COMPARISON OF ENERGY STORAGE TECHNOLOGIES FOR ISOLATED COMMUNITY MICROGRID APPLICATIONS

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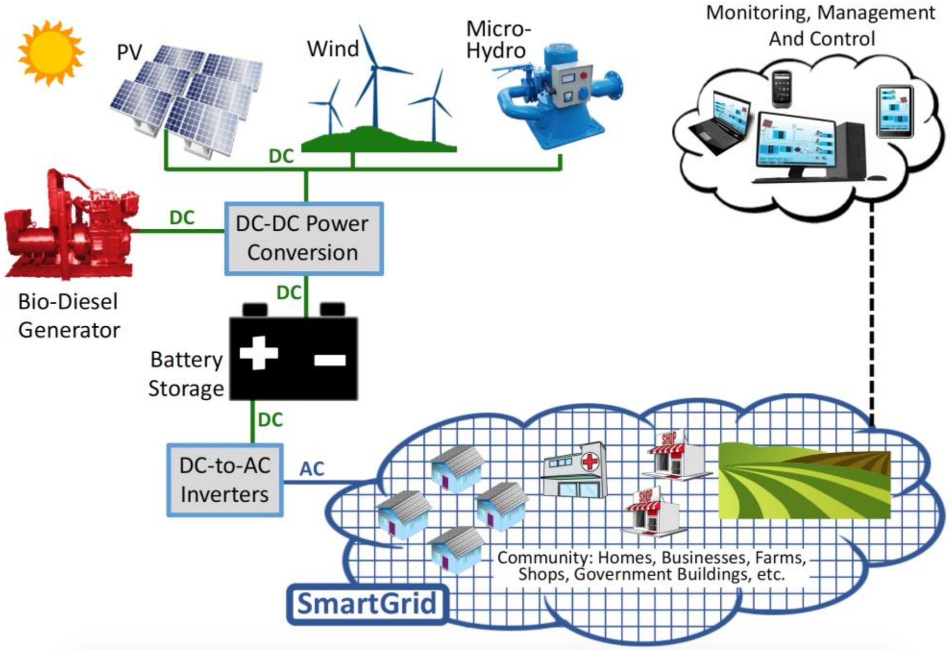
INTRODUCTION AND BACKGROUND

- International Energy Agency (IEA) - World Energy Outlook 2018
  - 2017 first year where < 1-billion people without electricity
  - Estimate by 2040, still > 700-million people worldwide without electricity
  - Many without electricity live in rural parts of the world
  - Access to reliable energy is crucial for rural inhabitants to improve quality of life
- Rural Electrification - Issues
  - Remote areas with low population density and low energy demand
  - High cost to build infrastructure - power lines to connect to main grid & maintenance
  - Transmission losses from long distance for power lines
- Local renewable energy production is a potential solution

RENEWABLE ENERGY FOR RURAL COMMUNITIES

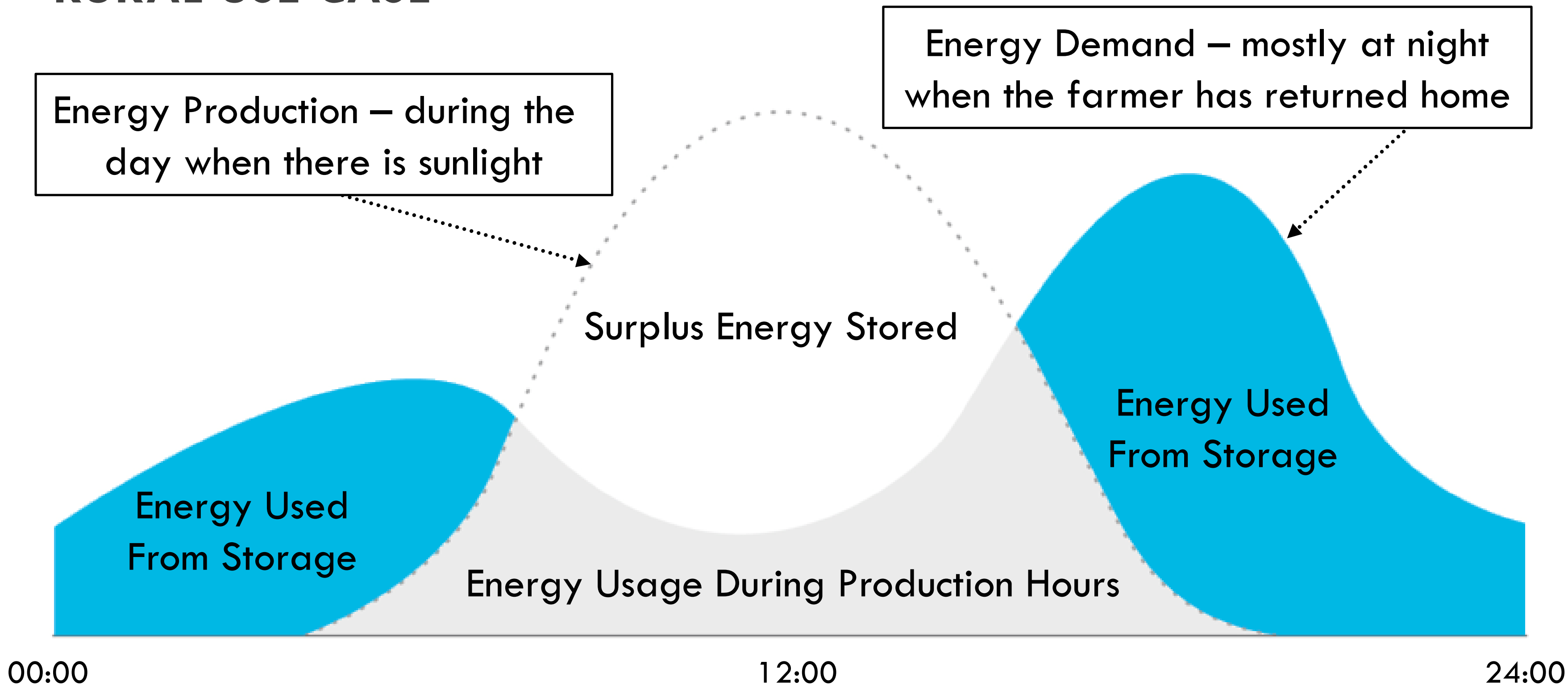
- Many poor rural areas have abundant solar power possibilities
  - Proven reliable and efficient source of electricity
  - PV price decreases – affordable
- Other sources also possible:
  - Wind
  - Hydro
  - Bio-diesel



