can be both electrically recharged and mechanically refueled, and can be fully discharged without harm to the battery
- All cells fed with same solutions and therefore are at the same state-of-charge
- High energy efficiencies (projected to range between 80 and 90% in large installations)
- Capacity and state-of-charge of the system can be easily monitored by employing an open-circuit cell
- Negligible hydrogen evolution during charging
- High temperature performance – can be used during severe Alaska winters.

Disadvantages

- Relatively early-stage technology
- Relatively expensive
- Relatively large footprint/occupied area – limited opportunities for standard sizes.

Major Applications

- Peak shaving for &TD upgrade deferral
- Small load leveling applications
- Backup power applications.

Perspectives

BATTERY CHARGE AND DISCHARGE CHARACTERISTICS

In the present project a vanadium battery of 5kW/20kWh has been installed and tested at ACEP, UAF. The project had the objectives to get hands-on experience with the technology, characterize it from a power system perspective and assess the potential applicability of the technology in an Alaska wind power integration context.

The presentation extends from a prior "procurement experiment" with a 10 kW VRB system to ACEP's forward looking vision on relevance of fast-acting storage to emerging applications such as integration of renewable energy resources, and implementation of Smart Grid concepts. It is anticipated that the flow battery will be integrated with the wind turbine simulator for extended evaluation of performance and capability[1].

The performance testing results on the VRB-ESS provide a very seductive argument in favor of flow batteries as viable options for energy storage in power systems in Alaska. The keyword is scalability. For the same power, flow batteries are typically dimensioned to store five times the energy stored in conventional battery storage systems[2].

EFFICIENCY AND LIFE-CYCLE

Efficiency and cycle life are two important parameters to consider along with other parameters before selecting a storage technology. Both of these parameters affect the overall storage cost: low efficiency increases the effective energy cost as only a fraction of the stored energy can be utilized, while low cycle life also increases the total cost as the storage device needs to be replaced more often. The present values of these expenses need to be considered along with the capital cost and operating expenses to obtain a better picture of the total ownership cost for a storage technology.

[1] ACEP is in the process of establishing a test bed system that can physically simulate the coupling between the wind turbine, diesel systems, and energy storage with small micro-grids found in rural Alaska. In the long run ACEP will integrate the battery with the wind turbine simulator (WTS) with generator sets to analyze:

a) Frequency stabilization (ms to seconds); and

b) Load shifting (minutes to hours).

This will serve to verify ability of flow battery to perform ancillary services in wind-diesel systems.

[2] The same facts presented in a slightly different way can lead to exactly the opposite conclusion. For the same storage capacity, conventional cells will provide five times the power of flow batteries and in addition they have no moving parts or energy consuming pumps.

COST CONSIDERATIONS

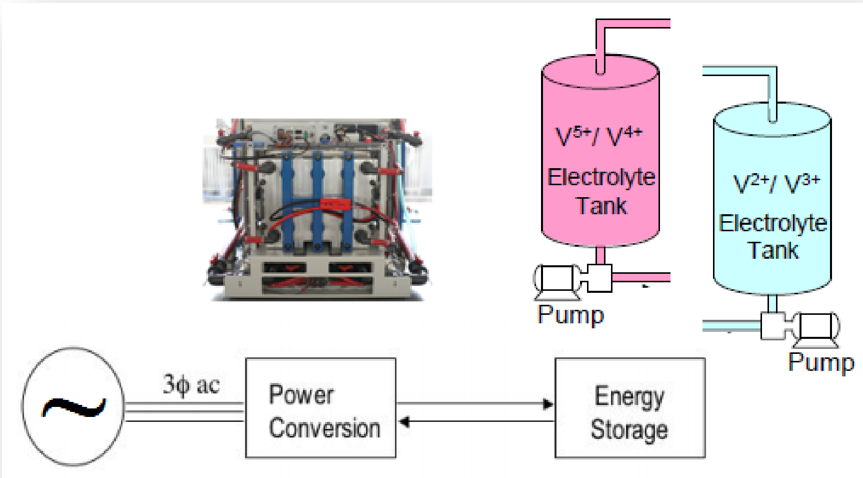


Fig. 16. Major cost components of the energy storage system: the power conversion unit ($/kW), and the storage unit ($/kWh). The BOP is typically costed with the storage unit.

Cost is calculated for a system by adding the cost of the storage unit and the power conditioning system. These subsystems are treated separately because they provide different functions and are priced by different ratings. Power components are priced in $/kW. Energy storage units are priced in $/kWh. For this reason, the individual subsystem costs are needed, although they are often difficult to separate from vendor system prices.

