COMPARISON OF ENERGY STORAGE TECHNOLOGIES FOR ISOLATED COMMUNITY MICROGRID APPLICATIONS

PAUL G. MARSHALL

A Thesis Submitted to University of Phayao
in Partial Fulfillment of Requirements
for the Master of Science in Energy Management and Smart Grid Technology
August 2020

การเปรียบเทียบเทคโนโลยีการเก็บพลังงานสำหรับแอปพลิเคชันไมโครกริดชุมชนที่แยกได้

Paul G. Marshall

วิทยานิพนธ์เสนอมหาวิทยาลัยพะเยา เพื่อเป็นส่วนหนึ่งของการศึกษา
หลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาการจัดการพลังงานและสมาร์ตกริดเทคโนโลยี
สิงหาคม 2563

COMPARISON OF ENERGY STORAGE TECHNOLOGIES FOR ISOLATED COMMUNITY MICROGRID APPLICATIONS

PAUL G. MARSHALL

A Thesis Submitted to University of Phayao
in Partial Fulfillment of the Requirements
for the Master of Science Degree in Energy Management and Smart Grid Technology
August 2020

Thesis

Title

Comparison of Energy Storage Technologies for Isolated Community Microgrid Applications

Submitted by Paul g. Marshall

Approved in partial fulfillment of the requriements for the
Master of Science Degree in Energy Management and Smart Grid Technology
University of Phayao

Approved by

.... Chairman
(Assistant Professor Dr. Prapita Thanarak)

.... Advisor
(Dr. Bunyawat Vichanpol)

.... Co Advisor
(Associate Professor Dr. Wattanapong Rakwichian)

.... Co Advisor
(Assistant Professor Dr. Watchara Wongpanyo)

.... Examiner
(Dr. Poramate Sittisun)

.... Dean of School of Energy and Environment
(Associate Professor Dr. Torpong Keertachat)

Title: COMPARISON OF ENERGY STORAGE TECHNOLOGIES FOR ISOLATED COMMUNITY MICROGRID APPLICATIONS

Author: Paul g. Marshall, Thesis: M.Sc. (Energy Management and Smart Grid Technology), University of Phayao, 2020

Advisor: Dr. Bunyawat Vichanpol Co-advisor Associate Professor Dr.Wattanapong Rakwichian Assistant Professor Dr.Watchara Wongpanyo

Keyword battery energy storage system, lithium-ion battery, vanadium redox flow battery, solid-state battery, lead-acid battery, microgrid

ABSTRACT

The International Energy Agency estimates that by the year 2040 there will still be more than 700 million people worldwide without access to electricity. Renewable energy production, particularly from photovoltaic systems, combined with affordable and effective energy storage provides a means to provide electricity to these poorer communities. This paper explores four battery energy storage system (BESS) technologies to support a notional, isolated village microgrid requiring a BESS capable of providing 605 kWh of usable storage over a 20-year scenario timeframe. Using this analysis scenario, the lead-acid battery is analyzed as a baseline against the current technology leader, the liquid electrolyte lithium-ion battery (LIB), and another current option, the vanadium redox flow battery (VRFB). The solid-state LIB is also reviewed as a future technology. The BESS technologies are analyzed in two parts. First, a cost analysis considering factors affecting initial battery bank sizing (depth of discharge limits, efficiency, capacity fade) as well as battery life which drives replacement frequency, and operations and maintenance costs for the years 2018 and 2025. Second, an analysis of four other significant factors not included in the cost analysis: energy density, operating temperature limits, safety issues, and environmental concerns. The findings show that the liquid electrolyte LIB is the current leading technology due mostly to its ever lowering cost, despite continued concerns over its safety. The VRFB is presented as a safer alternative that features a system lifespan several times that of the LIB, the capability to operate at high temperatures without cooling subsystems, and a much lower environmental impact. If VRFB manufacturers can achieve lifecycle cost reductions to achieve more parity with LIBs, these advantages may sway system designers to choose this technology.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to my advisor, Dr. Bunyawat Vichanpol, as well as the thesis review committee and the many members of the ASEAN Smart Grid Congress who contributed valuable suggestions to improve my work. I also want to thank my first thesis advisor, Dr Sulak Sumitsawan and Mr. Greg Cipriano from WattJoule for their valuable contributions. I want to sincerely thank my wife, Nancy Marshall who supported me through this process. Most importantly, I want to thank Dr. Wattanapong Rakwichian who has been an invaluable source of information, support, and encouragement.

Paul g. Marshall

LIST OF CONTENTS

Page

LIST OF TABLE

LIST OF FIGURE

Chapter 1

INTRODUCTION

This paper's objective is to conduct a comparison of four battery technologies with regard to their applicability as an energy storage system (ESS) for a renewable energy-based community microgrid that is disconnected from the main power grid.

Background

In the World Energy Outlook 2018, the International Energy Agency (IEA) [1] estimated that 2017 was the first year where the number of people without access to electricity fell below one billion. The IEA further estimates that by the year 2040 there will still be more than 700 million people worldwide without access to electricity, many of them living in rural areas of the world. About 80% of these people without electricity live in remote rural areas where population density and energy demand are low. Having access to a reliable source of energy is crucial for rural inhabitants to improve their quality of life. As much of the world's rural population is engaged in agriculture which keeps them outdoors during the day, access to electricity at night allows these rural residents to achieve higher living standards by making nighttime activities possible. Electricity powers basic needs such as lighting, heating, and cooking, and also powers computers, televisions, and other essential appliances [2]. In this way, electricity is a necessity for social and economic development. It is also vital to basic social services such as education, health care, clean water supply, and sanitation. Electricity allows for key activities after sunset such as health care and study for students [3].

The problem is especially acute for poor, remote communities which are disconnected from the main power grid. For these isolated communities, extending the grid over long distances or over difficult terrain or water may be unaffordable due to the high costs associated with building the infrastructure, lifecycle operations and maintenance costs, and energy transmission losses associated with long distances [4].

In recent years, significant reductions in the cost of renewable energy sources, particularly with photovoltaic (PV) technologies, has resulted in far more access to renewable energy production, even for poorer communities. Off-grid electricity generated by local renewable energy sources such as solar, wind or hydro can provide these remote communities with cost-effective and reliable electrical energy [5]. Renewable energy generation works well for smaller, distributed electrical energy generation systems, as opposed to traditional fossil fuel plants which needed to be large and centralized to provide return on investment. Remote areas also usually feature large amounts of open space where it is much easier and less costly to host solar farms which require significant land area [6].

Another added benefit for electricity produced from renewable sources over electricity from fossil fuel-powered generators is the reduction of the negative environmental impact on a global scale as well as a reduction of harmful effects on the local population [3]. Electricity from renewable sources can also replace the indoor use of firewood and kerosene in rural homes, which contribute significantly to respiratory health issues of the residents [2].

For many rural areas, solar energy provides the most reliable and efficient source of electricity. With the maturation and price decreases of PV technologies and systems, solar power has also become affordable for even the poorest families as governments and non-governmental organizations (NGOs) can provide systems for these poor communities that are not connected to the main power grid. Other renewable energy power sources such as wind, hydro, and bio-diesel can also provide additional power.

However, for rural communities a major issue is that solar energy production occurs during the day when the sun is out, while the key time for usage is after sundown when farm workers are back in their homes. Figure 1-1 shows the non-alignment between power production and power consumption for a rural household over a representative 24-hour period.

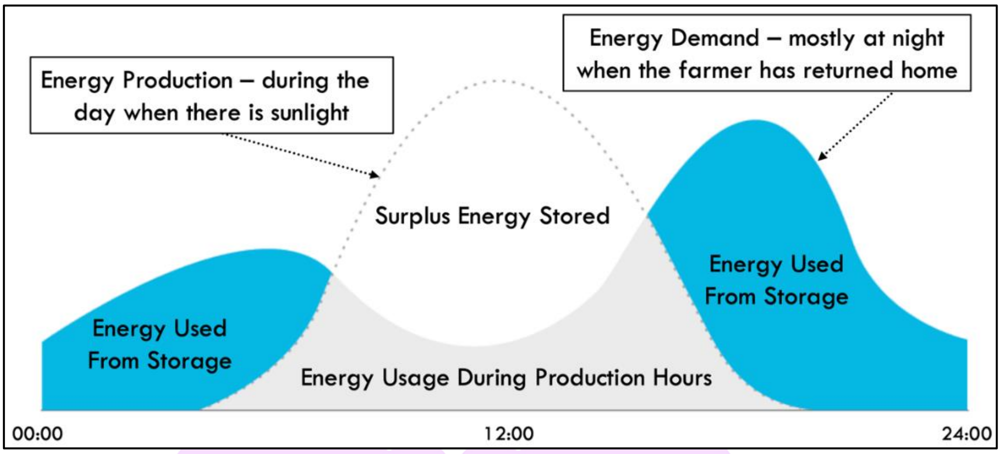


Figure 1 Representative solar energy production versus usage for rural households over a 24-hour period

While other renewable energy sources such as micro-hydro, wind, and bio-diesel generators are capable of providing electrical power for isolated rural communities, solar is currently the most viable energy source for these regions due to affordability and ease of use with minimal maintenance.

The solution to address the misalignment between solar energy production and energy consumption in the isolated rural scenario is to add an energy storage element into the system. Figure 1-2 shows a notional community electrical microgrid system, disconnected from the main power grid, featuring the aforementioned renewable power sources, and managed by a local smart grid.

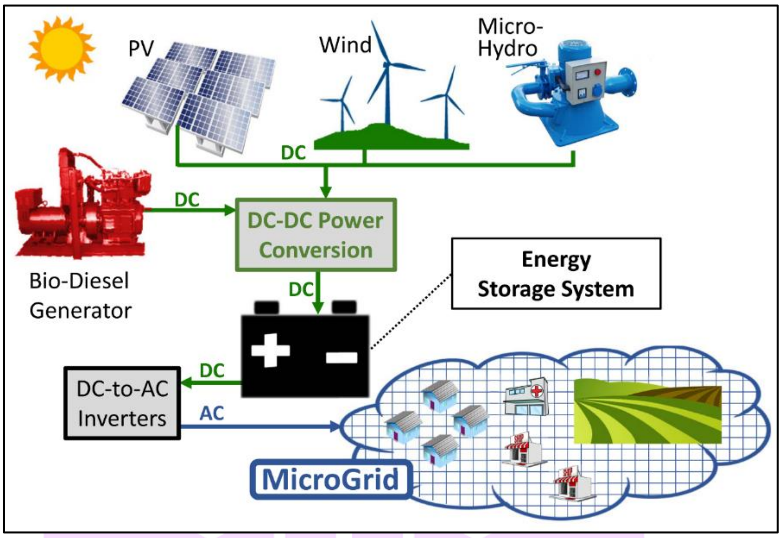


Figure 2 Notional disconnected community smart grid-based electrical system withrenewable energy sources

The electrical energy storage system provides the key element to overcome the solar production versus usage misalignment by allowing the rural user to use the stored energy produced during daylight areas upon returning home after a day working outdoors. Energy storage can be extremely useful even for a household connected to the main grid or in a situation with net metering, as it allows the user to use less expensive self-generated power at any time, and also provides power during outages. The storage could be a large, shared community-based system or a distributed system of smaller storage units for each household.

Mongird et al [7] state that as of 2018 nearly 173 GW of energy storage was in use worldwide, with the approximate breakdown shown in Table 1 Clearly, pumped storage hydropower (PSH) is by far the predominate technology accounting for about 98% of worldwide energy storage. Although PSH is a proven, mature, and common solution for energy storage, its major drawback is that it is not suitable for all locations as it requires two reservoirs at different elevations and an adequate amount of water [8]. This study is focused on battery systems where PSH would not be viable.

Table 1 Worldwide energy storage [7]

Energy Storage Technology	MW in Use
Pumped Storage Hydropower (PSH)	169,557
Lithium-ion battery (LIB)	1,629
Flywheels	931
Compressed Air Energy Storage	407
Sodium sulfur battery	189
Lead acid battery	75
Flow battery	72
Electrochemical capacitor	49
Sodium metal halide battery	19
Total	**172,928**

Until recently, the most common battery energy storage system (BESS) for this application has been a lead-acid battery-based system. As the oldest and still ubiquitous technology, the lead-acid battery is analyzed in this study to provide a baseline to compare with the newer technologies. However, as the home renewable energy market has expanded, particularly with solar production, commercial lithium-ion battery (LIB) storage systems have become available and are now the predominant choice in developed countries. Yet, LIBs have several inherent shortcomings which are described later in this paper. Research in solid-state battery (SSB) using lithium-ion technologies have accelerated in recent years to address the shortcoming of LIBs by providing a safer energy storage solution. However, SSBs currently face several obstacles before this technology is ready for widespread use as a solution for ESS applications. The Vanadium Redox Flow Battery (VRFB) is another storage solution which provides its own set of advantages over the other technologies and is in use today as a proven grid energy storage solution.

Research objectives

The objective of this paper is to conduct a comparison of these four battery technologies (lead-acid, liquid electrolyte LIB, lithium-based SSB, and VRFB) with regard to their applicability as a BESS for a renewable energy-based community microgrid that is disconnected from the main power grid. The specific objectives are:

1. Provide a description on the current status of the four battery technologies, including research and commercial systems.

2. Analyze each battery technology against two sets of evaluation criteria, with respect to the stated energy storage scenario, while also specifying the advantages and disadvantages of each. The first set of criteria is centered on a lifecycle cost analysis, which includes factors that are direct inputs into the cost analysis: (a) depth of discharge (DOD) limits, (b) efficiency, (c) capacity degradation, (d) battery life, and (e) operations and maintenance (O&M) requirements. The second set includes four additional analysis factors which have cost implications, but are not used in this study's cost analysis although they are still factors to consider: (a) energy density, (b) operating temperature limits, (c) safety issues, and (d) environmental concerns.

3. Project the future trends for each of the four battery technologies in regard to suitability in the rural community-based energy storage application.

Research benefit and scope

While a great many energy storage solutions are currently available or in research, this study focuses on lead-acid batteries, liquid electrolyte and solid-state LIBs, and VRFBs. Although the technology is over 130-years old, lead-acid batteries are still a viable solution for this energy storage application, mostly due to low cost. Liquid electrolyte LIBs and VRFBs are currently in commercial production and provide a more efficient, though often costly solution, with LIBs being the leading technology in developed countries. While SSB research is progressing, the technology is not yet ready for full commercialization with available products which can support the community microgrid energy storage scenario. This paper seeks to describe the current status of each technology by evaluating each against the criteria described above. This study will also attempt to identify which technologies are the most promising for the future.

Chapter 2

REVIEW OF RELATED LITERATURE

This section presents a basic battery model followed by a discussion of the four different battery types addressed in this study. It concludes with a summary of the community microgrid scenario which forms the basis of the analysis.

Battery basics

We start with a basic model of a battery, universal to all battery types, which is used as the model for this study. Batteries are devices which store and produce energy by the conversion (or transduction) of chemical energy into electrical energy. The basic battery consists of two electrodes (the anode and the cathode) immersed in a chemical medium (the electrolyte), with a semi-permeable separator between the two electrodes [9]. The basic battery model is shown in Figure 2-1. When an electrical circuit is externally connected to the battery, chemical reactions take place on the electrodes via the electrolyte which produce a flow of electricity through the external circuit [10].