Notional local community smart grid-based electrical system with renewable energy sources

Solar power from PV has proven to be an affordable, reliable source

SOLAR ENERGY PRODUCTION VERSUS DEMAND
RURAL USE CASE



- Non-alignment - power production & power consumption for a rural household
- Solvable with energy storage
  - Power generated and stored during the day
  - Power used from storage in the evening and night

FOCUS OF STUDY

- Conduct a comparison of four battery technologies as an energy storage system for a renewable energy-based community microgrid that is disconnected from the main power grid.

Liquid Electrolyte Lithium-Ion Battery

Vanadium Redox Flow Battery (VRFB)

Solid State Lithium-Ion Battery

Lead-Acid Battery

STUDY OBJECTIVES

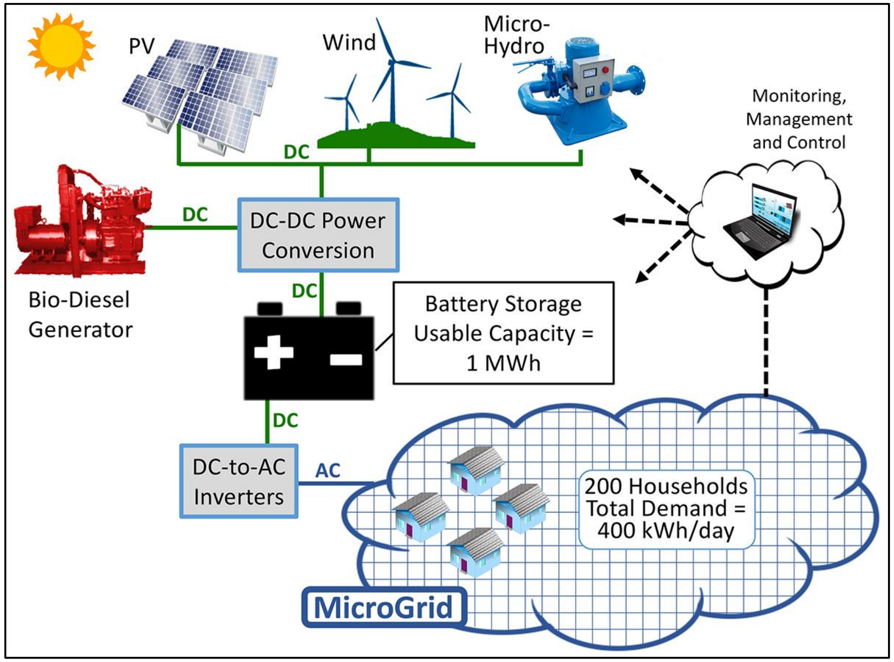
- 1. Provide an update on the current status of the four battery technologies
- 2. Analyze each battery technology for the following evaluation criteria, with respect to the stated energy storage scenario.
  - a. Energy density (gravimetric and volumetric)
  - b. Safety
  - c. Battery life (number of charge/discharge cycles)
  - d. Operating Temperature Range / Temperature Effects
  - e. Lifecycle cost (initial and post installation)
  - f. Maintenance complexity
- 3. Project the future trends for each technology.