It's hard to sort out the cost of electricity stored by flow batteries, because there are too many variables. Nonetheless, indications are favorable. For the particular 20 kWhVRB system under consideration, based on a formulation by Witmer[3], providing electricity using the battery, assuming 10,000 charge–discharge cycles, should cost 29 U.S. cents per kilowatt-hour—the more cycles, though, the lower the cost per kilowatt-hour.

This rudimentary economic analysis indicates that the battery is not adequate to justify use of these batteries in larger communities based simply on displacement of diesel fuel at current costs (around 16 to 17 cents per kWh). However, a battery used in conjunction with a wind turbine to stabilize delivered power (to provide spinning reserve in times of variable wind speed) may provide a higher economic return – this is the basis of the next phase of research: integrating the VRB with the hybrid wind-diesel test bed.

[3] Dennis Witmer, Presentation at the International Wind-Diesel Workshop

In general, present worth is based on ownership of the device over 10 years for a given application and includes the following factors:

- Efficiency
- Cycle Life
- Initial Capital Costs
- Operations and Maintenance
- Storage-device Replacement.

Thus the present worth (or present value) calculation includes not only capital cost, but operating costs as well. The most important characteristics include round-trip electrical energy efficiency (kWh out/kWh in) and cycle life. Because cycle life (or number of discharges before replacement is required) is an important cost driver, the use of the system, as defined by the planned application, must be considered.
The costs in Table III are based on certain standard assumptions for the applications and technologies considered, and on expert opinion. They are meant to be used for comparative purposes. The actual costs of any storage system depend on many factors and the assumptions and means of calculating some of the values used are subjective.

Table III: Cost and performance assumptions[4]

Technology	Cost		Round-trip Efficiency %	Cycles
	Power Subsystem $/kW	Energy Storage Subsystem $/kWh		
Advanced Lead-acid Batteries (2000 cycle life)	400	330	80	2000
Sodium/sulfur Batteries	350	350	75	3000
Lead-acid Batteries (w/Carbon-enhanced electrodes)	400	330	75	20000
Zinc/bromine Batteries	400	400	70	3000
Vanadium Redox Batteries	400	600	65	5000
Lithium-ion Batteries (large)	400	600	85	4000
CAES	700	5	N/A (70)	25000
Pumped hydro	1200	75	85	25000
Flywheels (high speed composite)	600	1600	95	25000
Supercapacitors	500	10000	95	25000

Based on the expected life time costs, the VRB-ESS offers an attractive solution with both economic and technical benefits for an installation in Alaska, in the form of peak shaving/load balancing, where spikes of demand are met by the battery; stand-alone off-grid power system that could meet remote area energy requirements; and back-up power solution to protect sensitive systems.

[4] SANDIA Report: Energy Storage Systems Cost Update – A Study for the DOE Energy Storage Systems Program, SAND2011-2730, April 2011.

APPLICATIONS OF THE TECHNOLOGY

Electricity storage devices serve various roles in a distributed power system, ranging from improving the overall operation of the system to directly mitigating the impact of a particular installation of renewable energy. With specific regard to wind power in Alaska, this technology can find application in these areas:

- Transmission curtailment – limiting output from wind power plant combined with storage to transmission capacity
- Time-shifting – shifting wind power from off peak hours to peak hours
- Grid-frequency support – provision of spinning reserve in case of large event(s)
- Fluctuation suppression – output smoothing from wind farm
- Forecast hedge – mitigating forecast errors.