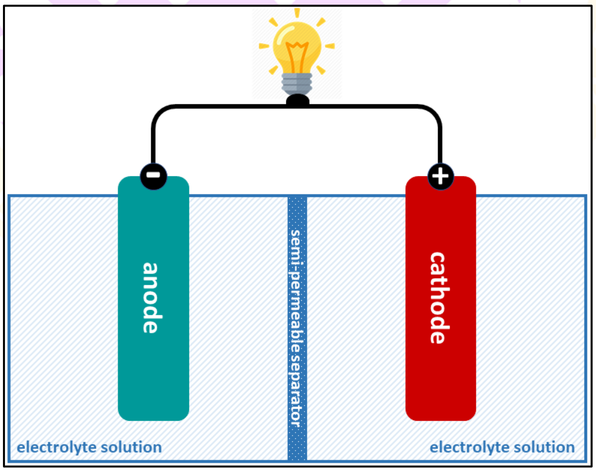


Figure 3 Basic battery model [11]

When electrical energy is flowing through the external circuit during a discharge cycle, the anode at the negative node releases electrons into the circuit at the negative battery terminal and positive ions into the electrolyte. The reaction at the anode is an oxidation reaction. Simultaneously, the cathode at the positive battery terminal receives electrons from the circuit while also receiving positive ions via the electrolyte in what is known as a reduction reaction, completing the circuit. Thus, electrons flow through the external circuit to produce useful electrical energy, while the ions flow through the electrolyte [11]. The battery's discharge cycle is show in Figure 4.

Together, these two half reactions, reduction and oxidation, are referred to as a redox reaction. The cathode is reduced, that is it gains electrons; and the anode is oxidized, that is it loses electrons. The difference in standard potential between the materials that make up the anode and cathode account for the overall battery's electrochemical potential (voltage) and allows for this flow of electrons [11].

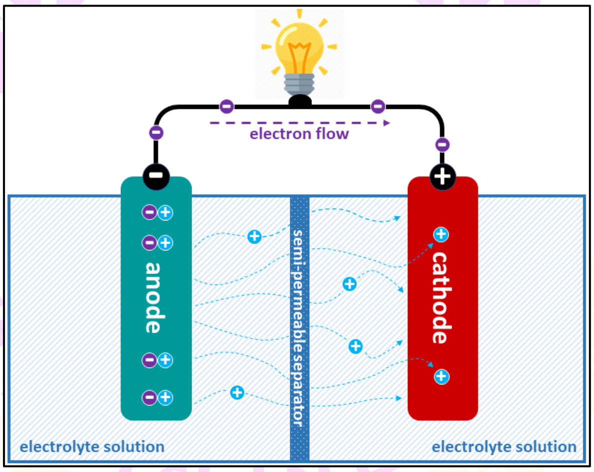


Figure 4 Battery discharge cycle [11]

Another key component of the basic battery is the electrolyte, which provides the pathway between the anode and cathode. During battery discharge, as the negatively charged electrons leave the anode, positive ions are also released by the anode into the electrolyte to maintain a neutral overall charge. Simultaneously, the cathode matches the electrons it is receiving via the external circuit by also receiving the positively charged ions released by the anode. This charge balancing occurs during the battery's discharge cycle to maintain the charge balance and to keep the reaction going.

The final key battery component is the semi-permeable separator. As with anodes, cathodes, and electrolytes, no one separator design or material is ideal for all battery types and designs. The separator is placed between the two electrodes with a primary function to keep the anode and cathode physically separated to prevent electrical short circuits while at the same time allowing ionic charges to pass through to complete the battery's circuit [12]. A key example where the separator comes into play is with the production of dendrites on the anode of a LIB. In the absence of a separator, these dendrites can grow over multiple charge and discharge cycles until they physically connect the anode and cathode causing a short circuit in the battery which can lead to a thermal runaway condition producing fires and explosions [13]. These incidents are described later in the sections on LIBs.

As the discharge cycle progresses, other chemical products are produced which create a resistance lowering the efficiency of the battery and eventually slowing down the primary redox reaction. All secondary batteries, such as those considered in this study, allow for a charging cycle to reverse this process. The charging cycle is accomplished by connecting an electrical power source to the external circuit between the anode and cathode. The flow of electrons back into the anode causes the pull of positively charged ions in the electrolyte to also migrate back to the anode, thus reversing the redox reaction. However, with most battery types the recharging cycle does not restore the battery 100% to its previous condition. Different battery types experience different rates of degradation with each charging cycle. Figure 2-3 illustrates the battery charging cycle.

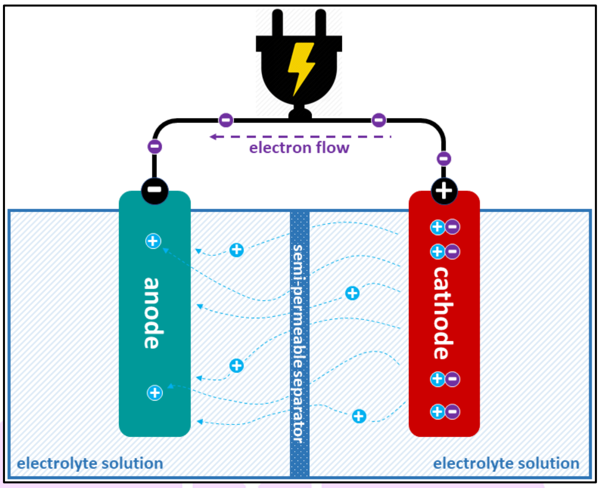


Figure 5 Battery charging cycle [11]

Lead-acid battery overview

This study considers the venerable lead-acid battery as a baseline comparison versus the newer battery technologies, as they are still a widely used battery type for community microgrid energy storage applications, especially in poor communities. Invented in 1859 by French physicist Gaston Plante, lead-acid batteries provide some advantages over other battery technologies, most notably in their relatively low cost for high performance, recyclability, and simplicity. These advantages have allowed this 130-plus year-old technology to maintain sales in the worldwide rechargeable battery market share both in terms of sales value and total storage capacity [14]. Lead-acid battery advantages include the following:

1. Low Cost [7]
2. Sustainability – recycling of lead-acid batteries is well established, with recycling rates approaching 100% in Western countries and very high rates are achieved elsewhere [14]
3. Safety – a relatively safe system with non-flammable active materials [14] but potential issues with hydrogen gas generation and corrosive sulphuric acid electrolyte [15]
4. High Reliability
5. Strong surge capacity
6. Large, well-established, worldwide supplier base [14].

Although disadvantages vary between different lead-acid batteries designs, lead-acid disadvantages may include the following:

1. Short life span (low number of lifetime cycles) [7]
2. Relatively low energy density [15]
3. Dependence on hazardous and restricted lead [16].
4. Requirement for regular maintenance
5. Emission of explosive gas and acid fumes [15]
6. Poor performance in cold conditions
7. Requirement for a thermal management system in hot climates [17]

New developments in lead-acid batteries have allowed for somewhat longer lifespans and greater number of charge/recharge cycles. These new developments include carbon-enhanced designs which alleviate issues with partial-state-of-charge duty, a common occurrence with solar PV generation systems. Other developments with technologies such as hybrid construction with supercapacitor elements promise more advances in the future [14].

There are dozens of major manufacturers of lead-acid batteries designed specifically for renewable energy storage applications. MarketsandMarkets™ estimates that the global lead-acid battery market will reach US$52.5 billion by 2024 from an estimated US$41.6 billion in 2019, with 25 key market players shown in Table 2-1 [18].

Table 2 World’s leading lead-acid battery manufacturers [18]

Manufacturer	Country	Manufacturer	Country
Rolls Battery	Canada	Panasonic	Japan
GS Yuasa	China	Hitachi Chemical	Japan
Chaowei Power	China	Hankook AltasBX	Kores
Narada Power	China	Camel Power	Malaysia
Xupai Battery	China	First National Battery	South Africa
Harbin Coslight Power	China	NorthStar	Sweden
Hoppecke	Germany	EnerSys	USA
Leoch International Technology	Hong Kong	Clarios	USA
Exide Industries	India	Crown Battery	USA

Table 2 (cont.)

Manufacturer	Country	Manufacturer	Country
Exide Industries	India	Crown Battery	USA
HBL Power Systems	India	Exide Technologies	USA
Amara Raja Power System	India	Teledyne Technologies	USA
Okaya Power	India	East Penn	USA
		C&D Technologies	USA

For the renewable energy storage application relevant to this study, three primary lead-acid technologies predominate: (a) flooded lead-acid batteries, (b) gel lead-acid batteries, and (c) absorbent glass mat (AGM) lead-acid batteries. Flooded lead-acid batteries contain a liquid mixture of deionized water and sulfuric acid (the electrolyte) inside the battery case that interacts with the matrix of lead and lead oxide plates. Some flooded batteries are maintenance-free or sealed, although most require periodic maintenance, usually requiring distilled water to be added and are vented to the atmosphere to allow hydrogen gas generated during the charging phase to be expelled. Flooded lead-acid batteries tend to be less expensive that gel or AGM models but have greater safety concerns and require more ventilation and more maintenance [19].

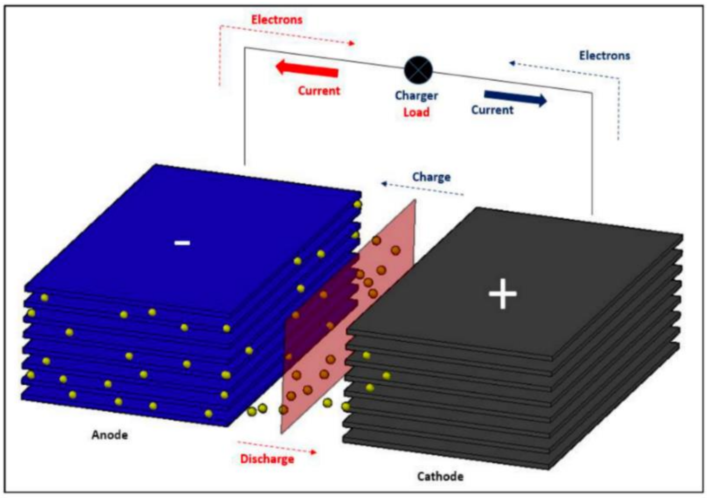
Both gel and AGM lead-acid batteries are sealed, with typically a small valve to allow for the escape of the hydrogen gas generated during charging. For this reason, these sealed models are often referred to as Valve Regulated Lead-Acid (VRLA) [19]. Gel lead-acid batteries are similar to flooded lead-acid batteries except the electrolyte is a thick silica gel allowing gel batteries to be maintenance-free and are ideal for deep cycle applications [20]. However, gel batteries are the costliest type of lead-acid batteries and do not allow for the higher charging and discharging rates of their AGM counterparts. Gel batteries require precise charging, requiring a charging controller to ensure they are charged correctly [19]. Gel batteries last longer than AGMs, particularly in heat, so they are well suited for hot climates where the batteries are subject to high temperature operating conditions [21]. AGM lead-acid batteries contain a very thin layer of glass fibers between the plates which suspends the electrolyte and also allows AGM batteries to be maintenance free

[20]. AGM batteries are currently the most popular VLRA type as they can operate in a wide variety of conditions, require much less maintenance [19], and can be charged and discharged at higher rates than gel and flooded types, although like gel types are sensitive to overcharging and require a charge controller [22].

Liquid electrolyte LIB overview

LIB technology has progressed to where LIBs are now a well-established battery technology in products we use in everyday life, from mobile phones and electric vehicles to larger applications such as a community-based microgrid BESS applicable to this study's scenario. But the current commercially available liquid electrolyte LIBs also have several critical disadvantages, most notably with safety as described later.

Liquid electrolyte LIBs are a family of rechargeable (or secondary) devices where both electrodes are intercalation materials, and the electrolyte is a lithium salt dissolved in an organic solvent [23]. As with the basic battery model, the liquid electrolyte LIB's primary components are its anode, cathode, electrolyte, and separator. In a liquid electrolyte LIB, lithium ions intercalate between the anode and cathode during discharge and de-intercalate between the anode and cathode during the charge cycle. Intercalation is defined as the insertion and extraction of ions between the layers of the anode and cathode. An electrically insulative separator prevents short circuiting between the electrodes [24]. Figure 2-4 shows a basic liquid electrolyte LIB design and function.



Schematic of battery charge (blue) and discharge (red) processes

Figure 6 Liquid LIB charge (blue) and discharge (red) processes [24]

Liquid electrolyte LIBs consist of multiple cells connected both in parallel to increase current and in series to increase voltage. Multiple cells are then integrated into modules, which are integrated into a full battery pack. For example, the Panasonic battery pack used in the Tesla Type S automobile provides 100 kWh from its 8,256 cells [25]. The first commercialized liquid electrolyte LIB in 1991 featured a Lithium Cobalt Oxide (LiCoO2) cathode (positive electrode) [23], which continues to be a common cathode material. The reduction reaction is as follows:

$$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2 \ [E^0 = 1\ V] \qquad (1)$$

Other liquid electrolyte LIB anode materials have been researched and developed, each with their particular advantages and disadvantages. These include Lithium Iron Phosphate ($LiFePO_4$), Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$), Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$), and Lithium Titanate (Li_2TiO_3) [26].

Correspondingly, Lithium graphite (LiC_6) is a common liquid electrolyte LIB anode (negative electrode) material, where the oxidation reaction is as follows:

$$LiC_6 \rightarrow Li^+ + C_6 + e^- \ [E^0 = 3\ V] \qquad (2)$$

The overall reaction is given by:

$$CoO_2 + LiC_6 \rightarrow LiCoO_2 + C_6 \qquad (3)$$

The overall open circuit voltage is given by: $E^+ - E^- = 4$ V [24].

Liquid organic solvent electrolytes are the most common liquid electrolyte used in most commercial LIBs today, the most common being lithium hexafluorophosphate ($LiPF_6$) salt dissolved in an organic carbonate solution. Despite their many safety issues, organic solvent electrolytes are used in many LIB applications from consumer electronics, to electric vehicles, and in energy storage systems [23]. Liquid electrolyte LIBs have grown in popularity due to their many advantages over other battery types:

1. High specific capacity and energy density
2. No memory effect [24]
3. Low self-discharge rate
4. Easy to form into different sizes and shapes for design flexibility [27]

However, liquid electrolyte LIBs also have key disadvantages. First is the formation of the Solid Electrolyte Interphase (SEI), a passive layer consisting of organic and inorganic electrolyte decomposition products which form over the surface of the anode during cycling. SEI formation results in eventual irreversible capacity degradation. LIBs also experience volumetric expansion, which can damage the electrodes and reduce battery life [24]. But the primary liquid electrolyte LIB disadvantage centers around safety concerns, most notably fires and explosions caused by thermal runaway. Thermal runaway initiates due to a failure in a LIB cell or cells, which propagates to surrounding cells causing a chain-reaction leading to catastrophic battery failure. Although the temperatures associated with thermal runaway vary with different liquid electrolyte LIB designs and chemistries, the following are representative:

1. Thermal runaway onset: 60°C to 100°C
2. Thermal runaway acceleration: 160°C to 170°C
3. Thermal runaway trigger: 170°C to 200°C [24].

Liquid Electrolyte LIB safety issues are discussed in detail in Section 4.2.3. Another disadvantage of liquid electrolyte LIBs centers around the formation of metallic lithium deposits, commonly known as dendrites, on the anode. Dendrite formation is especially significant on lithium metal anodes, which currently precludes their use with liquid electrolytes due to the high probability of damage and short circuiting from the dendrites. That is why current commercial liquid electrolyte LIBs use the anode materials presented previously. However, even those anode materials exhibit dendrite formation, which can pose a significant safety issue, particularly in high current density batteries which can experience catastrophic and dangerous incidents due to dendrite formation. Dendrite growth mechanisms are complex due to the inherent electrochemical instability of lithium metal, combined with the complex microstructural environment provided by organic liquid electrolytes. Dendrites are the subject of current research, as solving this problem could lead to the use of the more efficient lithium metal anodes [13]. SSBs, with their innate ability to physically limit dendrite growth, allow the use of the higher performing lithium metal anodes as will be described in later sections.