DEFINE THE STUDY SCENARIO

- World Bank's Energy Sector Management Assistance Program (ESMAP) 5-tier framework
  - Tier 2: General lighting, TV, fan, phone charging
  - Tier 3: Tier 2 + medium-power appliances
- Using published studies, defined the energy demand scenario:
  - Isolated (no grid connection) village
  - 200 households at twice the ESMAP Tier 3 threshold
  - Household energy demand = 2.0 kWh/day
  - Village energy demand = 400 kWh/day
- Define energy storage requirement
  - Capacity = 1 MWh

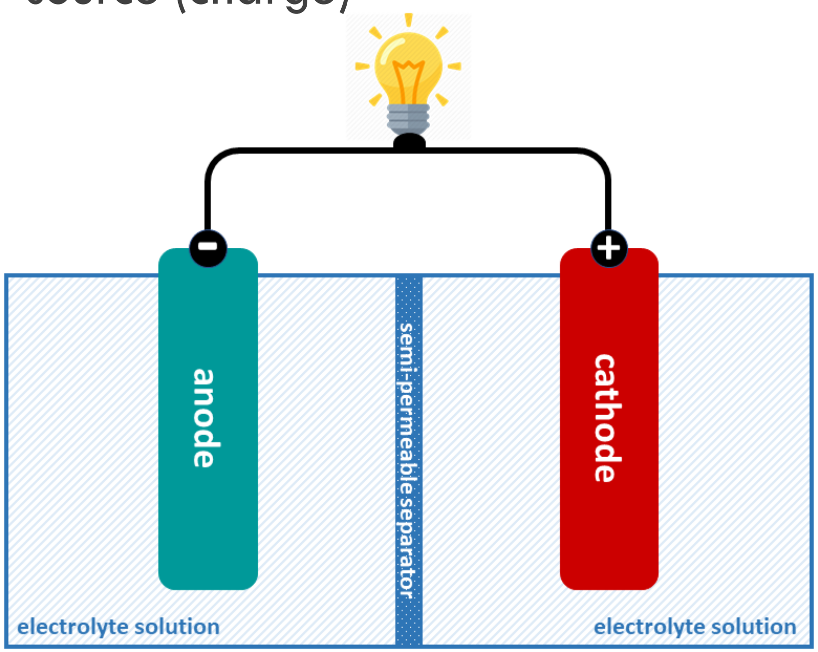
	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Annual consumption levels, in kWhs		≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption levels, in Whs		≥12	≥200	≥1,000	≥3,425	≥8,219

Source: World Bank (2015) – Beyond Connections: Energy Access Redefined, Technical Report 008/15



BATTERY BASICS – MAIN COMPONENTS

- Definition: A device which stores and produces energy by the conversion of chemical energy into electrical energy.
- Connects to an External Circuit with a load (discharge) or power source (charge)



- Two half reactions: Reduction and Oxidation – Redox Reaction
- Basic Components:
  - Anode: Negative Electrode
  - Cathode: Positive Electrode
  - Electrolyte – pathway for ions between the anode and cathode
  - Separator – semi permeable for ions to pass, but keeps anode / cathode separate

LIQUID ELECTROLYTE LITHIUM ION BATTERY (LIB)

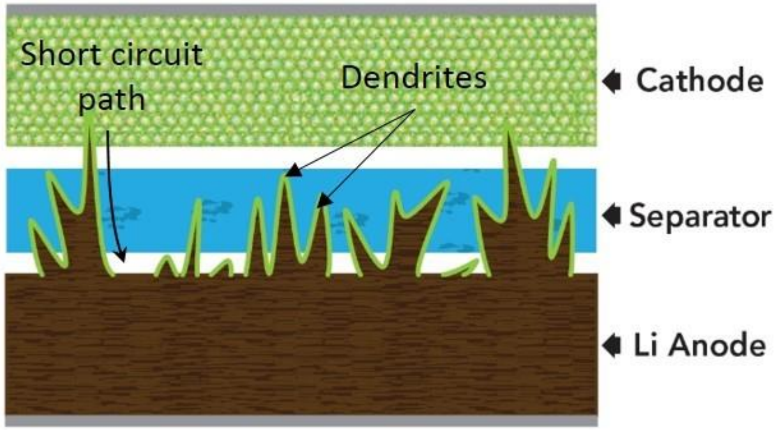
- Definition: a family of rechargeable (or secondary) devices where:
  - Both electrodes are intercalation materials
  - Electrolyte is a lithium salt dissolved in an organic solvent
- Primary components: anode, cathode, electrolyte, separator
- Typical Liquid Electrolyte LIB (e.g., in mobile phone and electric vehicles)
  - Liquid organic solvent electrolytes are most common - volatile
  - Lithium hexafluorophosphate ($LiPF_6$) salt dissolved in an organic carbonate solution
- Lithium ions:
  - Intercalate between anode and cathode during discharge
  - De-intercalate between anode and cathode during the charge cycle
  - Intercalation: the insertion and extraction of ions between the layers of the anode and cathode
  - Electrically insulative separator prevents short circuiting between the electrodes

LIQUID ELECTROLYTE LIB ADVANTAGES & DISADVANTAGES

- Advantages:
  - High energy density - Wh/kg and Wh/liter
  - No memory effect
  - Low self-discharge rate
  - Easy to form into different sizes/shapes - design flexibility
- Disadvantages:
  - Formation of Solid Electrolyte Interphase (SEI)
    - Passive layer of organic and inorganic electrolyte decomposition products
    - Forms over the surface of the anode during cycling
    - SEI formation results in eventual irreversible charge loss.
  - Volumetric expansion - damages electrodes and reduce battery life
  - Dendrite Formation: Can cause separator breech → short circuit → **Thermal Runaway**
  - **#1 liquid electrolyte LIB Disadvantage: Safety**