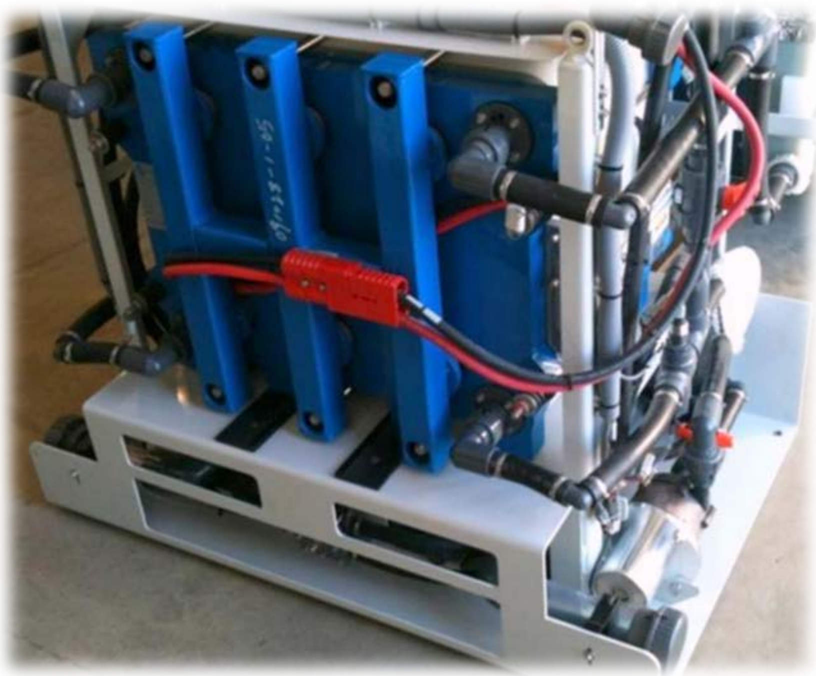
Other general areas of application include[5]:

- Grid stabilization
    - Angular stability – mitigation of frequency oscillations in the range of a few seconds
    - Voltage stability – provision of voltage support by injecting both active and reactive power
    - Frequency excursion suppression – frequency support by droop control
- Grid operational support
    - Regulation control – frequency regulation in concert with load following in the 10 minute range
    - Conventional spinning reserve – reserve power for at least 2hour duration
- Distribution
    - Short duration power quality – voltage distortion mitigation
    - Long duration power quality – voltage distortion mitigation combined with several hours of reserve power
- Load-shifting
    - Short duration load shifting – 3 hour load shift
    - Long duration load shifting – 10 hours load shift

The battery has not shown signs of degradation in performance during the testing period, and its response time is fast enough to deliver the ancillary services including frequency support for a power system (it is only limited by the power electronics). From a renewable energy perspective the VRB technology has potential to be a part of future power systems in Alaska provided the technology is further matured and competitive with other potential technologies offering similar service to the grid.

[5] EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington, DC: 2004. 1008703.

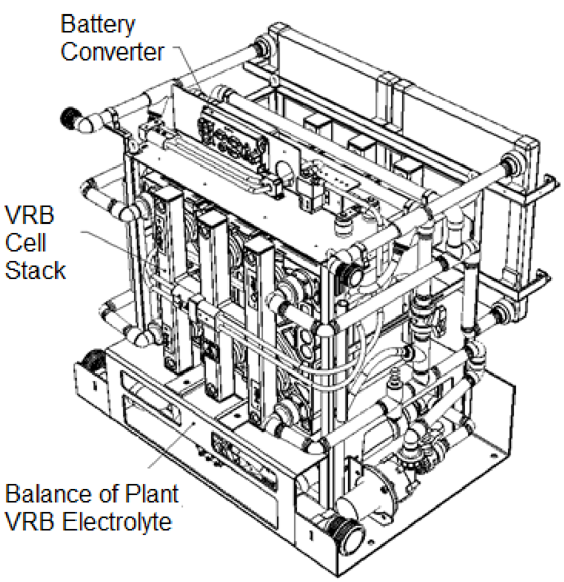
Appendix



The following pages give specs and other details pertaining to the VRB.

SYSTEM OVERVIEW

Product Definition



VRB power module major components

The VRB-ESS is an electrical energy storage system whose functional capabilities are generally analogous to a conventional battery, and incorporates all required structures, fluid systems, sensors, and controls. The VRB-ESS also incorporates controls to prevent damage to the system as a result of improper operation.

The VRB-ESS is designed as a component for integration into end-user energy management systems.

The functional components comprising the VRB-ESS include:

- Power module
- Process module, and
- Storage module.