As stated by Nitta et al [28], LIBs have clear advantages buoyed by decades of research which have developed to the point where it is a dominant battery technology today. Due to its commercial popularity, liquid electrolyte LIB research continues on new electrode, electrolyte, and separator materials to lower costs while increasing energy density, cycle life, and safety.

This study focuses on containerized liquid electrolyte LIB ESS appropriate for the small, isolated village microgrid energy storage application. Some of the currently available commercial systems that are included in this study are shown in Figure 7

Figure 7Figure 2-5. Containerized liquid electrolyte ESS, clockwise from top-left: Aggreko Y.Cube 60, Fluence EnergyEdge, Saft Intensium Max, BYD ESS

Solid-state LIB overview

As described in previous sections, LIBs have the highest specific energy and energy density of the battery chemistries having reached energy densities of about 260Wh/kg and 700Wh/liter [29]. However, current liquid electrolyte LIBs pose safety concerns due to their highly reactive electrolyte solutions. To overcome the safety issues while still leveraging lithium's advantages, researchers have been experimenting with solid electrolytes as an alternative to liquid electrolytes for LIBs over the past 50+ years. These batteries are also known as solid-state batteries [30].

SSB research can be traced back to the pioneering work of Michael Faraday (1791-1867), who was the first to identify the movement of electrical charge via ions through an electrolyte in the process of electrolysis. In the 1830s, Faraday experimented with solid electrolytes of silver sulfide. From Faraday's time into the 20th century a long list of researchers built upon Faraday's work. The first galvanic cell was introduced in 1836 by John Frederic Daniell in England, followed by Gaston Planté's groundbreaking invention of the lead acid battery in 1859 [31]. Although research in solid-state electrolytes continued into the mid-20th century, there were limited electrolyte materials found to provide sufficient ionic conductivity for practical applications. During the 1960s and 1970s, two primary approaches were pursued to overcome this limitation. First, the solid electrolytes were fabricated into very thin film configurations with a relatively high surface area. Secondly, new solid materials allowing for higher levels of ionic transport were researched [32].

Li^+ ionic transport is dependent on the inherent disorder found in the most promising solid electrolytes in the form of point defects in their crystalline structure. As shown in Figure 2-6, the concept of electrolyte disorder can be presented in a series of levels. The baseline Level-1 is a perfectly ordered crystalline structure which has no potential for ionic conductivity. At Level-2, the static point defect will allow for some ionic transport. But solid electrolytes actually feature a much more complex behavior with regard to defects as the mobile Li^+ ions interact with each other and also with the electrolyte matrix. This complex behavior occurs in ionic crystals with point disorders (level 3a), ion-conducting glasses (level 3b), polymer electrolytes (level 3c), and nanosized systems such as nano-composites and thin films (level 3d) [31].

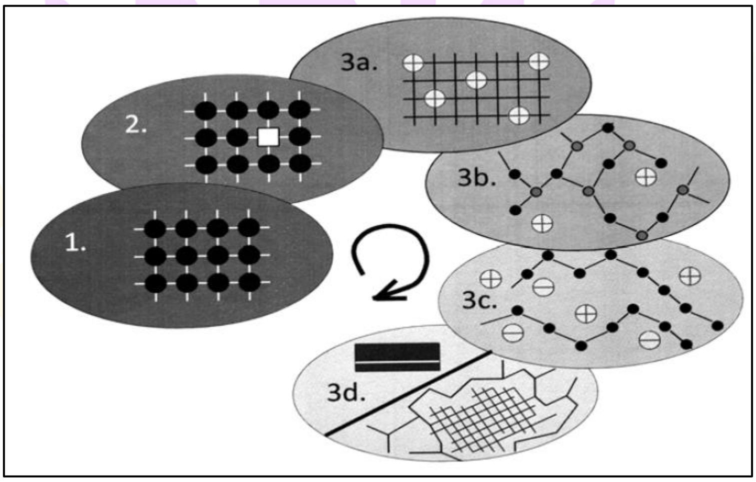


Figure 8 Solid-state electrolyte levels [31]

Level-3a electrolytes such as rubidium silver iodide ($RbAg_4I_5$) were first developed in the 1960s. By the late 1970s, glassy (Level-3b) and polymer (Level-3c) electrolytes were the primary focus in solid-state electrolyte research. Examples of ion-conducting glasses include lithium phosphosilicate glasses, lithium chalcogenide glasses, and glass–ceramic compounds [31]. These glassy electrolytes featured ionic conductivity performance comparable to liquid electrolytes, but they also exhibited very low electrical resistivity, poor temperature stability, and poor LIB electrode stability [30]. The polymer electrolytes (Level 3c) exhibited lower ionic conductivity than their glass counterparts, but the aforementioned technique of fabricating them into thin film configurations compensated for the low conductivity. Since the 1970s, these thin film polymers have become a major focus of solid-state electrolyte research [31]. In Italy in March 1972, a heart pacemaker powered by a LIB with a solid lithium-iodide (LiI) electrolyte was implanted into a human patient for the first time. Since then, LiI batteries have proven to be a highly reliable battery in millions of pacemakers around the world [31].

On the liquid electrolyte front, research continued into the 1980s with new layered intercalation compounds for cathodes such as $LiCoO_2$, $LiNiO_2$ and $LiMnO_2$. This culminated in the creation of the first commercial LIB developed by the Sony corporation, a graphite-liquid electrolyte ($LiCoO_2$) in 1993. Since then, the development of liquid electrolyte LIBs has progressed as described earlier. However, advances in solid-state electrolytes have also progressed in parallel, although without the massive commercialization realized by liquid electrolyte LIBs [31].

In the 1990s the Oak Ridge National Laboratory produced a new solid-state electrolyte by introducing nitrogen into Li_3PO_4 to produce lithium phosphorus oxynitride (LIPON) (Level 3d in Figure 2-6). Although LIPON's ionic conductivity is significantly lower than liquid electrolytes, LIPON electrolytes also feature very high electrical resistivity, good temperature stability, and excellent chemical stability with metallic lithium. LIPON's characteristics make it viable for use in thin-film-lithium metal batteries [30]. The basic operations of a solid-state LIB are the same as for the more common liquid electrolyte LIB described in the previous section. During the discharge cycle, Li+ ions deintercalate from the anode material and transport through the electrolyte into the cathode, while electrons are transported through the external circuit to provide electrical energy for useful work. The main difference is that the SSB uses an inorganic solid electrolyte SSB as opposed to a more volatile liquid organic electrolyte [33].

As described in the section on LIB basics, the more lithium that can be stored in the electrodes, the higher the battery's energy capacity. A significant advantage of solid electrolytes is they allow the use of metal lithium instead of carbon as an anode material, providing about ten times the gravimetric capacity (Ah/g). As shown in Figure 2-7, when lithium metal anodes are used with liquid electrolytes, dendrite formation becomes a significant concern after a number of charge and discharge cycles. These dendrites can grow to the point where they can breach the battery's separator and electrically connect the anode to the cathode. This connection can result in severe negative consequences, as it provides a short circuit path for electrons to flow between the electrodes thus bypassing the external circuit where useful work should be performed. This short circuiting leads to extremely high self-discharge rates producing temperature excursions capable of igniting the flammable electrolyte, resulting in possibly catastrophic fires and explosions. For this reason, liquid electrolyte LIBs use carbon-based anodes instead of metal lithium [34].

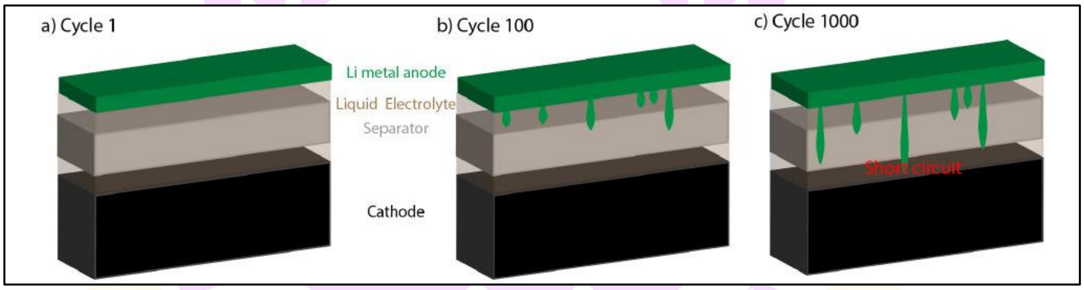


Figure 9 Dendrite formation in liquid electrolyte SSBs [25]

Solid-state electrolytes solve the dendrite problem as the solid nature of the electrolyte prevents the dendrites from establishing the unwanted connection by providing a physical barrier. Solid electrolytes are also significantly less flammable than liquid electrolytes composed of volatile organic solvents, and thus safer even in the case where dendrites may form [25].

Figure 9 provides an SSB schematic with typical materials for key components. This SSB model described by Kim et al [33], features an anode made of lithium metal, a $LiCoO_2$ cathode, and a Lithium Phosphate (Li_3PO_4) solid electrolyte. In the electrolyte, mobile Li^+ ions exist in equilibrium with immobile oxygen bound lithium in the $LiCoO_2$. During discharge, the immobile Lithium undergoes ionization to become Li^+ ions with a negative charge electron e^-. The electrons travel through the external circuit while the Li^+ ions travel from the anode through the electrolyte to the cathode where they are intercalated.

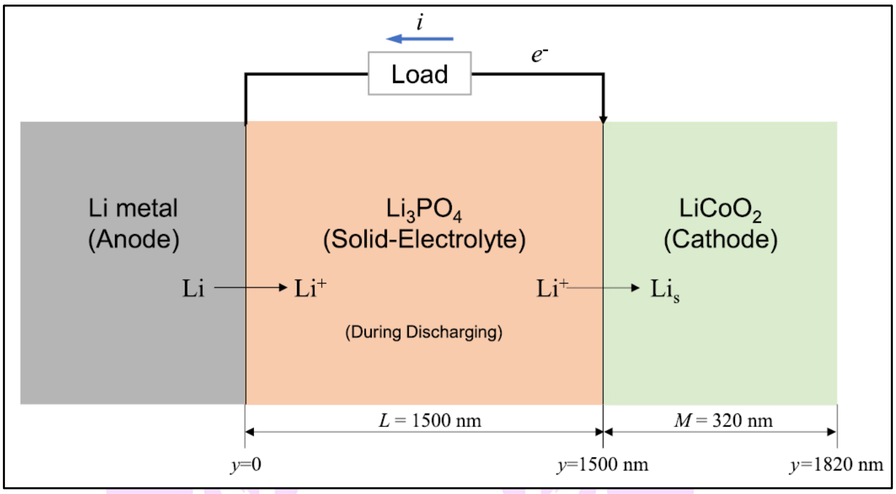


Figure 10 Solid-state battery schematic [33]

Current research in solid-state electrolytes for LIBs centers around three primary goals: (a) improving ionic conductivity, (b) analyzing stability with lithium metal anodes, and (c) minimizing electrical resistance at the electrodes [34]. Table 2-2 provides a high-level comparison between liquid electrotype LIBs and solid-state LIBs.

Table 3 Liquid electrolyte and solid-state LIB comparison [31]

Characteristic	Liquid Electrolyte	Solid State Electrolyte
Manufacturing cost	Inexpensive to manufacture	Expensive to manufacture
Format size	Large format in production	Only small format in production
Interfacial impedance	Low interfacial impedance	Higher interfacial impedance
Ionic Conductivity	Higher near room temperature	Maintained over broader temp range
Electrical Resistance	High electrical resistance	High electrical resistance
Flammability	Flammable electrolyte – safety hazard	Non-flammable electrolyte – safer

Table 3 (cont.)

Characteristic	Liquid Electrolyte	Solid State Electrolyte
SEI layer formation	Degrades performance, shortens life	No formation, longer cycle life
Thermal stability	Poor thermal stability	Excellent thermal stability
Self-discharge	Limits shelf life	Low self-discharge – longer shelf life
Overcharging	Sensitive to overcharge	Not sensitive to overcharge
Inactive materials	More – reduced energy density	Less – higher energy density

There are many types of SSB electrolytes being researched, their advantages and disadvantages differ widely from one to the next. For many, a low electrical conductivity results in a lower power battery. Others are technically viable but suffer from high fabrication costs or are constructed of expensive materials. Several are also unstable in normal environments or react with moisture. Not all SSB electrolytes have every disadvantage, but no one current SSB electrolyte has no disadvantages. Table 2-3 provides a high-level summary from Zheng et al [35] of nine SSB electrolytes which have been the subject of recent research with their primary advantages and disadvantages. In addition to the LiPON type described earlier, the table includes the following types: Sodium Super Ion Conductor (NASICON), Garnet, Perovskite, Lithium Super Ionic Conductor (LISICON), Lithium Nitride (Li_3N), Sulfide, Argyrodite, and Anti-perovskite.

Table 4 Comparison of SSB electrolyte types [35]

SSB Type	Advantages	Disadvantages
NASICON	High ionic conductivity (3-7x10-4 S/cm)	Not cost effective; GeO2 is expensive
Garnet	Good chemical and electrochemical stability	Not stable with moisture/CO2 in atmosphere
Perovskite	High ionic conductivity (≤ 1.8x10-3 S/cm)	Complex Fabrication
LISICON	Stable with Lithium	Low ionic conductivities (≤ 3x10-5 S/cm)
LiPON	Moderate ionic conductivity (≤ 4x10-4 S/cm)	Low ionic conductivities (≤ 1x10-5 S/cm)

Table 4 (cont.)

SSB Type	Advantages	Disadvantages
Li3N	Good chemical and electrochemical stability	Low decomposition voltage (poor stability)
Sulfide	Suitable for thin-film SSBs	Unstable in atmosphere; reacts with moisture
Argyrodite	Reasonable conductivity (≤ 4x10-4 S/cm)	Unstable in atmosphere; reacts with moisture
Anti-perovskite	Highest ionic conductivities (≤ 1x10-2 S/cm)	Very hygroscopic; inert atmosphere required

In summary, the primary advantages of SSBs over their liquid electrolyte LIB counterparts are they are safer, have a longer cycle life, and higher energy density. Current research is focused on improving SSB cycle performance induced by the development of the interfacial resistance layer between the cathode and electrolyte and improving the power output [36]. If these can be overcome, and manufacturing costs lowered, SSBs may overtake liquid electrolyte SSBs particularly in the electric vehicle and portable electronics applications. This is why companies such as Toyota, Solid Energy, Infinite Power Solution, Seeo, Sakti3, Front Edge Technology Inc., Quantum Scape, and Bolloré, are investing heavily in SSB development. However, projections place full SSB development and commercialization at least a decade away [36].

There are other emerging lithium-based battery technologies that have been the focus of promising research such as lithium-air and lithium-sulfur batteries. However, these technologies are probably even further from development and commercialization [27] than SSBs. For that reason, they will not be included in this study.