LIQUID ELECTROLYTE LIB – DENDRITE FORMATION

- Dendrites are metallic lithium deposits on the anode
- Material failures caused by dendrites – breech of separator leading to short circuit and thermal runaway
- Dendrite growth mechanisms are complex
  - inherent electrochemical instability of lithium metal
  - complex microstructural environment provided by organic liquid electrolytes
- Dendrite formation is much more prevalent on the more efficient lithium metal anodes



Source: SLAC National Accelerator Laboratory, Stanford University

- Solid State LIBs provide a solution to the dendrite issue
  - The inherent nature of the solid electrolyte physically blocks dendrite formation

LIQUID ELECTROLYTE LIB – SAFETY ISSUES

- Primary liquid electrolyte LIB disadvantage is safety
- Fires and explosions caused by **thermal runaway**
  - Initiates due to a failure in a LIB cell or cells
  - Failure propagates to surrounding cells causing a chain-reaction
  - Can lead to catastrophic battery failure
- Thermal Runaway associated temperatures, the following are representative:
  - Thermal runaway onset: 60°C to 100°C
  - Thermal runaway acceleration: 160°C to 170°C
  - Thermal runaway trigger: 170°C to 200°C
- Low thermal stability/flammability of liquid electrolytes is the primary disadvantage

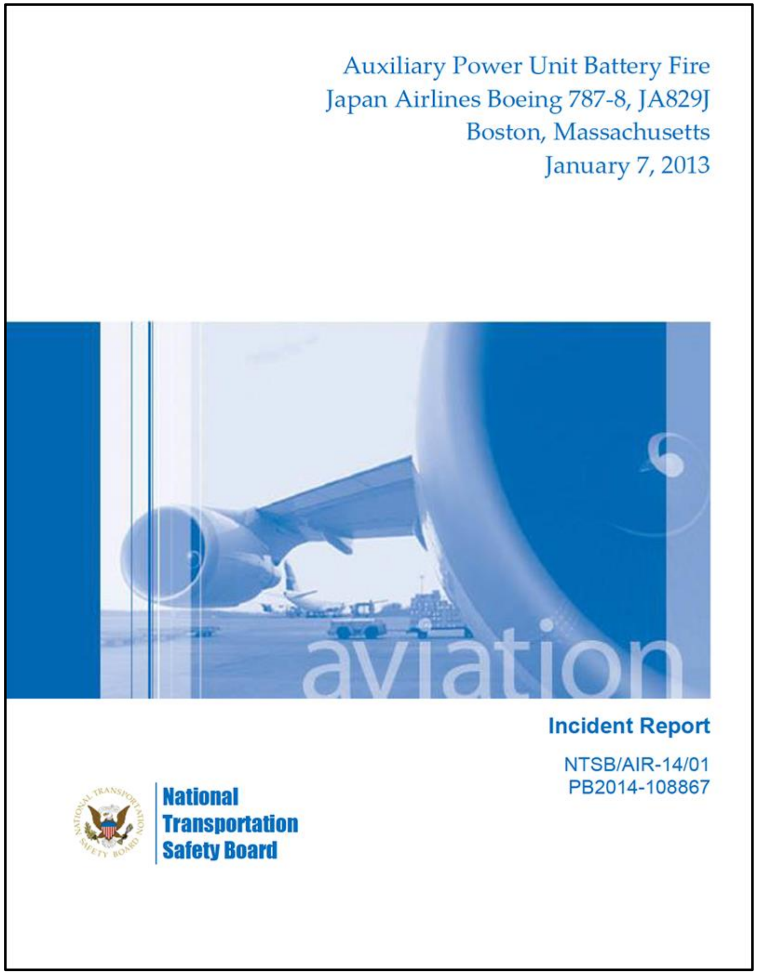
LIQUID ELECTROLYTE LIB – AIR SAFETY INCIDENTS

- January 2013:
  - Faulty LIB caused 2 fires on Boeing 787 Dreamliners, 1 week apart
  - U.S. National Transportation Safety Board grounded all Boeing 787s for over 3 months
- October 2014:
  - US FAA bans Samsung Galaxy Note 7 mobile phones from all flights in the U.S. due to explosions and fires caused by the LIB
- August 2019:
  - Apple MacBook Pro banned by FAA as checked baggage or carry-on
  - Apple admits the LIB "can overheat, potentially swelling or igniting"
  - Worldwide battery recall

LIQUID ELECTROLYTE LIB – AIR SAFETY INCIDENTS

- May 2019 US FAA report cited 258 air or airport incidents involving LIBs carried as cargo or baggage that have been since March 20, 1991
- NTSB's Aircraft Incident Report cited a long list of LIB safety issues:

  "cell internal short circuiting and the potential for thermal runaway of one or more battery cells, fire, explosion, and flammable electrolyte release; …[and] thermal management of large-format lithium-ion batteries."