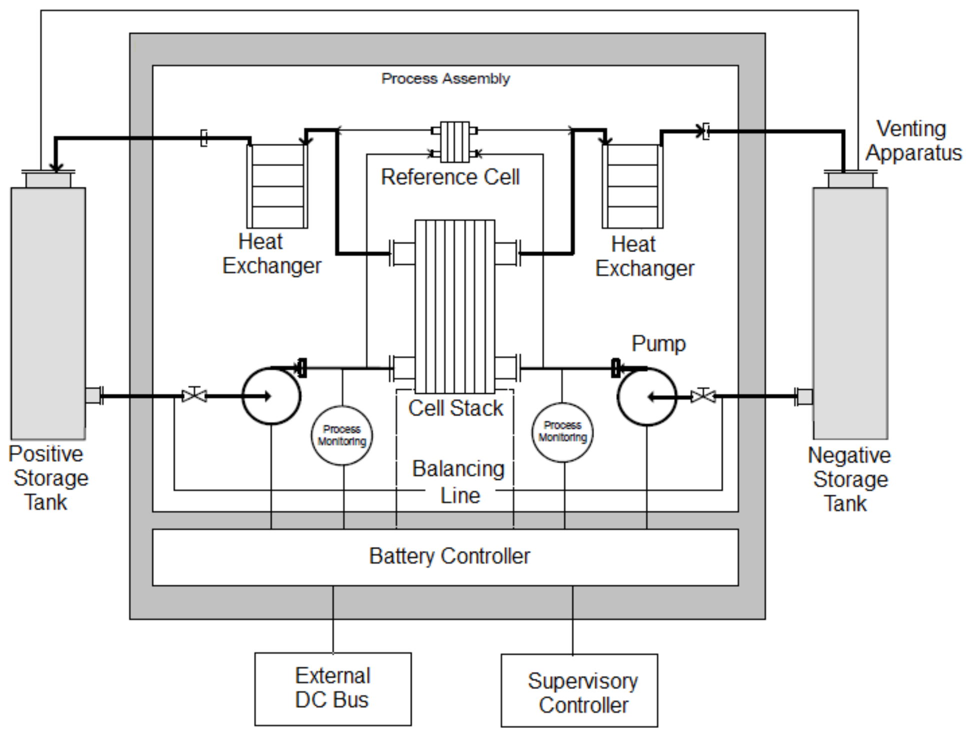
Power module – comprises an electrolyte-primed cell stack and process module. Alone the power module cannot deliver power to the end user without appropriate volumes of electrolyte.

Process module – this is the electromechanical interface that connects physical, electrical power, and electrical data signals between the VRB-ESS and the end user. It includes the balance of plant and battery controller but without the cell stack installed.

Storage module – determines the electrical capacity. It comprises two electrolyte storage tanks and plumbing connecting to the VRB-ESS.

The power rating of 5kW is determined by the installed VRB cell stack. The load capacity is determined by the total volume of electrolyte – the Prudent Energy VRB-ESS product is rated for 20kWh.

Components and Related Handling



Schematic of VRB operation (Courtesy: Prudent Energy).

The figure depicts the essential components and working principle of the VRB-ESS. The main systems are: the power module comprising the cell stack, the electrolyte, and the BOP elements.

1. *VRB-ESS Cell Stack (Power Module)*

The cell stack is the component in which electro-chemical reactions take place allowing the VRB-ESS to store and deliver electrical energy. The cell stack is installed into the balance of plant frame using fasteners that are electrically isolated from metal-to-metal contact. The front end plate of the cell stack is secured rigidly into place while the rear end plate is secured only from translation in the vertical direction.

2. *Balance of Plant (BOP)*

The BOP is the major process handling and electrical interface to the VRB-ESS and incorporates these functional components: pumps and pump motors, valves (manually operated), fluid pressure and temperature sensors, reference cell, electrolyte-to-air heat exchanger, fluid circuit, including all pipes, hoses, and external connections, and the battery control module.

Electrical Control Module

The electrical control module contains two groups of components: the battery controller and the sensors, and electrical hardware required to control the battery operation. The module consists of the following: DC bus contactor, DC current transducer, DC mains connections, ambient temperature sensor, internal DC bus (battery controller side of contactor), external DC bus (system connector side of contactor), system ground bus, power connector, and cell stack connector.

Battery Controller/Data and Control Interfaces

The battery controller is a microprocessor-based controller that controls, monitors, and ensures the safe operation of the VRB-ESS. The controller also provides a communication interface that allows:

- Information to be passed to external systems to ensure proper charge control;
- The VRB-ESS to be charged and discharged appropriately; and
- External systems to monitor the operation.

Data and control interfaces for data and control signals are made to the VRB-ESS at the battery controller quick-disconnect plugs (see figure below).

Battery controller interfaces (Courtesy: Prudent Energy).

Data transmission is based on SMA Net communication protocol that is binary, master/slave, and the messages transmitted are frame based (9600 Baud Rate, 8 Data Bits, No Parity, 1 Stop Bit). The Command and Data Messages are the two message frames transmitted: the Command Message is a request to receive data from the auxiliary equipment by the Battery Controller, and the Data Message is the response of transmitting data to the auxiliary equipment. The battery controller connectors service both onboard components of the battery and outside connections to the auxiliary system. The Battery Controller has 32 predefined addresses, 20 in hexadecimal, and a transfer mask is used to communicate which data channels shall be transmitted.