Vanadium redox flow battery (VRFB) overview

Lourenssen et al [37] describe the VRFB as differing from the other electrochemical batteries by how it stores energy in its electrolytes in external tanks separate from the battery cell itself. The vanadium ions exist in four different oxidation states in the system:

(a) V^{2+}, (b) V^{3+}, (c) V^{4+} (VO^{2+}), and (d) V^{5+} (VO_2^{+}). As shown in Figure 11 there are two distinct sides to the system, the positive side and the negative side.

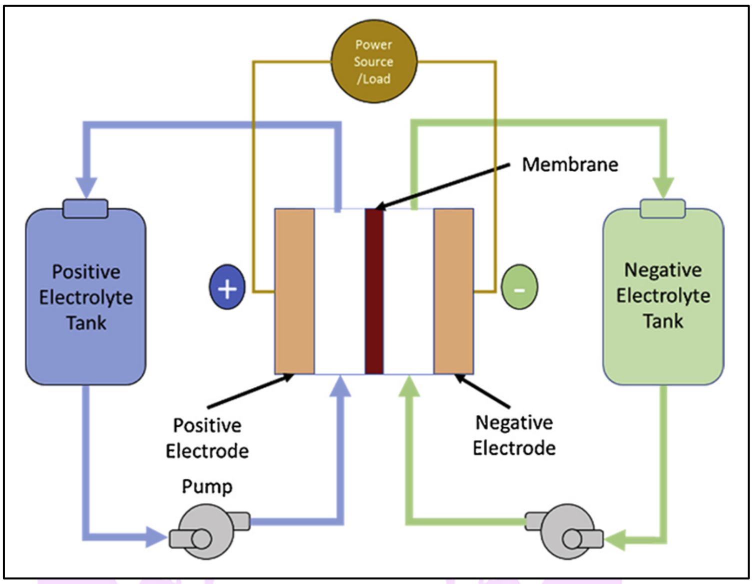


Figure 11 Basic VRFB diagram [37]

The electrolyte on the positive side contains the V^{4+} and V^{5+} ions, while the negative side electrolyte contains the V^{2+} and V^{3+} ions. The electrolytes are pumped through their separate half-cells, returning to their respective storage tanks for recirculation. Each half-cell also contains an electrode and a bipolar plate, while the two sides are separated by a semi-permeable membrane separator which allows the protons (H^+) and electrons to pass while keeping the electrolytes and vanadium ions separated. Following are the half-cell reactions and the overall reaction:

Positive cell reaction: $VO_2^{+} + 2H^{+} + e^{-} \rightleftharpoons VO^{2+} + H_2O$ (4)

Negative cell reaction: $V^{2+} \rightleftharpoons V^{3+} + e^{-}$ (5)

Overall cell reaction: $VO_2^{+} + V^{2+}\ 2H^{+} \rightleftharpoons VO^{2+} + V^{3+} + H_2O$ (6)

Multiple VRFB cells are typically stacked and electrically connected to create an array. The electrolytes are usually fed in parallel to the cells, which maintains a constant concentration of redox ions in each stack. As shown in Figure 12, when completely discharged, the negative side contains only V^{3+} and the positive side contains only VO^{2+}

(V^{4+}). As the battery is charged, the negative electrode is reduced to V^{2+} and the positive electrode is oxidized to V^{5+} (VO_2^+), while electrons move through the bipolar plate from the positive side to the negative side and causes the protons (H^+) to diffuse through the membrane from the positive side to the negative side.

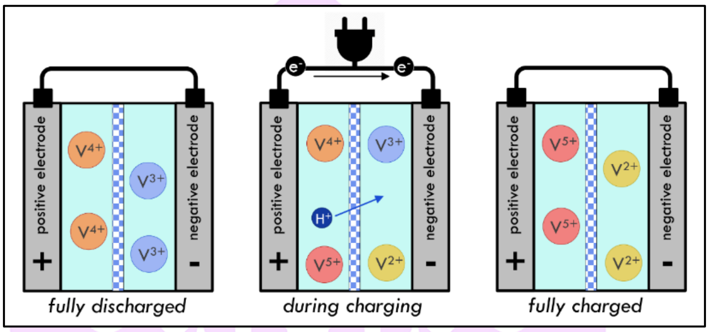


Figure 12 VRFB charging [37]

As shown in Figure 13, the reaction occurs in reverse during discharge. Starting at a fully charged state, the positive side electrolyte has V^{5+} (VO_2^+), while the negative side has V^{2+}. As the battery discharges, hydrogen (H^+) ions (protons) diffuse through the membrane from the negative side to the positive side, while electrons move through the bipolar plate from the negative side to the positive side through the external circuit to do useful work. When the battery is fully discharged, it returns to the state where negative side contains V^{3+} and the positive side contains VO^{2+} (V^{4+}).

A VRFB cell generates an output voltage of 1.26 V and can typically store between 20 and 30 Wh/liter of electrolyte, depending on chemical concentrations.

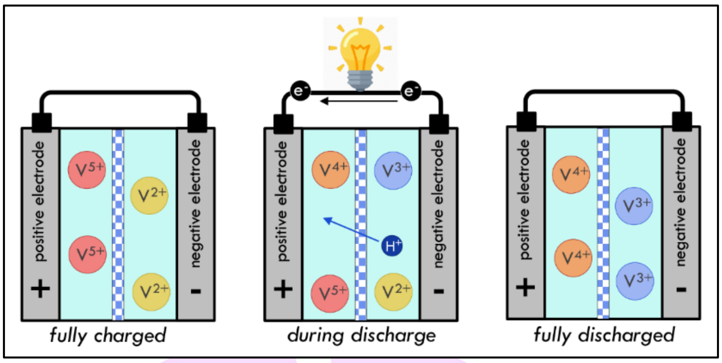


Figure 13 VRFB discharging [37]

Shibata et al [38] describe how the advantages of a VRFB stem from the fact that the battery reaction is simply the change of valence of the vanadium ions in the electrolyte without any solid phase battery reactions:

1. Very long charge/discharge cycle service life
2. Electrolyte life not susceptible to deep–discharge or a complex charge/discharge pattern
3. Uses a safe, incombustible electrolyte
4. Capable of storing bulk energy (high output, large capacity)
5. Capable of short–term, high–output operations.

Lourenssen, et al. [37] state that the VRFB also has the following disadvantages:

1. High cost
2. Thermal precipitation within the electrolyte
3. Limited energy density
4. Degradation that can occur within the cell from the harsh environment created by the sulfuric acid and vanadium.

Claims by VRFB manufacturers indicate that many of these issues have been overcome in current systems, although the VRFB continues to have low power densities.

This study focuses on containerized VRFB ESS appropriate for the small, isolated village microgrid energy storage application. Some of the currently available commercial systems that are included in this study are shown in Figure 14

Figure 14 Containerized VRFB ESS; clockwise from top-left: Sumitomo AC250kW, Rongke Vmodule1-A, StorEn ST 50-500, WattJoule ElectriStor500

Community microgrid analysis scenario

The US Department of Energy (DOE) [39] defines "the grid" as the "network of transmission lines, substations, transformers and more that deliver electricity from the power plant to your home or business". Ton and Smith [40] provide the US DOE definition of a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode". As stated in Section 1.0, this paper is examining BESS technologies in the specific application of a microgrid in "island-mode", that is disconnected from the main power grid.

The US DOE [41] in its New Mexico Smart Grid Demonstration project (2015), describes how an isolated microgrid which relies on renewable power sources, primarily PV and in some cases wind and micro-hydro, is subject to a wide variation in energy production between days and even hours due to cloud cover, sun angle, wind speed, and other factors. Energy storage systems provide the key role in these renewable-based microgrids, and in particular disconnected microgrids, by shifting energy by storing it during peak production times and providing it during times when demand exceeds production. DOE also describes the other key function of storage systems in smoothing fluctuations in renewable power production by flattening spikes and troughs in the energy system's total output [41]. Bush [42] further describes how storage systems can correct sources of "noise" which impact power quality such as power factor, transient instability, flicker, voltage sags or swells, and harmonics.

Bowen, et al. [43] describe how several battery chemistries are available or under investigation for these microgrid-scale applications, including the four types reviewed in this study. The current market for grid-scale battery storage in the United States and globally is dominated by lithium-ion chemistries Figure15 The recent surge in LIB usage is mainly due to significantly increased manufacturing which has prompted a steep price decline of over 70% from 2010-2016. However, in many small systems designed for use in poor rural communities, lead-acid batteries still feature due to their lower initial cost, greater availability, and simpler maintenance and operation.

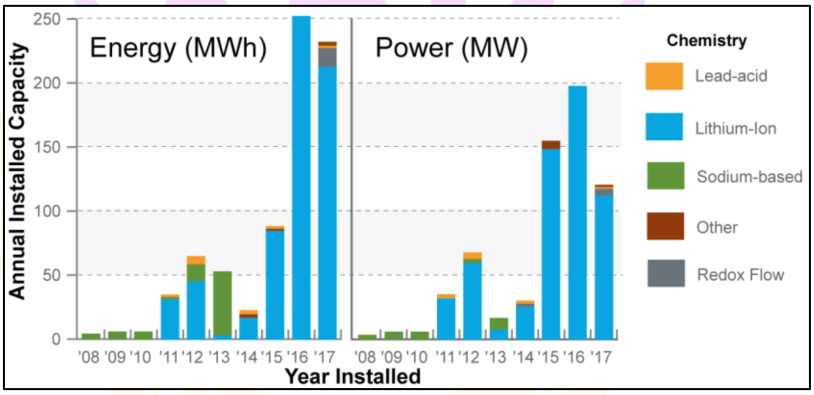


Figure 15 Utility-scale battery storage capacity in the U.S. [43]

The amount of energy storage required for any application depends on a variety of characteristics, including the following listed by Bowen et al [43]:

1. The mix of energy generation technologies
2. Flexibility in existing generation sources
3. Interconnections with neighboring power systems

4. The hourly, daily, and seasonal profile of electricity demand, and

5. The hourly, daily, and seasonal profile of renewable energy sources.

Furthering the analysis scenario for this study of a poor, isolated, off-grid rural community, there are many definitions of “rural”, but in general rural areas feature small population clusters (villages) and a low population density. When these rural areas are isolated from larger population centers, the challenge to bring electrical power to them via transmission lines can easily become too costly due to the large distances and many times difficult terrain for so few recipients.

In the developing world, a common solution for these disconnected communities has been for local diesel generator electrical production and crude local transmission lines. However, in recent years advancements in renewable energy technologies, accompanied by rapidly decreasing costs and availability of outside funding, has allowed rural communities to build integrated renewable energy systems, essentially a microgrid, to provide a more sustainable source of electrical power for their residents. These village microgrids combine various renewable energy generation technologies (e.g., PV, wind, micro-hydro, biodiesel, etc.), electrical conversion and monitoring systems, local distribution lines, and an ESS [44].

Zimmerle and Manning [45] remark that there is a lack of real world measured electrical demand data for off-grid scenarios especially for remote agricultural villages. So, for many studies, demand data is determined from analysis. David Mackay’s [46] widely cited country-by-country graph of human power-consumption is show in Figure 16 The developing nations at the bottom of the graph show a daily electrical demand of about 5-10 kWh per person. But these national statistics include urban areas which tend to have higher levels of electrification, so the rural areas can be assumed to be less, and poorer rural areas being far less [47].

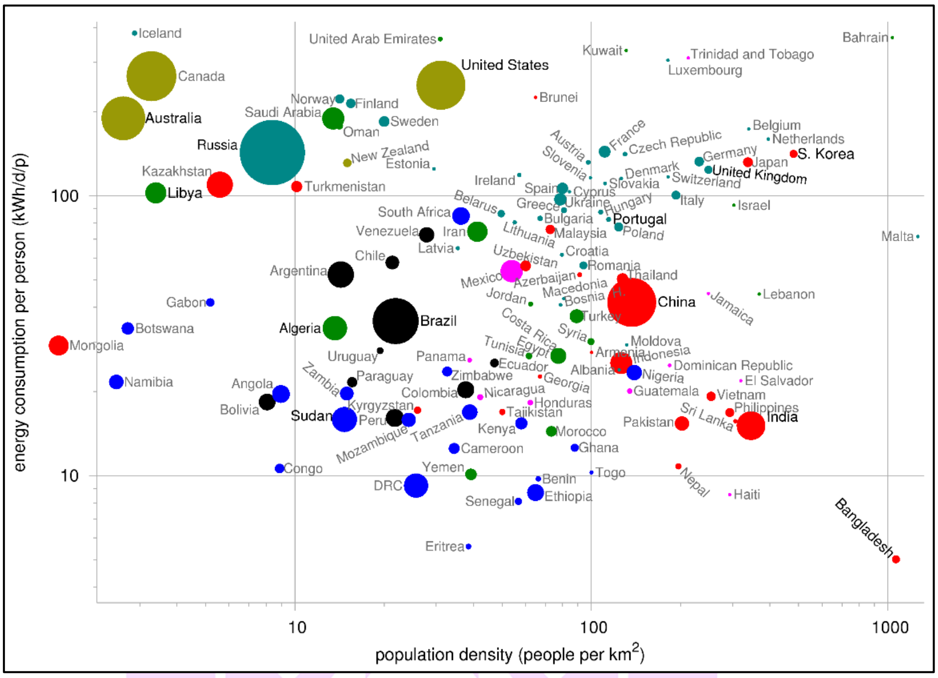


Figure 16 Country–by country energy consumption per person [from 46]

The World Bank's [48] Energy Sector Management Assistance Program (ESMAP) provides a multi-tier framework for defining and measuring access to energy through metrics. This multi-tier approach measures access to energy supplies, with successive tiers capturing improved levels of quantity, quality, reliability, and affordability of energy supply. The framework's tiers for households range from Tier 0 (no access) to Tier-5 (highest level of access), with the access criteria shown below:

1. Tier 0: No access
2. Tier 1: Task lighting AND Phone charging
3. Tier 2: General lighting AND Phone Charging AND Television AND Fan (if needed)
4. Tier 3: Tier 2 AND any medium-power appliances
5. Tier 4: Tier 3 AND any high-power appliances
6. Tier 5: Tier 2 AND any very high-power appliances

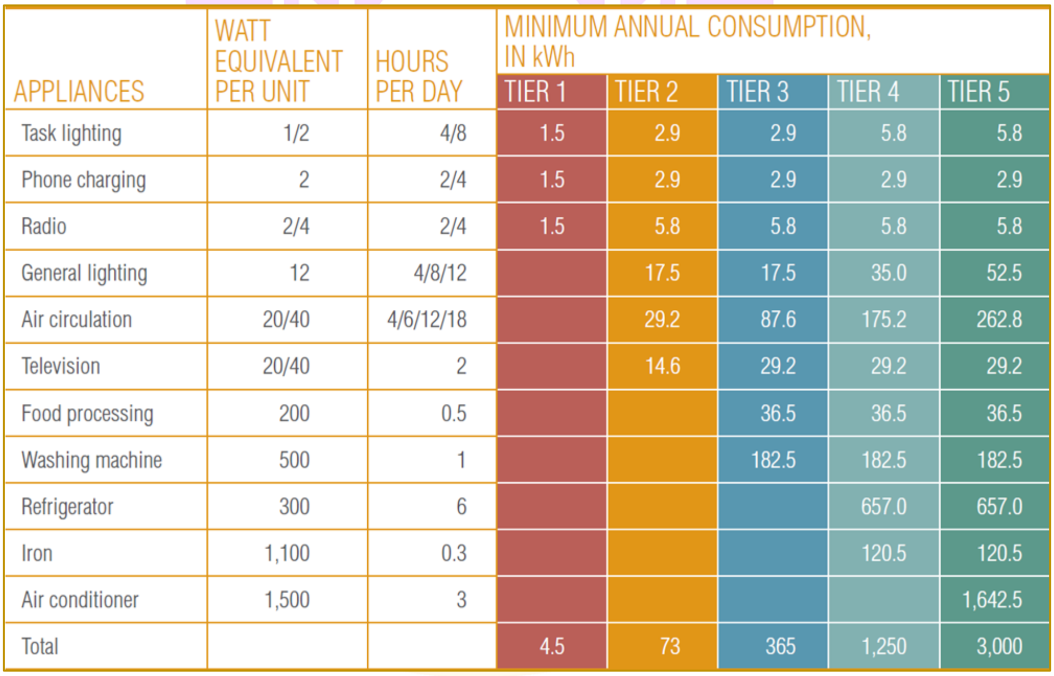
Figure 17 summarizes the household energy consumption level for each tier while Figure 18 lists the detailed household loads for each tier.