LIQUID ELECTROLYTE LIB – SAFETY INCIDENTS

- Vehicle-related LIB incidents
  - Larger batteries → Greater damage
  - July 2019: LIB in a 3 month old 2019 Hyundai Kona Electric exploded in owner's garage in Montreal, Canada
  - Several Tesla cars have also recently had their LIBs explode
- May 2018: Florida man killed at home by an exploding e-cigarette
  - 18650 drop-in LIB malfunctioned and exploded
- 2017 George Mason Univ. study:
  - 2035 e-cigarette battery explosions between 2015-2017 in US resulting in injuries requiring a trip to hospital emergency room

APRIL 19, 2019: SURPRISE, ARIZONA LIB EXPLOSION

- Arizona Public Service (APS) Liquid Electrolyte LIB Storage Facility
  - Small 2-MW / 2-MWh grid scale energy storage system
  - Fluence (joint venture - AES Energy Storage and Siemens)
  - Installed in 2016 with safety systems
- Explosion and fire:
  - Due to thermal runaway of LIBs
  - Battery rack "melted itself all together" into a column of aluminum
  - Release of toxic and combustible gases which exploded, causing most of damage
  - 4 responding firefighters injured, 3 seriously with extended hospital stays

ARIZONA LIB FIRE RESULTS

- Affected cities in Arizona enacted new laws for LIBs in August 2019 (see letter)
  - Current battery facilities shut down
  - Permits, inspections, safety systems required
  - Letter quote: "lithium ion batteries – specifically those that will release hydrogen fluoride – are not prudent and create unacceptable risks."
- Issues in the US:
  - No US standard – varies city by city
  - Many cities have no rules – new tech
- Issues in developing world:
  - How will rules/laws be made and enforced?
  - How are installations safeguarded?
  - How is safety maintained?

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ARIZONA CORPORATION COMMISSION

August 2, 2019

RE: IN THE MATTER OF THE COMMISSION'S INQUIRY OF ARIZONA PUBLIC SERVICE BATTERY INCIDENT AT THE MCMICKEN ENERGY STORAGE FACILITY PURSUANT TO ARIZONA ADMINISTRATIVE CODE R14-2-101. (DOCKET NO. E-01345A-19-0076)

Dear Commissioners, Staff, and Interested Parties:

After reviewing the reports and pertinent Material Safety Data Sheets (MSDS) about the 2019 battery fire at the APS McMicken Energy Storage Facility in Surprise and the 2012 battery fire at the APS Elden Substation facility in Flagstaff, what has become apparent is that utility scale lithium ion batteries using the chemistries in those types of lithium ion batteries are not prudent and create unacceptable risks, particularly those with chemistries that include compounds that can release hydrogen fluoride in the event of a fire and/or explosion. Other utility scale battery technologies or those with chemistries that do not have an associated risk of a release of hydrogen fluoride should be utilized.

In the matter of the November 26, 2012 APS Elden Substation (Flagstaff) facility fire, the Root Cause Analysis also identifies a near miss in May 2012 when a battery cell was severely discharged and the cell was continuously charged against the intended design of the Lithium Ion Battery Energy Storage System. There were no changes to the facility's control logic to address the issues nor was an evaluation performed by Electrovaya, the designer and installer of the system. The event was not communicated to APS staff.

Also, the investigation determined inadequate electrical circuit protection and issues with the design of the temperature sensors within the modules.

There was also a June 2012 event that started when the HVAC cooling system tripped and caused multiple cells to overheat.

Two severely discharged cells in less than a year is considered a high rate of failure. But according to the Material Safety Data Sheet (MSDS) for that lithium ion battery at the Elden Substation, failed cells are "anticipated," and there were supposed to be safeguards built in to prevent an incident such as the fire.

The report highlights a serious concern with these types of lithium ion battery systems:

> "Charging a severely discharged cell (to a voltage below 2.7V) can result in internal cell breakdown and damage to the neighboring cell (thermally)."

ACC - Docket Control - Received 8/2/2019 4:24 PM
ACC - Docket Control - Docketed 8/2/2019 4:29 PM

LIQUID ELECTROLYTE LIB – SAFETY INCIDENT CAUSES

- Mostly attributed to manufacturing defects
  - More common as demand for inexpensive LIBs increases
  - New factories, manufacturing in locations with relaxed safety and QC standards
- Danger is inherent in Liquid Electrolyte LIBs:
  - High power density
  - Very thin permeable polyethylene separator ~ 10 microns thick
  - Flammable organic solvent liquid electrolyte
  - Tendency for dendrite formation on the anode

Safety is a major concern for using Liquid Electrolyte LIBs in the rural electrical power storage application

SOLID-STATE LITHIUM ION BATTERIES (SSB)

- Solid electrolyte instead of liquid or gel electrolyte in most of today's LIBs
- Advantages:
  - Much safer than liquid electrolyte LIBs:
    - Dendrite formation physically suppressed
    - Non-flammable inorganic electrolyte vs. flammable organic electrolyte
  - Simplified packaging less wasted weight = lighter batteries/higher power density (2-3 times more than liquid electrolyte LIBs)
  - Higher electrochemical stability - compatible with higher potential electrode materials to increase energy density
  - Longer cycle life
  - Much faster charging rates

Extensive research is in progress with many different solid electrolytes but none so far have proven to be able to replace liquid electrolytes despite the safety issues because of a variety of issues