3. ***VRB-ESS Electrolyte***

The VRB-ESS uses electrolyte to accept, store, and release electrical energy. It is composed of a solution of dilute sulfuric acid with dissolved vanadium species. While the positive and negative electrolytes are initially identical, as the VRB-ESS charges, the two electrolytes take on significantly different properties. Because the electrolyte is, at certain states of charge, a powerful oxidizing or reducing agent, many materials typically used with corrosive fluids cannot be used with the VRB-ESS.

Electrolyte Handling

- Care must be taken in the on-site assembly of all external process components to minimize the possibility of leaks.
- The electrolyte is corrosive so operating personnel must wear appropriate personal protective equipment.
- Due to the corrosive nature of the electrolyte, all components used in external fluid handling circuits, including external tanks, must be compatible with the electrolyte.
- Conductivity – the VRB-ESS electrolyte is electrically conductive, and a significant shock hazard can exist when the electrolyte forms a conductive path between charged equipment and either personnel or grounded equipment. Also, process sensors that incorporate electrically conductive components may be affected, as the electrolyte may impart an electric potential on the sensors.

Spill Containment

While the VRB-ESS is designed to minimize the possibility of electrolyte leaks, it is possible that leaks can occur either by system failure or by an external event. In the unlikely case of a major leak, a means of containing spilled electrolyte is required. The product contains design features to limit the amount of electrolyte that will seep from the system if severely damaged, but it is possible that a large volume of electrolyte may escape. Therefore, the *volume of the containment means must equal or exceed the volume of electrolyte contained within the VRB-ESS* (or within any single VRB-ESS in an installation that includes multiple independent systems).

In designing the containment means, care must be taken to ensure that other fluids, such as rain water and fire sprinkler discharge, do not leak into the containment area and reduce its capacity. If a means of draining the containment area is provided, the drain must include redundant seals to prevent leaking, and the drain and seals must be checked regularly to ensure proper operation.

Cost Calculations

This section of the report contains a description of the life-cycle cost analysis as relates to energy storage systems in a power installation, or other domestic/commercial use. This results in the in the present worth of costs (capital and operating) for 10-year operation. (Note that the term "life-cycle" sometimes refers to an analysis that includes the eventual disposal of the spent capital equipment, and the disposal component is not included in the analysis).

Cost Methodology

Energy storage system components are shown in Figure 1.

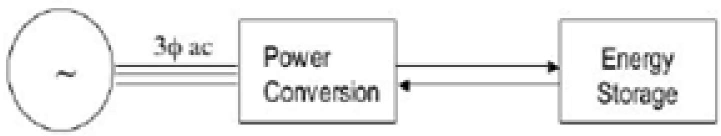


Figure 1. Major cost components of the energy storage system are the storage unit ($/kWh) and the power conversion unit ($/kW). The balance of plant is typically costed with the storage unit.

Capital Cost

The capital cost calculation, in its simplest form is—

$$\mathrm{Cost}_{total}\ (\$) = \mathrm{Cost}_{pcs}\ (\$) + \mathrm{Cost}_{storage}\ (\$) \tag{1}$$

The cost of the power conversion equipment is proportional to the power rating of the system:

$$\mathrm{Cost}_{pcs}\ (\$) = \mathrm{UnitCost}_{pcs}\ (\$/\mathrm{kW}) \times \mathrm{P}\ (\mathrm{kW}) \tag{2}$$

For most systems, the cost of the storage unit is proportional to the amount of energy stored—

$$\mathrm{Cost}_{storage}\ (\$) = \mathrm{UnitCost}_{storage}\ (\$/\mathrm{kWh}) \times \mathrm{E}\ (\mathrm{kWh}) \tag{3}$$

where E is the stored energy capacity.

In the simplest case, E is equal to $P \times t$, where P is Power and t is the discharge or storage time.

All systems have some inefficiency. To account for this, Equation 3 is modified as follows—

$$\mathrm{Cost}_{storage}\ (\$) = \mathrm{UnitCost}_{storage}\ (\$/\mathrm{kWh}) \times (\mathrm{E}\ (\mathrm{kWh}) / \eta) \tag{4}$$

where η is the efficiency.

Prudent Energy
VRB™ Systems

VRB™ Battery System Specifications

Note: Battery System performance specifications are based on preliminary testing; actual measured values may vary.