	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

Figure 17 ESMAP household electricity consumption tiers [48]

Other studies provide additional information to scope the demand and battery storage requirements of the notional rural community.

Nandi and Ghosh [49] examined a hybrid solar-wind integrated renewable energy system for 120 homes in an off-grid rural area in Sitakunda, Bangladesh. Their analysis determined the electrical demand for the village to be 169 kWh/day which equates to 1.41 kWh per household per day. This places Sitakunda just above Tier 3 in the ESMAP framework.



APPLIANCES	WATT EQUIVALENT PER UNIT	HOURS PER DAY	MINIMUM ANNUAL CONSUMPTION, IN kWh				
			TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Task lighting	1/2	4/8	1.5	2.9	2.9	5.8	5.8
Phone charging	2	2/4	1.5	2.9	2.9	2.9	2.9
Radio	2/4	2/4	1.5	5.8	5.8	5.8	5.8
General lighting	12	4/8/12		17.5	17.5	35.0	52.5
Air circulation	20/40	4/6/12/18		29.2	87.6	175.2	262.8
Television	20/40	2		14.6	29.2	29.2	29.2
Food processing	200	0.5			36.5	36.5	36.5
Washing machine	500	1			182.5	182.5	182.5
Refrigerator	300	6				657.0	657.0
Iron	1,100	0.3				120.5	120.5
Air conditioner	1,500	3					1,642.5
Total			4.5	73	365	1,250	3,000

Figure 18 ESMAP household electricity consumption details, by tier [48]

In a 2016 study, Patel and Singal [50] analyzed the Indian village of Khatisitara located in the Banaskantha district of the Gujarat state. Khatisitara's study area had a population of 562 in 101 households and is also representative of the rural village considered for this study. Patel and Singal designed and analyzed a renewable energy-based system using HOMER software, which considered a routine rural daily lifestyle of hourly domestic, commercial, agriculture and community activities. The village's energy load demand was estimated at 394 kWh/day, which equates to 3.90 kWh per household per day. This places Khatisitara just above Tier 4 in the ESMAP framework.

Rajanna and Saini [51] conducted a study on models to optimally size a renewables-based microgrid in unelectrified villages in four different zones in the Chamarajanagar district of the Karnataka state in India. There are 513 small, scattered, and thinly populated villages in the district, where the poor villagers are principally engaged in agriculture and animal husbandry. The district includes 2240 households with a population of 4440. The study used HOMER to calculate energy demand, which included domestic loads (lighting, TV, fan and radio/music system), community loads (primary health center, street lights, and school lighting), commercial loads (lighting for shops and flour mill), and small scale industrial loads (saw mill and paddy rice huller). Table 5 summarizes their results, which provides an estimated daily household energy demand ranging from a low of 1.86 kWh/day for Zone 3 to a high of 2.47 kWh/day for Zone 1. This places Chamarajanagar in the lower range of Tier 3 in the ESMAP framework. The maximum load demand occurred as expected in summer and ranged from a low of 110 kW for Zone 2 to a high of 210 kW for Zone 4 [51]. All 4 zones would be at ESMAP Electricity Consumption Tier 3.

Table 5 Analysis summary for unelectrified villages in Chamarajanagar district of the Karnataka state in India [summarized from 51]

	Zone 1	Zone 2	Zone 3	Zone 4	Total
Annual Energy Demand (kWh/yr)	272,398	344,819	516,873	673,416	1,807,506
Number of Households	302	395	763	780	2240
Household Energy Demand (kWh/yr)	902	873	677	863	807
Household Energy Demand (kWh/day)	2.47	2.39	1.86	2.37	2.21 (avg)
Max Load Demand (kW)	165	110	155	210	160 (avg)
ESMAP Electricity Consumption Tier	3	3	3	3	3

Based on the ESMAP framework and the cited studies, this analysis scenario will assume a notional village with 125 households at twice the ESMAP Tier 3 threshold; this equates to a daily household energy demand of 2.0 kWh per day and a village demand of 250 kWh/day. The storage system should be capable of providing a minimum of 200 kW power to support a maximum summertime load when no energy is being generated.

Ma et al [52] conducted a 2014 study for a stand-alone hybrid solar-wind-battery system for a grid-isolated island, a scenario similar to the isolated rural village. Their simulation results from HOMER determined the number of Hoppecke deep-cycle, lead-acid batteries required for various daily loads. Table 6 shows the conversion of their results into energy storage capacity requirements for the daily loads.

Table 6 Battery usable capacity requirements for various daily loads [52]

Mean Daily Load (kWh/day)	Energy Storage Requirement (kWh)
150	202
200	504
250	605
300	706
350	806
400	907

Based on the notional village analysis scenario, a BESS with a usable capacity of 605 kWh at end of life is required for the 250 kWh/day, 200 kW microgrid system, as shown in Figure 2-17.

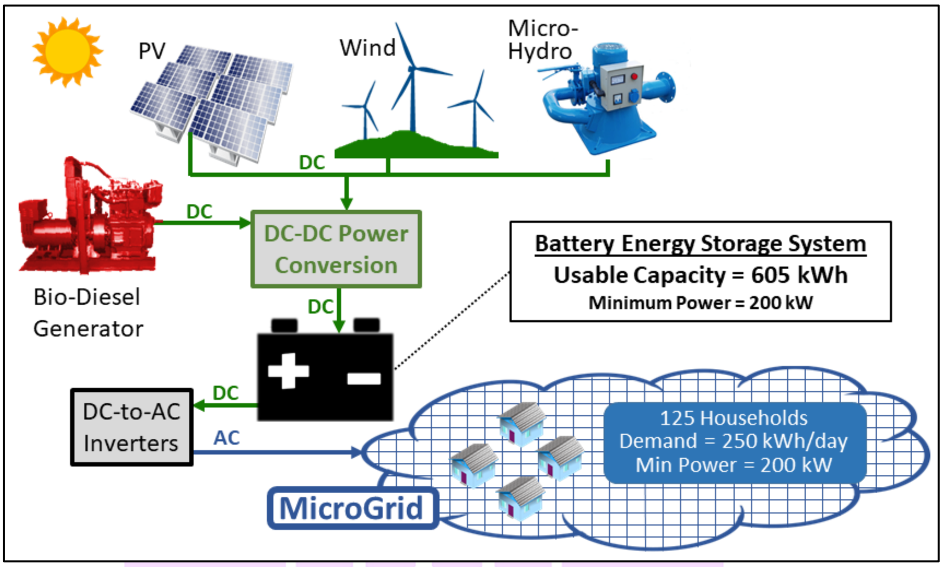


Figure 19 Analysis scenario notional microgrid system with BESS

Chapter 3

RESEARCH METHODOLOGY

This section describes the steps taken for this research as shown in Figure 20 Section 2.0 defined the four BESS technologies and the analysis scenario, which serve as inputs into the Section 4 analysis.

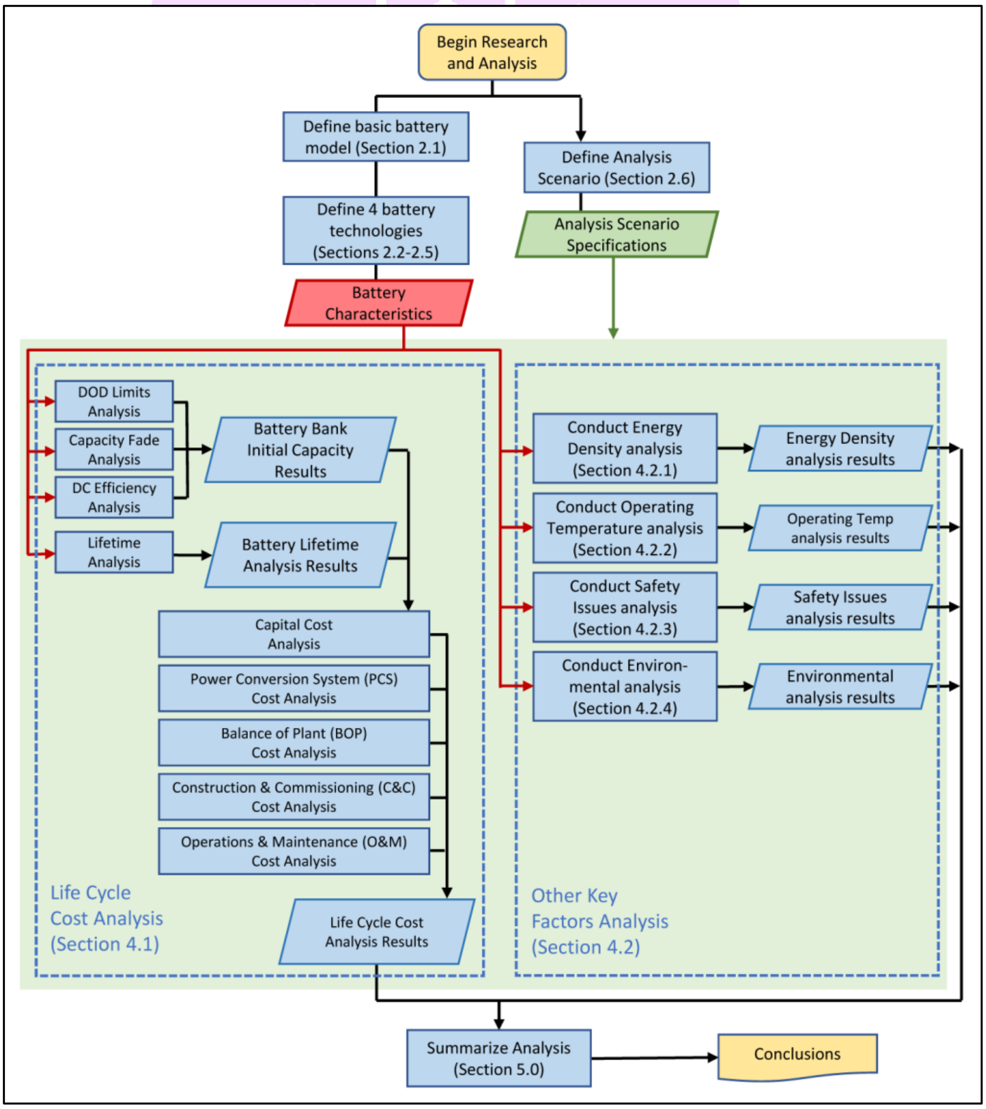


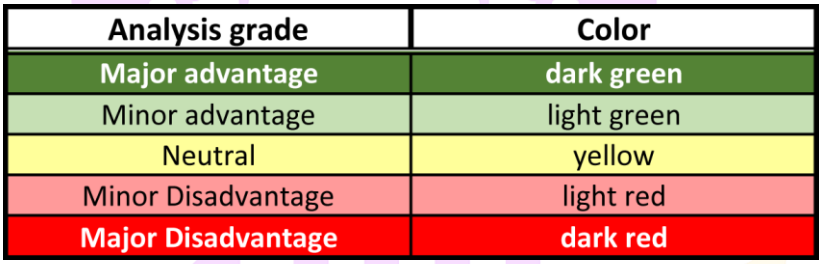
Figure 20 Research methodology

The scenario provides a set of common criteria against which each of the four technologies are evaluated in two parts in Section 4:

1. Part 1 (Section 4.1): life cycle cost analysis, including factors used as inputs into the capital cost analysis: DOD limits, efficiency, capacity degradation, battery life expectancy, and O&M requirements.

2. Part 2 (Section 4.2): an analysis of four other factors that were not inputs into the cost analysis, but are still key considerations: energy density, operating temperature limits, safety issues, and environmental concerns.

For each analysis area, a rubric analysis was conducted to assess each technology for that respective area against a set of evaluation criteria. An overall evaluation grade was assigned for each technology in each category based on the rubric analysis. The color-coded grading scale used in the rubric grading system is shown in Figure 21



Analysis grade	Color
Major advantage	**dark green**
Minor advantage	light green
Neutral	yellow
Minor Disadvantage	light red
Major Disadvantage	**dark red**

Figure 21 Color-coded rubric analysis grading scale

With the financial incentives associated with the rapid growth in importance of grid-level energy storage comes a significant amount of research. This research has the effect of steadily improving BESS performance while lowering costs due to improvements in manufacturing. As a rapidly changing technology, this paper reflects the state of the BESS technologies at about the time of publication in mid-2020.

Life cycle cost analysis research methodology

Mongird et al [7] characterized costs for 11 ESSs (including non-battery-based systems) in a 2019 report for the US Department of Energy (DOE), which provides the methodology for this study's lifecycle cost analysis. Table 3-1 displays their cost calculation factors for three of our ESS technologies: lead-acid batteries, liquid electrolyte LIBs, and redox flow batteries. A life cycle cost analysis was not conducted for solid-state lithium-ion batteries as batteries using that technology are not yet in production, so the cost data is not yet available. As shown in Table 3-1, Mongird's [7] methodology defines Total Project Cost as the sum of Capital Cost, Power Conversion System (PCS) costs, Balance of Plant (BOP) costs, and Construction and Commissioning (C&C). The methodology includes Fixed and Variable O&M costs separately.

Table 7 Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type [7]

Parameter	Lead-Acid Battery		Liquid Electrolyte LIB		Redox Flow	
	2018	2025	2018	2025	2018	2025
Capital Cost ($/kWh)	260[1]	220[2]	271	189	555	393
PCS ($/kW)	350	211	288	211	350	211
BOP ($/kW)	100	95	100	95	100	95
C&C ($/kWh)	176	167	101	96	190	180
Total Project Cost	Sum of Capital Cost, PCS, BOP, and C&C					
O&M Fixed ($/kW-yr)	10	8	10	8	10	8
O&M Var. (cents/kWh)	0.03	0.03	0.03	0.03	0.03	0.03
Total Estimated Cost	Sum of Total Project Cost and O&M Costs					

Note: [1] Actual cost data for lead-acid batteries obtained from Internet battery vendors used in the analysis

[2] Annual cost reduction data from Mongird [7] (2.35%) applied to actual costs for out years

Capital Cost (estimated by $/kWh) pertains to the procurement of the DC battery system to provide the energy storage capability required by the scenario, that is 605 kWh of usable energy storage at the battery's end of life. It also includes procurement of replacement batteries over the course of the 20 year scenario. Power Conversion System

(PCS) costs (mostly the inverter) and Balance of Plant (BOP) costs (wiring, transformers, other ancillary equipment) are estimated using the power output of the ESS in kW, which is 250 kW for the analysis scenario. Mongird [7] makes the assumption that PCS and BOP costs can be estimated by $/kW then converted to $/kWh by multiplying by four (given the assumed energy-to-power ratio of four). Construction and Commissioning (C&C) costs consist of site design costs, costs related to equipment procurement/ transportation, and the costs of labor/parts for installation, estimated by $/kWh. Total project cost for this analysis equals the sum of the 20 year capital cost, PCS, BOP, and C&C costs.