LITHIUM METAL ANODES

- Lithium (Li) metal is the best anode for high-energy-density rechargeable batteries – 2 to 3 times higher than anodes commonly used in current LIBs
  - High volumetric energy density: 2046 mAh/cm^3
  - High gravimetric specific capacity: 3862 mAh/g
  - Lowest reduction potential -3.04 V vs. standard hydrogen electrode
- However, major problem: **Dendrite growth**
  - The reason Lithium metal is not used in liquid electrolyte LIBs today
- SSBs allow the use of Li Metal anodes, while it is still too dangerous with Liquid Electrolyte LIBs

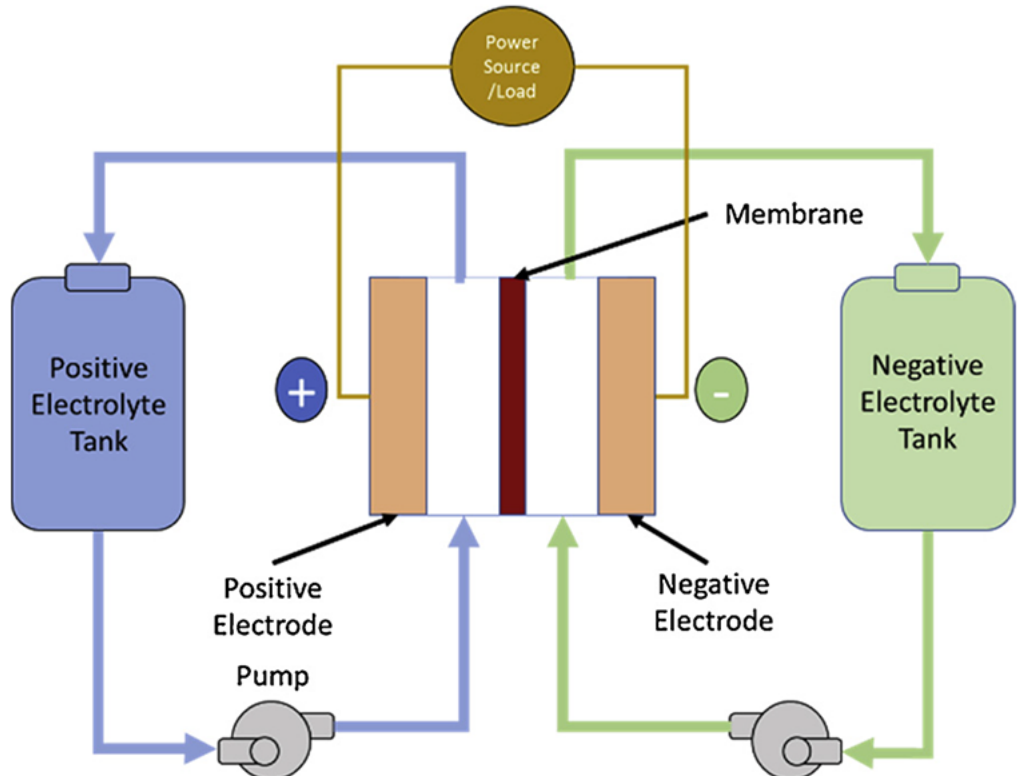
SSB DISADVANTAGES

- There are many types of SSB types being researched, their disadvantages differ
- Not all SSB types have every disadvantage, but no one current SSB electrolyte has no disadvantages
  - In general, lower electrical conductivity of electrolyte → lower power
  - Expensive to fabricate or expensive materials – currently not cost effective
  - Some are not stable in normal environments or with moisture
- Not all SSB electrolytes have every disadvantage, but no one current SSB electrolyte has no disadvantages
- SSB future: Extensive research being conducted due to huge commercial potential of an affordable, safe, high-density battery for consumers

SSBs are a promising technology but in the near-term maybe more so for personal electronics and vehicles as opposed to grid storage solutions

VANADIUM REDOX FLOW BATTERY (VRFB)

- Electrolytes stored in external tanks separate from the battery cell
- 2 distinct sides to the system with 4 Vanadium oxidation states
  - Positive side: V^{4+} (VO^{2+}) , and V^{5+} (VO_2^{+})
  - Negative side: V^{2+} and V^{3+}
- Electrolytes pumped thru separate half-cells, return to storage tanks for recirc
- Each half-cell also contains an electrode and a bipolar plate
- 2 sides separated by a semi-permeable membrane separator
  - Allows protons (H^{+}) and electrons to pass
  - Separates electrolytes and vanadium ions
- Multiple VRFB cells can be stacked