Performance Characteristics	
Open circuit voltage at 0% and 100% capacity	50 VDC to 56 VDC
Maximum charge voltage (at battery terminals)	58.9 VDC
Minimum voltage on discharge	42 VDC
Maximum charge current	140 ADC
Maximum discharge current (continuous)	140 ADC
Maximum discharge current (< 300 s)	175 ADC
Continuous power at beginning of discharge	7.0 kW
Continuous power at end of discharge	5.25 kW
Duty cycle	100%
Physical Specifications (Approximate)	
Dimensions (D x W x H) (power module only) Dimensions (D x W x H) (with 40 kWh storage)	1.0 m x 1.2 m x 1.1 m 1.3 m x 1.15 m x 1.90 m
Mass (power module) Mass (power module plus 40 kWh storage)	510 kg 5,300 kg
Operating Limits	
Electrolyte Temperature range	10°C to 35°C
Humidity	0% to 95%, non-condensing
Altitude range (no derating)	0 m to 3,000 m
Environmental Limits – Shipping and Storage (Class 2K3 in IEC 60721-3-2)	
Allowable temperature range	-25°C to 70°C
Humidity	0% to 95%, non-condensing
Altitude range	0 m to 3,000 m
Reliability and Design Life	
Cycle life	> 10,000 cycles
Service life	100,000 hours

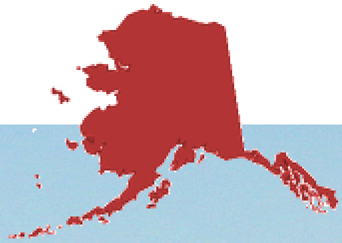
Maintenance Intervals	**Frequency**	**Offline Duration**
Maintenance interval “A”	9,000 hours	< 2 hours
Maintenance interval “B”	27,000 hours	< 8 hours
Service life	90,000 hours	N/A

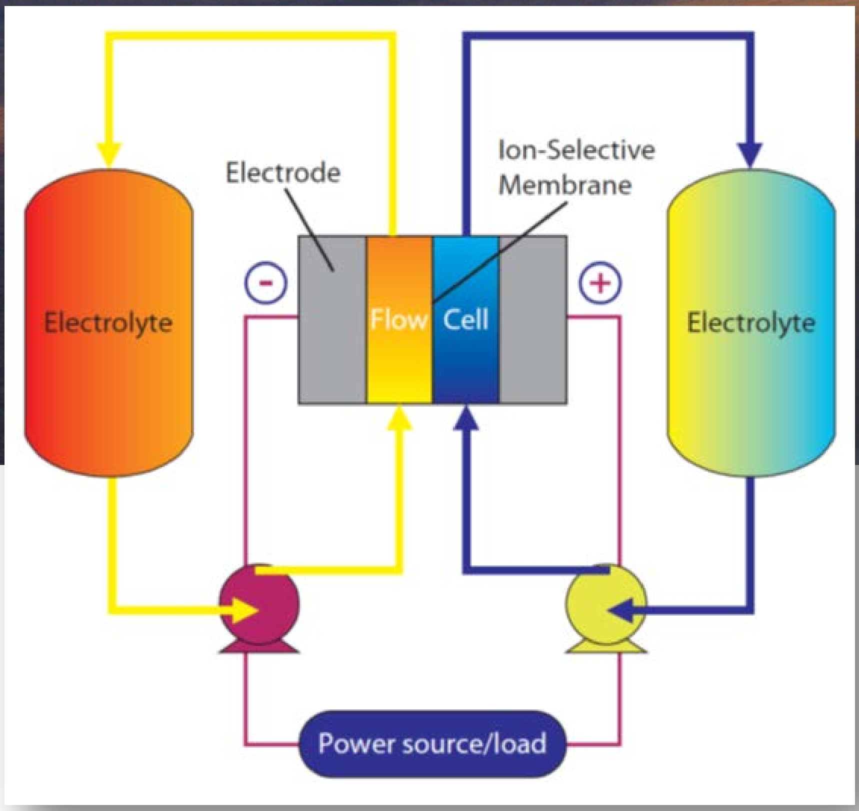
Back cover picture credits:

Background: Mt McKinley, Denali Park, Alaska, USA by Todd Paris

Insert: Flow battery schematic courtesy of Leonardo Energy (http://www.leonardo-energy.org)

ACEP ENERGY STORAGE RESEARCH





Advanced Battery Storage Systems Testing at ACEP

5 kW, 20 kWh PRUDENT ENERGY VRB-ESS

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