The British Standards Institute [53] defines maintenance as “a combination of all the technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition”. Mongird [7] defines fixed O&M as those costs necessary to keep the storage system operational throughout the duration of its life that do not fluctuate based on energy usage, estimated with respect to the rated power of the storage system and calculated by $/kW-yr. Variable O&M includes all costs necessary to operate the storage system throughout the duration of its life normalized with respect to the annual discharge energy throughput, calculated as cents/kWh. Variable O&M costs account for wear and tear of the system during operation. Based on two energy storage cost studies by Aquino et al [54, 55] which show O&M costs to be roughly equal for all BESS, Mongird [7] uses the same factors for all three technologies.

As shown in Figure 22, a BESS’s initial capacity at time t_0 must be scaled up from the base 605 kWh scenario requirement to account for three factors: (a) operational limits to DOD, (b) DC round-trip efficiency, and (c) capacity degradation over the system’s lifetime to ensure that the BESS continues to provide 605 kWh of useful storage capacity at the battery’s end of life or just prior to replacement at time t_r.

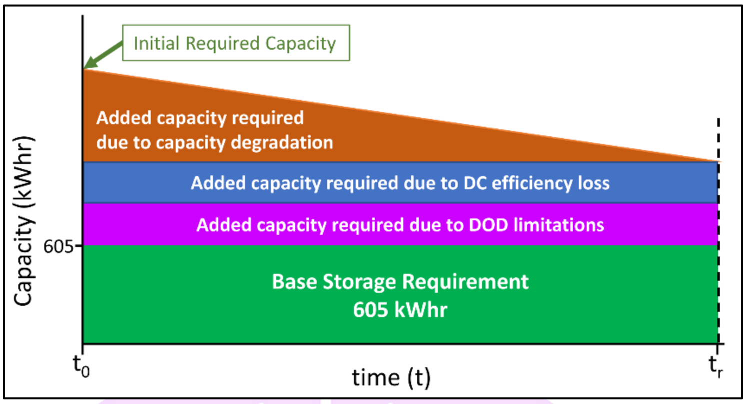


Figure 22 BESS initial capacity factors

Depth of discharge (DOD) is a measure in percent of how deeply a battery is or can be discharged. For example, when a battery is 100% charged, its DOD is 0% and conversely when it has been fully discharged, its DOD is 100% [56]. The effects of deep discharge events and DOD differs between the battery technologies considered in this study. For example, deep discharge events for lead-acid batteries cause them to lose capacity and lead to shorter lifetimes [17]. However, VRFBs can be fully discharged to 100% DOD and be restored to a full charge for a large number of cycles over many years and not lose capacity [37]. For this reason, manufacturers impose operational DOD limits on their batteries which limits the usable capacity, necessitating initially procuring a larger battery.

DC round-trip efficiency is defined as the ratio of net energy that is discharged to the net energy used to charge the battery, where the losses are usually attributable to internal resistances and auxiliary loads such as pumps, thermal control systems, and battery management systems [7]. A BESS's efficiency therefore requires accordingly more capacity to be sized into the initial battery bank design.

The third factor considered is capacity degradation over a battery's lifetime. The initial battery bank should be sized such that by the replacement time, the system still provides the required amount of storage. A common example is the LIB in a mobile phone, which loses capacity during its lifetime as described in Section 2.3.

Once these three factors are applied, the initial battery bank capacity size can be determined. The next consideration affecting capital cost is battery life as it determines when a battery system needs replacement, which drives overall lifecycle costs. As the scenario spans 20 years, if a BESS has a life expectancy of less than 20 years, then enough replacements must be factored into the capital cost to ensure the required storage capacity is still available at the 20 year point.

For the LIB and VRFB, procurement cost was estimated using the factors shown in Table 3-1, based on $/kWh from Mongird [7]. For lead-acid batteries, actual current system costs were obtained from Internet sources. Lead-acid battery capacity data was obtained from manufacturer specifications, while procurement cost data was obtained from independent Internet-based vendors. For all battery systems, costs were decreased over the 20 year scenario time based on the rates assumed by Mongird [7]. The life cycle cost analysis results are presented in Section 4.1.

Other key factors analysis methodology

Energy density research methodology

A battery's energy density is defined as a battery's energy per unit volume; sometimes referred to as volumetric energy density. Energy density is expressed in units of Wh/liter and determines the battery size required to store a given amount of energy. A battery's specific energy is defined as a battery's energy per unit mass and is expressed as Wh/kg [57]. Specific energy determines the battery's weight required to store a given amount of energy.

A key concept to be considered in volumetric energy density measurements pertains to what is actually being measured for the volume. At the first level are the individual battery units, such as a lead-acid battery case, or a rack of batteries. Next are integrated battery systems such as a battery wall unit for a residence, which may include user interface components, thermal controls, and ventilation components. Then there are fully containerized systems typical of grid storage applications. These can include large heating, ventilation, and air conditioning (HVAC) and fire suppression subsystems, inverters, distribution cabling, as well as adequate space for maintenance personnel to access the systems inside. These distinctions were considered in this analysis to allow for an apples-to-apples comparison.

Lead-acid batteries were analyzed for energy density by making calculations based on the rated capacity and battery enclosure sizes from a number of manufacturers' specifications. The results from this analysis are presented in Section 4.2.1.1.

Energy density is a key attribute for why liquid electrolyte LIBs have become the dominant energy storage technology in so many current applications. Energy density for electric vehicle and personal electronic batteries is one of the key battery attributes with massive research efforts being funded to improve this parameter [58]. The Panasonic liquid electrolyte LIB in the Tesla Model S is representative of the state of the art for liquid electrolyte LIB energy density, delivering 100 kWh from its 8,256 cells. Ulvestad estimates that this equates to a volumetric energy density of 732 Wh/liter and a gravimetric energy density of about 270 Wh/kg [25]. These numbers roughly agree with Inside EVs' [59] teardown of a Tesla Model 3 2170 which measured 246 Wh/kg and 711 Wh/liter. But as with lead-acid batteries and battery rooms, the total enclosure size of an integrated LIB grid storage system is more applicable to our analysis than the energy density in the stand-alone battery unit. This considers necessary auxiliary systems such as HVAC for thermal control, fire suppression, battery management, and AC inverters. Also, volumetric energy density is more significant than gravimetric energy density for a stationary grid storage system. For the analysis, liquid electrolyte LIB energy density was calculated by examining the rated capacity and enclosure sizes from a number of containerized, integrated LIB systems manufacturer's specifications. The results from this analysis are presented in Section 4.2.1.2.

As SSBs are not yet a commercialized system, manufacturer specifications do not exist. But based on research findings, some generalized energy density conclusions were made and presented in Section 4.2.1.3.

Compared to the other technologies, VRFBs have low energy densities, making them unsuitable for applications where size and weight are key concerns, such as personal electronic devices and electric vehicles [37]. The capacity of a VRFB is determined solely by the amount of electrolyte in the system and is independent of the electrical power output which is determined by the size of the cell. To increase the energy storage capacity, the size of the tanks just needs to be increased and more vanadium electrolyte used [38]. To increase system power, more cells need to be added to the stack. In this way for any given system, capacity and power can be designed independently [60], a significant advantage of VRFBs. At the electrolyte level, the energy density of the vanadium electrolyte has been steadily improving over the past decade. In 2011, Li et al [60] demonstrated “high” energy density electrolytes with energy densities between 22.3 to 43.1 Wh/liter in their single cell experiments. WattJoule’s currently available ES500 system has an electrolyte energy density of 25 Wh/liter but projects its Generation 2 system will double that to 50 Wh/liter in 2021 and increase it to 150 Wh/liter by 2024 [61]. As with LIB-based systems, the size of an integrated VRFB system is a more applicable metric than the energy density of the electrolyte or the battery cell. VRFB systems appropriate for our scenario system are typically containerized, with the stack, tanks, piping, pumps, and auxiliary systems all within the container. For the analysis, VRFB energy density was calculated by examining the rated capacity and enclosure sizes from the manufacturers’ specifications for a number of containerized, integrated VRFB systems. The results are presented in Section 4.2.1.4.

Temperature limits research methodology

The effect of temperature on a battery’s performance is a key consideration for our scenario. As shown in Figure 23, the poorer areas of the world indicated by the light and dark blue shades are predominantly in hotter regions, where the effects of high temperatures on energy storage systems must be considered.

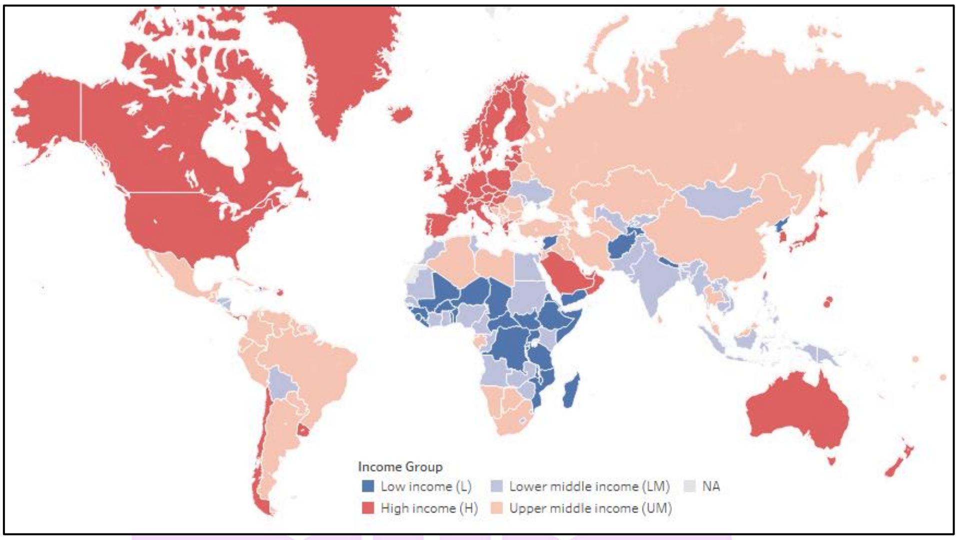


Figure 23 The world by income – World Bank [62]

A battery's life can be defined as the number of cycles it can deliver before its end of life. Along with DOD, operating temperature has a major effect on lead-acid battery life. High temperatures result in a higher chemical reaction rate which increases battery capacity, but also reduces the battery's life. The effects of operating temperature for lead-acid batteries was gathered from research literature and manufacturers' recommendations and the analysis results are presented in Section 4.2.3.1.

As described by Liu et al [63], liquid electrolyte LIB systems experience significant issues with operation at both the low and high end of the operational temperature range. At low temperatures, the LIB's internal resistance increases and available capacity decreases, i.e., both available energy (Wh) and maximum power (kW) are reduced. At high temperatures, the LIB suffers from both safety issues and reduction in battery life. As a result, integrated LIB systems designed for grid energy storage applications all feature thermal controls to maintain temperature within the LIB's operating range. The operating temperature ranges for containerized LIBs were researched from various LIB manufacturers' specifications with the analysis results presented in Section 4.2.3.2.

As described in Section 2.4, operating temperature limits on SSBs differ between the various potential SSB technologies. Some generalized analysis was conducted from SSB research literature, with the results presented in Section 4.2.3.3.

For VRFBs, Zhang et al [64] described how precipitation in the vanadium electrolyte occurs at both high and low temperature limits, which can lead to degradation of energy capacity and can cause maintenance problems with the pumps. However, since this 2015 study, researchers and manufacturers have made significant progress in the chemistry of the vanadium electrolyte solutions to significantly widen the operating temperature range at both the low and high end. Pioneering work in this area was conducted by the US Department of Energy's Pacific Northwest National Laboratory [65] in their development of new vanadium electrolytes that relied on reactions with a chloride solution which solved many of the early problems with the vanadium electrolyte. These new electrolytes featured both higher energy densities and wider temperature ranges, as seen in current VRFB manufacturers' specifications. The operating temperature ranges for containerized VRFBs were researched from various VRFB manufacturers' specifications with the analysis results presented in Section 4.2.3.4.

Safety issues research methodology

Across all battery technologies, standard electrical safety precautions are required when working around live circuits. However, beyond that each of the technologies has its own unique safety issues.

Lead-acid batteries have been in use for well over a century and are generally considered safe, but there are several dangers associated with their use which must be considered. These dangers are collected and summarized from research literature and online sources with the analysis provided in Section 4.2.3.1.

Most liquid electrolyte LIB explosions and fires are attributed to manufacturing defects, but the volatile liquid electrolyte's inherent properties create the primary safety concerns. Dendrite formation, discussed in Section 2.3, is a key mechanism which can lead to thermal runaway caused fires and explosions. There have been numerous safety incidents and even deaths attributed to liquid electrolyte LIBs since Sony introduced the first commercialized LIB in 1991. Section 4.2.3.2 presents some of these incidents as well as an analysis of overall LIB safety.

The safety record for large scale SSB systems is not well-established as there is far less history on these systems and safety considerations will likely vary between the different competing SSB technologies. Section 4.2.3.3 presents the analysis of projected SSB safety based on research literature.

Much higher safety is an advantage that VRFBs have over the other technologies. VRFB safety information was collected from research literature with the analysis presented in Section 4.2.3.4.

Environmental considerations research methodology

There are many aspects to the environmental impact of stationary battery systems designed for grid storage applications. Figure 3-5 from the Environment Directorate General of the European Commission [66] shows many of these aspects.

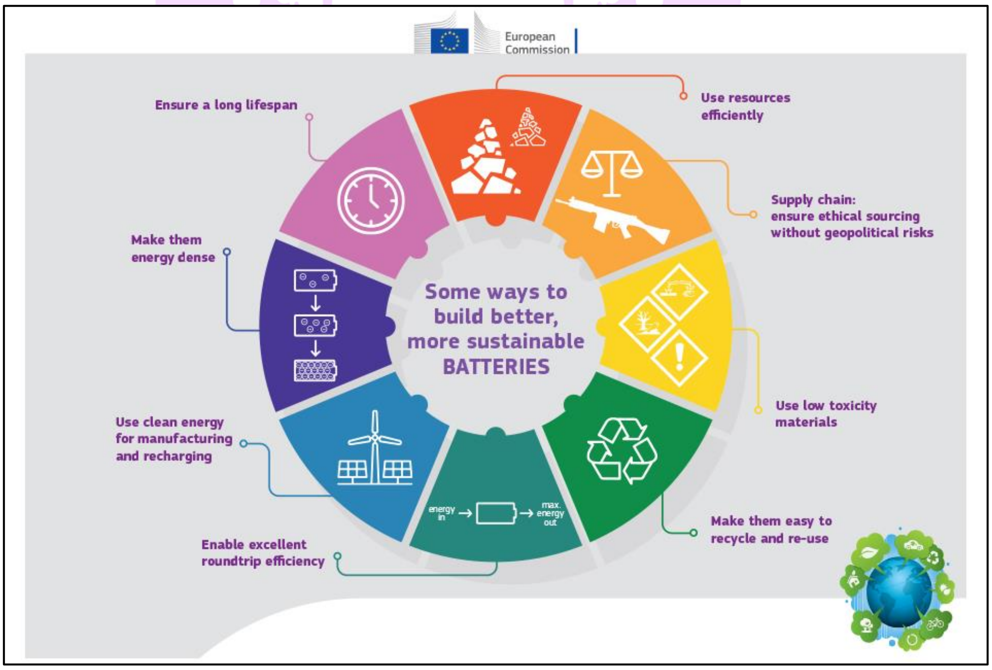


Figure 24 Sustainable batteries [from 66]

Although considerations such as use of scarce resources, energy use during manufacture, and ethical supply chain practices are important, this study focuses on the environmental impacts at end of life in regard to system disposal and recycling.