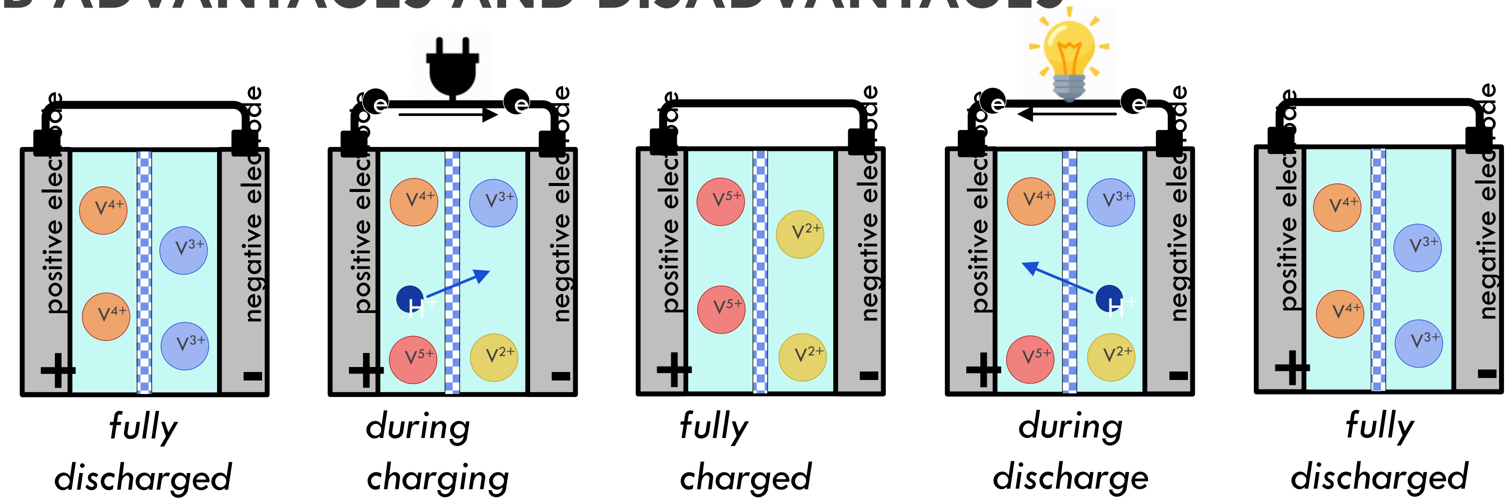


Source: Lourenssen et al (2019)

Reactions:

- Positive cell: $VO_2^{+} + 2H^{+} + e^{-} \rightleftharpoons VO^{2+} + H_2O$
- Negative cell: $V^{2+} \rightleftharpoons V^{3+} + e^{-}$
- Overall: $VO_2^{+} + V^{2+}\ 2H^{+} \rightleftharpoons VO^{2+} + V^{3+} + H_2O$

VRFB ADVANTAGES AND DISADVANTAGES



- Advantages:
  - Long service life (>25 years)
  - Electrolyte life is not susceptible to deep-discharge (can discharge 100%)
  - Incombustible, non-toxic, non-reactive electrolyte
  - High output, large capacity, scalable
  - Capable of short-term, high-output operations
  - Minimal maintenance – low O&M costs
    - No special safety subsystems
    - No cooling subsystems

- Disadvantages:
  - Relatively high cost – but cost per kWh dropping
  - Limited energy density – compared to other technologies
  - Some cell degradation from the harsh environment

TOP VRFB MANUFACTURERS

- Sumitomo Electric Industries
- Rongke Power
- UniEnergy Technologies
- RedT Energy
- Vionx Energy
- WattJoule
- Big Pawer
- Australian Vanadium
- Studer Innotec
- H2, Inc.
- Beijing Pu Neng Energy
- Anhui Meineng Store Energy System
- Primus Power

LEAD ACID BATTERY

- Invented in 1859
- Still a leader in the worldwide rechargeable battery market
- Provides a baseline for comparison vs. other battery types

- Lead-acid advantages:
  - Low Cost
  - Sustainable - recycling well established
  - Relatively safe: aqueous non-flammable electrolyte
  - Sealed lead-acid - AGM (absorbed glass mat) and Gel Cell - require minimal maintenance
  - High Reliability
  - Easy to produce

Due to cost and availability, lead-acid batteries are still viable for small grid storage applications in the developing world

LEAD ACID BATTERY DISADVANTAGES

- Uses lead (hazardous)
- Relatively low energy density: 60-75 Wh/l
- Relatively low specific energy (it's heavy):
  30-40 Wh/kg
- Relatively short life span – frequent battery replacement
- Flooded lead-acid batteries require regular maintenance (watering) and ventilation (H_2 gas produced)
- Emits explosive gas and acid fumes
- Poor performance in cold conditions
- May require a thermal management system

STUDY OBJECTIVES

- 6 evaluation criteria, with respect to the energy storage scenario
  - a. Energy density (gravimetric and volumetric)
  - b. Safety
  - c. Battery life (number of charge/discharge cycles)
  - d. Operating Temperature Range / Temperature Effects
  - e. Lifecycle cost (initial and post installation)
  - f. Maintenance complexity

ENERGY DENSITY COMPARISON

- Energy density = amount of energy that can be stored in a system [battery] for a given volume (volumetric) or weight (gravimetric)
- Considerations: Battery cell level? Battery enclosure level? Entire system enclosure, with monitoring, communications, safety equipment, cooling, etc.?
- Comparison:
  - Liquid Electrolyte LIB: 90-300 Wh/kg (from literature)
    - Saft Intensium Max Grid Storage System: 6.1x2.4x2.9m container with controls, etc.: 28 Wh/L; 60.5 Wh/kg
    - Tesla Model 3 LIB (Panasonic 2170): approx. 700 Wh/L and 250 Wh/kg at cell level
    - Home LIB Batteries (Tesla, Sonnen, LG, BYD): 35-100 Wh/L, 45-115 Wh/kg (with enclosure)
    - Panasonic NCR18650GA: 693 WH/liter; 224 Wh/kg [from product spec]
  - Solid Electrolyte LIB: theoretically 2-3x energy density of liquid electrolyte LIBs (use of Li metal anodes) – cell level
    - IMEC announced SSB at 400 Wh/liter, goal of 1000 Wh/L by 2024
    - >2500 Wh/kg in Lab [Kim et al 2019, Tohoku University]