The environmental track record of lead-acid batteries is well established. Environmental-related information for lead-acid batteries was collected from research literature and online resources and analyzed, with the results presented in Section 4.2.4.1.

As newer technologies, the environmental track record of liquid electrolyte LIB and VRFB systems is less established, but data was collected and analyzed as presented in Sections 4.2.4.2 and 4.2.4.4, respectively. Again, since SSBs are not yet commercialized, the environmental impacts are not well established, but it can be assumed they will be similar to current liquid electrolyte LIBs, as presented in Section 4.2.4.3.

Chapter 4

RESULTS

Cost analysis results

Lead-acid battery cost analysis results

Frequent deep cycling is a major cause of shortened lead-acid battery service life, but daily cycling is expected in an off-grid solar-based renewable BESS. Modern lead-acid batteries designed for this application perform better than batteries from the past, but DOD limits still force the installation of larger capacity battery banks to limit the detrimental effects of deep cycling as shown in Figure 4-1 for Trojan lead-acid batteries.

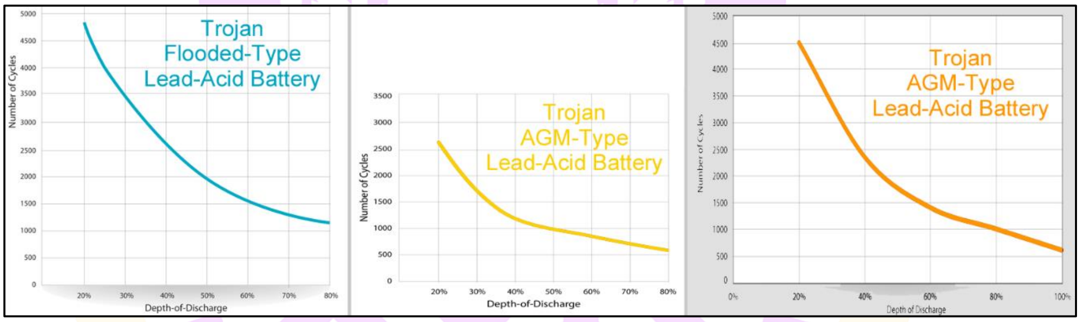


Figure 25 Lifetime cycles vs. DOD for lead-acid batteries [67-69]

The recommended operational DOD limit for lead-acid batteries is assumed to be 50% based on recommendations from lead-acid battery manufacturers and vendors [70-72]. This limitation alone requires a doubling in size of the initial battery bank as half the capacity would never be used. On top of that, an 85% DC round trip efficiency [14] and a capacity degradation to 80% of initial capacity at end of life [18] determines that the lead-acid battery bank's initial rated capacity be 1780 kWh to deliver 605 kWh of usable energy storage at the end of each replacement cycle for the village scenario.

As will be described further in Section 4.2.2.1, elevated operating temperature is a key factor that shortens lead-acid battery life. Other life shortening factors include overcharging and undercharging, DC ripple current, and expansion and corrosion of the positive grid structure due to oxidation of the grid and plate materials [73]. Battery University states that deep-cycle lead-acid batteries deliver 100–200 cycles before a gradual decline begins and advises that the batteries be replaced when capacity drops to 70-80% [74]. Assuming that the off-grid scenario system experiences one primary cycle per day (charging during the day and discharging at night) down to the recommended 50% DOD, and ideal operating temperatures are maintained, the lifetime expectancy for each type was determined as follows:

1. Flooded: 2000 cycles or 5.5 years based on the Trojan Solar Premium
2. Gel: 1000 cycles or about 3 years based on the Trojan Deep Cycle Gel
3. AGM: 1700 cycles or 4.5 years based on the Trojan Solar AGM Line.

These values were compared with at least four other manufacturers for each of the three lead-acid types and are representative for the purposes of this analysis, although the expected number of lifetime cycles varied from manufacturer to manufacturer. Using these life expectancies, replacement frequency was determined for the 20 year scenario:

1. Flooded: Three replacements in years 6, 11, and 16
2. Gel: Seven replacements in years 3, 5, 8, 10, 13, 15, and 18
3. AGM: Four replacements in years 5, 9, 13, and 17

Capital cost in year-0 was determined by averaging battery costs for each of the three types, then extending the unit costs and capacities to the1780 kWh total, then accounting for the 20-year scenario battery bank lifetime based on lead-acid battery life expectancy. To determine initial cost, data was collected for 103 different lead-acid battery models from four leading manufacturers:

1. Flooded type - 42 total models
    1.1 17 models from Trojan's Solar Industrial and Solar Signature lines
    1.2 4 models from Crown's CRP Monobloc and Power Module Series lines
    1.3 21 models from Exide's GNB Classic Solar line
2. Gel type - 33 total models
    2.1 7 models from Trojan's Solar Deep-Cycle Gel line
    2.2 26 models from Hoppecke's sunlpower VR line

3. AGM type – 28 total models
    3.1 11 models from Trojan's Solar Deep-Cycle AGM line
    3.2 7 models from Crown's AGM CRV Monobloc Series line
    3.3 10 models from Exide's GNB Sonnenschein SOLAR line

For each of the 103 models, cost per kWh was calculated from Internet cost data and manufacturers' capacity data. Cost per kWh was then averaged for each of the three types, then these averages were used to cost the initial 1789 kWh scenario battery bank. Replacement cost in any given year was determined using a linearly decreasing cost scale of 2.36% per year starting from year-0, based on the cost reduction rate from Mongird's [7] 2018 and 2025 data. The final capital cost results are shown in Table 8

Table 8 Lead-acid battery capital cost summary

Battery Type	Cost per kWh	Initial Cost	Replacement Cost	Total Capital Cost	Cost Source
Flooded	145	258,139	612,903	871,042	[75-77]
Gel	258	460,081	2,598,857	3,058,937	[75, 78]
AGM	291	517,540	1,639,956	2,157,496	[75, 76, 79]
Average	231	411,920	1,617,238	2,029,158	

Note: All Costs in US Dollars

The 20 year total project cost was then calculated using the capital costs from Table 4-1 and PCS, BOP and C&C costs calculated using Mongird's [7] assumptions, with the results presented in Table 9

Maintenance requirements differ significantly between the three different lead-acid battery types in this analysis. IEEE [80] advises that regular maintenance of lead-acid batteries is required to prevent failures and avoid early replacement. This includes monthly, quarterly, and annual inspections and cleaning with a cloth or brush and a sodium bicarbonate solution. For flooded batteries only, distilled or deionized water needs to be added to discharged or partially discharged batteries to just cover the plates when the plates are exposed. Flooded lead-acid batteries also require periodic freshening or equalization charges [81].

Trojan [82] recommends that their flooded lead-acid batteries receive an equalization charge every 30 days or when batteries have low specific gravity after fully charging. Although gel and AGM type lead-acid batteries are also known as “maintenance free”, periodic inspections and cleaning is recommended to ensure continued performance through normal end of life [80]. The level of expertise to operate and maintain lead-acid batteries is very low, and for the analysis scenario it can be assumed that a person from the local community would have experience as lead-acid batteries are also used in automobiles and other applications. This is a significant advantage of lead-acid batteries over the other more complex systems. Fixed and variable O&M costs for lead-acid batteries were calculated using Mongird’s [7] cost analysis methodology, with the results presented in Table 4-2.

Table 9 Lead-acid battery overall cost summary

	Flooded	Gel	AGM	Average
Capital Cost (20 yrs)	871,042	3,058,937	2,157,496	2,029,158
PCS Cost	350,000	350,000	350,000	350,000
BOP Cost	100,000	100,000	100,000	100,000
C&C Cost	313,280	313,280	313,280	313,280
Total Project Cost (20 yrs)	1,634,322	3,822,217	2,920,776	2,792,438
O&M Cost (fixed and var.)	40,548	40,548	40,548	40,548
Overall Estimated Cost	1,674,869	3,862,765	2,961,324	2,832,986

Note: All Costs in US Dollars

The extremely high 20-year cost of the gel type battery bank can be attributed to its low 2.7 year expected lifetime requiring seven replacements in 20 years. Because of its low cost and long life, the flooded type is significantly less expensive than the AGM and gel types, although its maintenance requirements (battery watering) are higher. O&M Costs are not included in this analysis.

Liquid electrolyte LIB cost analysis results

DOD also has a significant impact on a LIB's life expectancy [83] with ten times more degradation when LIBs are operated at near 100% cycle DoD compared to when operated at 10% DoD for the same amount of charged power [84]. Australia's independent Lithium Ion Battery Test Centre [85] conducted tests of six LIBs where the manufacturers' recommended DOD limit averaged at 88.5%. Efficiency also has effect on battery sizing, with the efficiencies of commercially available containerized LIB systems applicable to our scenario ranging from 85% to 95% [86]. For the purposes of this cost analysis, a 90% DOD operating limit and a 90% efficiency were assumed.

Capacity degradation over their lifespan is a key negative attribute of LIBs. Xu et al [87] summarized LIB battery degradation test results which recorded capacity fading versus number of cycles (cycling aging tests) and time (calendar aging tests) for different ambient conditions and operational patterns. They summarized this experimental degradation data into the curve shown in Figure 4-2. The implication for the life cycle model is that the LIB should be sized such that it still provides the required capacity at its end of life, so it should be initially sized at 125% of the capacity requirement as 80% of capacity will remain at that time.

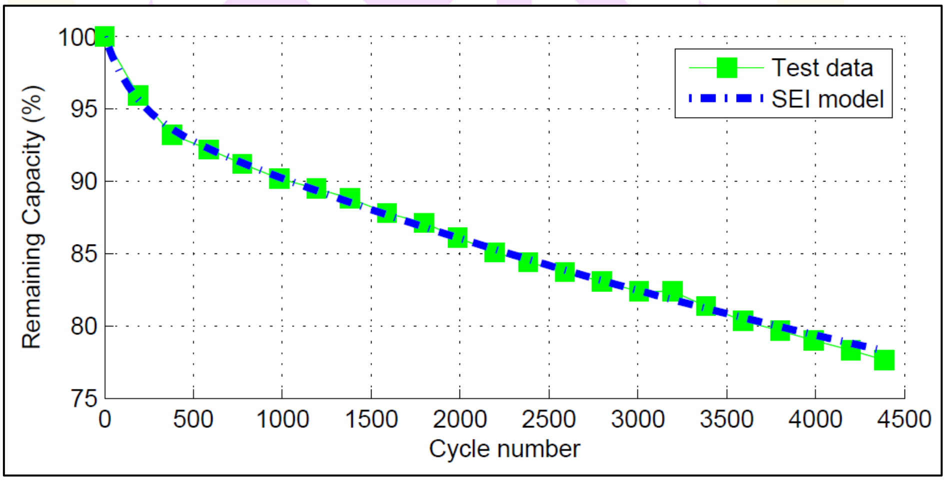
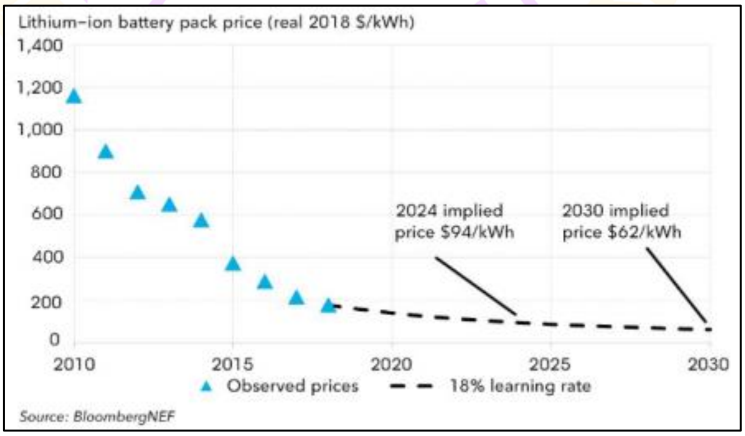


Figure 26 Battery life degradation curve [87]

The three assumptions, 90% DOD operating limit, 90% efficiency, and an initial sizing at 125% result in the requirement for a 934 kWh rated LIB to provide the scenario's 605 kWh of energy storage throughout its operating life.

Smith et al [88] determined that with active thermal management LIB energy storage systems can be expected to last for 10 years in a grid connected application. The 10-year lifespan agrees with other studies [7, 89]. As integrated containerized LIB ESSs all have thermal management subsystems, this appears to be a good assumption. This also correlates with the 10-year warranty that many of the manufacturers offer with their integrated LIB energy storage systems. The implication is that the model should assume a complete LIB replacement at the 10-year point which should last until the scenario end of life at the 20 year point.

Liquid electrolyte LIB costs have been falling steadily since they have been commercially available with further reductions forecast at least through 2030. Figure 4-3 shows the cost reduction curve for electric vehicle batteries [90] but is representative for all liquid electrolyte LIBs. Mongird et al [7] estimated the capital cost of a LIB system for a grid storage application as US$271/kWh in 2018 and projects a cost of US$189/kWh for 2025. However, a more recent study in a March 26, 2019 BloombergNEF report cites a one year drop in LIB prices of 35% percent between 2018 and 2019 [91, 92]. Using the BloombergNEF chart, a 50% price reduction is assumed for the replacement battery over the initial battery.



Source: BloombergNEF

Figure 27 LIB cost history and projection [90]

Liquid electrolyte LIBs require comparatively low maintenance, and do not require scheduled cycling to maintain battery life [93]. Battery calibration to identify degradation levels, software updates, and inspection [94] are some of the few required O&M actions. Mongird et al [7] estimated that LIBs will require major maintenance every 5 to 8 years. An issue with the liquid electrolyte LIBs is that specialized maintenance technicians are required for major maintenance events, such as battery replacement. The travel costs for technicians to visit remote areas, along with the cost of shipping, would add to the O&M costs. Integrated containerized LIB systems also have several subsystems that require periodic maintenance, such as HVAC and fire suppression systems. While local expertise to maintain and repair these subsystems may exist, this is an added concern and O&M cost for this technology.

Table 10 provides the estimated liquid electrolyte system costs for our scenario battery over a 20-year lifetime using the methodology from Mongird [7] for initial installations in both 2018 and 2025. As described, a battery bank changeout can be expected halfway through the 20 year scenario. O&M costs are also calculated to determine the overall estimated cost.

Table 10 Liquid electrolyte LIB cost summary

	Year 2018	Year 2025
Initial battery bank capital cost	253,114	176,526
Replacement battery bank capital cost	126,557	88,263
PCS Cost	288,000	211,000
BOP Cost	100,000	95,000
C&C Cost	94,334	89,664
Total Project Cost (20 years)	862,005	660,453
O&M Cost (fixed and variable)	40,548	32,548
Overall Estimated Cost	902,553	693,001

Note: All Costs in US Dollars

The dramatically lower LIB costs as compared to lead-acid batteries can be attributed to the frequent replacement, lower efficiency, and low maximum DOD of lead-acid batteries, which requires a much larger rated battery bank to provide the same storage capability. Although the cost per kWh between the two technologies is similar, the lead-acid battery bank requires almost double the rated capacity of a LIB to deliver the same usable storage, even before replacements costs are factored in.