ENERGY DENSITY COMPARISON

- Comparison (continued):
  - VRFB:
    - WattJoule (in electrolyte): Gen 1: 25 Wh/L; Gen-2 (2021): 50 Wh/L; Gen-3 (2024): 150 Wh/L
    - UET ReFlex Home VRFB: 15.6 kWh/L; 15.9 kWh/kg
    - Sumitomo Grid Storage – full enclosure: 4.2 Wh/L; 6.8 Wh/kg [220 metric ton 1500 kWh full system]
  - Lead-Acid Battery: 60-115 Wh/liter, 30-70 Wh/kg [from product spec sheets]
- For many applications, energy density is extremely important:
  - Consumer electronics & electric vehicles: longer between charges
- For the microgrid energy storage application, energy density is not so important
  - Usually installation space is plentiful, especially in rural areas
  - System footprint (m^2) may be more important than Volume (m^3) – stackable modules
- Energy density factor is out-weighed by other factors for this application
  - Why VRFB are becoming more popular

SAFETY

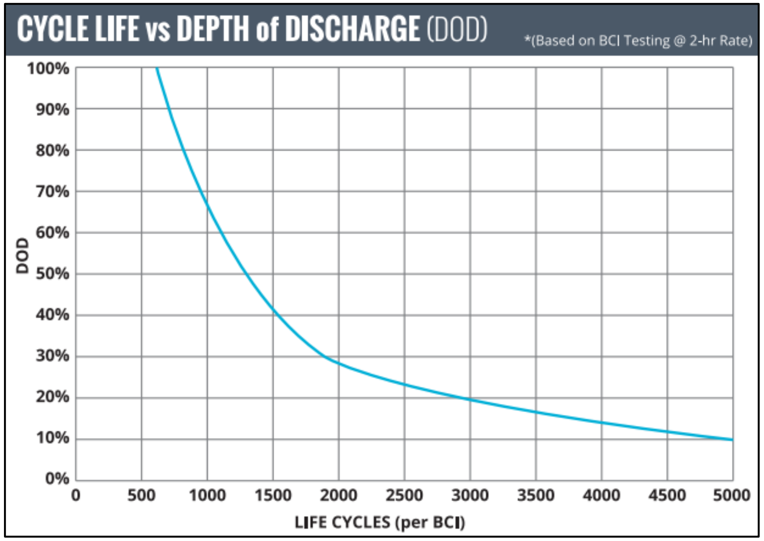
- Liquid Electrolyte LIBs: many safety issues
- Solid Electrolyte LIBs: probably far less safety issues
- VRFBs: no significant safety issues
  - Vanadium is relatively safe - even if ingested in small amounts
  - Aqueous, non-flammable, non-toxic, not highly reactive electrolyte
- Lead-Acid batteries:
  - Floodable lead-acid - sulphuric acid electrolyte – corrosive, causes burns, poisonous
  - Sealed lead-acid batteries - safer

Safety is a significant concern for installations in the developing world where operators and maintainers may not have adequate training

BATTERY LIFE (NUMBER OF CHARGE/DISCHARGE CYCLES)

- Liquid Electrolyte LIBs:
  - Battery life - disadvantage - 500-3000 cycles
  - SEI formation
  - Battery change out necessary
- Solid Electrolyte LIBs:
  - Less SEI formation – longer cycle life
- VRFBs:
  - Extremely long life - >10,000 cycles – well over 20 years
- Lead-Acid batteries:
  - Battery Life is a significant disadvantage
  - Life expectancy is 2-3 years
  - Replacement must be figured into lifecycle costs

Sealed AGC Lead-Acid Battery Life Cycles



source: Full River DC400-6 Deep Cycle AGC Battery Data Sheet

REMAINING RESEARCH AND ANALYSIS

- Operating Temperature Range / Temperature Effects
  - Cooling required for LIBs, Lead-Acid
  - Cooling not required for VRFBs
- Maintenance Complexity and Cost
  - LIB subsystems – cooling, safety, monitoring
  - VRFBs – low maintenance, 2 pumps
- Affordability
  - Initial system cost
  - Installation
  - Operations and Maintenance

SUMMARY

- Renewable energy is a viable means to provide power for poor communities disconnected from the main grid
  - Community microgrids can provide distribution and control
  - Energy storage is key to solve production-demand alignment issues
- Lead-acid batteries still a primary option due to much lower cost
- Liquid electrolyte LIBs are the current leader in developed countries
  - Research pushing continued improvement
  - Safety still a major issue
- Solid-state LIBs are a promising technology but appear to be years away from commercialization
- Vanadium Redox Flow Batteries provide a viable alternative to LIBs
  - Projections for increased installations in near-future
  - Lower energy density not an issue, cost the main concern

The final answer will come down mainly to COST