Solid-state LIB cost analysis results

As a future technology still as much as a decade away from commercialization, lithium-based SSB costs, as well as their performance, are difficult to project, and estimates are not readily available in the literature. Technical details such as DOD limits, efficiency, capacity degradation, and lifespan will not be known until production units are developed, as there are so many different potential SSB technologies being researched today. For these reasons, a quantitative cost analysis was not conducted for SSBs.

It is assumed that SSB lifespan will exceed that of liquid electrolyte LIBs (in terms of both number of charge/discharge cycles and time after production) due to less side reactions between their electrodes and the solid electrolyte. But there are uncertainties due to SSB's issues with capacity fading [95], insufficient Li-ion transport, and instability [96]. Current SSBs have a significant issue at the interface between the solid electrolyte and the cathodes where ionic transport occurs. Active material particles mechanically deform during the electrochemical reactions due to ion insertion and removal. This stresses the solid electrolyte matrix causing microcracks or delamination at the interface increasing impedance, which leads to capacity fading over the SSB's lifetime [97]. Once these technical issues are resolved, a low-cost manufacturing process would still need to be developed before SSBs can compete commercially with liquid electrolyte LIBs [98].

A primary current disadvantage of SSBs is their very high cost. Even with all of their technical advantages, manufacturing advances will need to be made before they are affordable enough that a business case can be made for their commercial production.

VRFB cost analysis results

VRFBs have the unique characteristic of being able to scale power capacity independently of storage capacity. If more power is needed, a bigger stack can be used; if more capacity is needed, larger tanks, and thus more vanadium electrolyte, can be used [38]. Because of this, capital cost based on storage can vary considerably depending on VRFB design and the balance between power and storage. In 2017, Mongird [7] estimated the 2018 capital cost of a VRFB at US$555/kWh, significantly higher than the other technologies.

Another feature of VRFBs are that they can be discharged to 0% capacity, then charged again to 100% without any negative effect on the components, electrolyte, or future battery performance [37]. This stands in contrast to the other technologies where DOD is a significant consideration when trying to maximize the lifetime of the battery, and significant degradation can occur when these non-VRFBs are fully discharged.

The primary loss of DC efficiency in VRFBs is due to thermal losses from chemical reactions that occur on charge and discharge; the vanadium electrolyte heats up and needs to be cooled by using a heat exchanger. According to WattJoule, powering the pumps adds another 2% in efficiency loss. Mongird [7] estimated VRFB DC efficiency at 67.5% in 2018, projecting to 70% in 2025, although current VRFB system manufacturers claim higher efficiencies. The DC round trip efficiency for VRFB systems appropriate for a microgrid ESS application for this analysis is assumed to be 79%, based on an average of manufacturer data from four containerized VRFB systems appropriate for our scenario:

1. Storen ST 50-500: 70-80% [99]
2. VRB Energy Gen 3: 85% [100]
3. WattJoule ElectriStor500: 80-90% [61]
4. Rongke Power Vmodule1-A: 65-76% [101]

VRFBs do not experience capacity degradation over time, .

Current VRFB manufacturers claim long system life expectancies as shown in Table 11 The calculated lifetime column assumes one cycle per day for a primarily solar-based energy generation system such as in our scenario. As even the lowest lifetime estimates exceed the 20 year scenario lifetime, it can be assumed that no battery replacement will be required for the VRFB.

Table 11 VRFB life expectancy for currently available VRFBs

Manufacturer Name	Model Name	No. of cycles	Calculated Lifetime	Lifetime (stated)	Ref.
Storen	ST 50-500	15,000	41 years	25 years	[99]
VRB Energy	VRB Gen 3	25,000+	68+ years	30 years	[100]
WattJoule	ElectriStor500	10,000+	27+ years	N/A	[61]
Rongke Power	Vmodule1-A	>10,000	>27 years	>10 years	[101]
Sumitomo	AC250kW	unlimited	unlimited	20 years	[102]

Together, these findings and assumptions result in the requirement for a single VRFB initially rated at 765 kWh to provide the usable 605 kWh storage required for the duration of the 20 year scenario. Using this data and assumptions, the capital cost and total project cost analysis results for VRFBs is provided in Table 12

Operations and maintenance costs for VRFBs are typically described as very low. [61,103] WattJoule claims their ElectriStor VRFBs require very little maintenance, the primary cost being pump replacement every 10 years. The fact that VRFBs do not require HVAC systems to maintain operating temperatures is a significant maintenance savings. HVAC systems typically require their own maintenance which adds to O&M costs and requires specialized expertise [61]. Lourenssen [37] observes that VRFB are “relatively simple systems with few moving parts and often require little operator input, making them low maintenance with little attention once set up and running. The combination of all these properties allow the battery to have relatively low running and capital costs, especially compared to other emerging energy storage technologies”. However, like lithium-ion-based systems, maintenance involving VRFBs would usually require specialized technicians not available in remote areas, thus increasing costs. VRFBs’ long life though eliminates the need for battery replacement, a major and costly maintenance event. Table 4-5 also includes VRFB fixed and variable O&M costs, estimated using Mongird's [7] methodology. The fixed O&M factor for 2020 for the WattJoule ElectriStor (9.7) was linearly extrapolated from the 2018 and 2025 factors.

Table 12 VRFB cost summary

	Year 2018	WattJoule 2020 [61]	Year 2025
Initial battery bank capital cost	425,032	555,411	300,968
Replacement battery bank capital cost	0	0	0
PCS Cost	350,000	250,714	211,000
BOP Cost	100,000	0	95,000
C&C Cost	145,506	140,036	137,848
Total Project Cost (20 years)	1,020,538	946,162	744,816
O&M Cost (fixed and variable)	40,548	39,405	32,548
Overall Estimated Cost	1,061,085	985,566	777,364

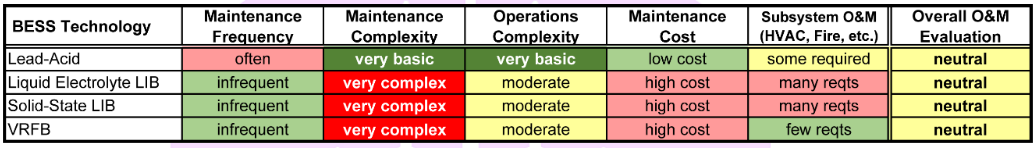
Note: All Costs in US Dollars

Table 12 includes an analysis of real-world data for the WattJoule 5MWh ElectriStor system using the same methodology. 2020 factors for PCS and C&C for WattJoule's ElectriStor were extrapolated linearly from Mongird's [7] 2018 and 2025 values, while BOP costs are included in capital costs. According to WattJoule, the current (2020) cost of their 5MWh ElectriStor is approximately US$1-million, with the vanadium electrolyte accounting for much of the cost of the system at $105/kWh. Assuming the cost of the rest of the system remains constant and reducing the amount of electrolyte to accommodate a 745 kWh system, the ElectriStor cost computes to US$555,325, but this includes the BOP costs. The 2020 ElectriStor total project costs fit right in line with Mongird's [7] estimates and actually would be somewhat less, as the included BOP costs are for a 5000kWh system and the 765 kWh scenario system would require far less piping, smaller tanks and pumps, and a smaller stack.

Cost analysis summary and conclusions

Although this cost analysis uses many assumptions and approximations, the results are consistent with current cost generalizations in research and the media.

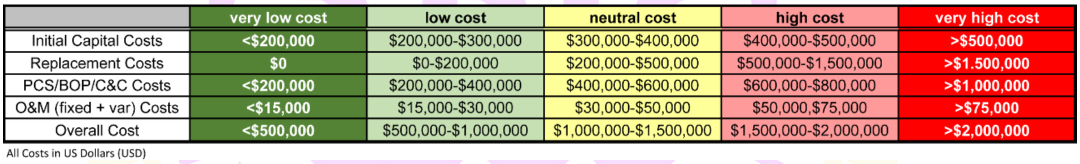
As described in Section 3.1, the Mongird [7] cost methodology assumes a consistent O&M cost factor for all technologies based on previous studies. Figure 28 provides a more detailed rubric analysis of O&M considerations for each technology.



BESS Technology	Maintenance Frequency	Maintenance Complexity	Operations Complexity	Maintenance Cost	Subsystem O&M (HVAC, Fire, etc.)	Overall O&M Evaluation
Lead-Acid	often	**very basic**	**very basic**	low cost	some required	**neutral**
Liquid Electrolyte LIB	infrequent	**very complex**	moderate	high cost	many reqts	**neutral**
Solid-State LIB	infrequent	**very complex**	moderate	high cost	many reqts	**neutral**
VRFB	infrequent	**very complex**	moderate	high cost	few reqts	**neutral**

Figure 28 Qualitative O&M rubric analysis results

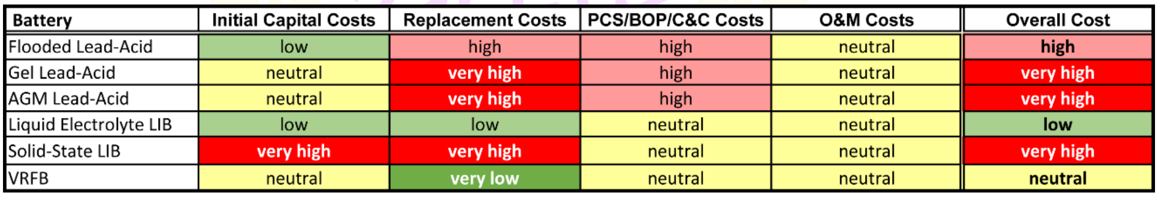
To rank the technologies for overall cost, a rubric scoring methodology was devised based on the criteria for overall cost shown in Figure 29, with the results provided in Figure 30.



	very low cost	low cost	neutral cost	high cost	very high cost
Initial Capital Costs	**<$200,000**	$200,000-$300,000	$300,000-$400,000	$400,000-$500,000	**>$500,000**
Replacement Costs	**$0**	$0-$200,000	$200,000-$500,000	$500,000-$1,500,000	**>$1.500,000**
PCS/BOP/C&C Costs	**<$200,000**	$200,000-$400,000	$400,000-$600,000	$600,000-$800,000	**>$1,000,000**
O&M (fixed + var) Costs	**<$15,000**	$15,000-$30,000	$30,000-$50,000	$50,000,$75,000	**>$75,000**
Overall Cost	**<$500,000**	$500,000-$1,000,000	$1,000,000-$1,500,000	$1,500,000-$2,000,000	**>$2,000,000**

All Costs in US Dollars (USD)

Figure 29 Cost rubric analysis criteria



Battery	Initial Capital Costs	Replacement Costs	PCS/BOP/C&C Costs	O&M Costs	Overall Cost
Flooded Lead-Acid	low	high	high	neutral	**high**
Gel Lead-Acid	neutral	**very high**	high	neutral	**very high**
AGM Lead-Acid	neutral	**very high**	high	neutral	**very high**
Liquid Electrolyte LIB	low	low	neutral	neutral	**low**
Solid-State LIB	**very high**	**very high**	neutral	neutral	**very high**
VRFB	neutral	**very low**	neutral	neutral	**neutral**

Figure 30 Cost rubric analysis results

Lead-acid batteries, especially the flooded type, have low initial capital costs but their short operating life increases their lifetime costs well above liquid electrolyte LIB and

VRFB costs due to frequent and costly battery replacements and DOD limitations requiring much larger capacity batteries to deliver the same usable storage.

The dramatic cost reduction in liquid electrolyte LIBs over the last decade along with their longer expected operational life and low maintenance requirements has resulted in this being the current technology of choice for grid BESS applications.

Long life expectancy is one area where VRFBs shine, with expected life and numbers of cycles far exceeding the 20 year scenario lifespan, making this one of the most attractive features of VRFBs. This factor, along with recent cost reductions, are making VRFBs more cost competitive with LIBs, as shown by this analysis. VRFB's many other advantages make them an attractive alternative for the microgrid BESS application, as further described in Section 4.2.

Operations and maintenance are key considerations when comparing the different energy storage technologies in the analysis scenario. O&M cost is a key factor, but also the technical expertise required to operate and maintain a system warrants consideration as it can be assumed that the technical skill level of local residents will be relatively low. For this reason, system reliability is a key metric, although reliability statistics are difficult to obtain. Lead-acid batteries have the advantage of being "low tech" and as this technology has been used for decades in automobiles and other common applications, it can be expected that the expertise to maintain these batteries will exist even in communities with low education levels. However, flooded lead-acid batteries require periodic watering, and all lead-acid types have limited expected lifetimes, so replacement costs must be factored in. LIBs have the advantage of low O&M requirements for the batteries themselves, but their supporting auxiliary subsystems such as HVAC and fire suppression require more frequent maintenance. The expertise to service these subsystems may exist in the local community. Also, the costs of procuring, shipping, and installing the replacement LIB battery bank needs to be factored in. VRFBs are relatively simple systems which do not require as many support subsystems as LIBs, but their maintenance would also typically done by outside specialists who must come to the battery site. Some routine maintenance such as pump or gasket replacement could be done by community members in some cases, but any maintenance to the stack, including membrane replacement, would require a specialist.

Other key factors analysis results

Energy density analysis results

Lead-acid battery energy density analysis results

To determine energy density for the three types of lead-acid batteries, data was analyzed from 142 different models from five manufacturers: Trojan, Hoppecke, Crown, Exide, and Hankook. The results are summarized in Table 4-6:

1. Flooded type – 59 models:
    1.1 17 models from Trojan's Solar Industrial and Solar Signature lines [104]
    1.2 15 models from Crown's CRP Monobloc and Power Module lines [105]
    1.3 27 models from Exide's GNB Industrial Power Classic Solar line [106]
2. Gel type - 48 total models
    2.1 7 models from Trojan's Solar Deep-Cycle Gel line [104]
    2.2 26 models from Hoppecke's sunlpower VR line [107]
    2.3 15 different gel type models from Hankook AtlasBX's VGS line [108]
3. AGM type - 35 total models
    3.1 11 models from Trojan's Solar Deep-Cycle AGM line [104]
    3.2 9 AGM models from Crown's AGM CRV Monobloc Series [105]
    3.3 15 models from Exide's Sonnenschein [109] and Absolyte GX [110] lines.

Table 13 Lead-acid battery energy density and specific energy summary

Lead-acid battery type	No. of models	Average energy density (Wh/liter)	Average specific energy (Wh/kg)
Flooded	59	98.4	44.4
Gel	48	67.1	31.4
AGM	35	92.1	36.4
Overall average	142	86.3	38.0

These energy density calculations only consider the batteries themselves; they do not consider the battery room or enclosure/container that provides protection from the elements as well as ventilation and cooling. Lead-acid batteries emit hydrogen gas during charging, so adequate space is required to ventilate the battery room and maintain hydrogen levels below 1%, the level stipulated by regulations such as the Uniform Fire Code and the International Fire Code (hydrogen is explosive at 4% and higher concentrations) [111]. Although battery room regulations vary from country to country, standards such as from the Institute of Electrical and Electronics Engineers (IEEE), US Occupational Safety and Health Administration, the US National Electrical Code, and the US National Fire Protection Association specify a variety of requirements beyond ventilation and temperature control for battery room design ,which increases the overall system footprint. These requirements include storage area for personal protective equipment, eyewash or shower stations, hydrogen gas monitors, spill kits, cleaning supplies, as well as the racks to mount the batteries [111]. This larger battery room size is more relevant when comparing to integrated containerized systems commonly produced by LIB and VRFB manufacturers, which also include the auxiliary subsystems required for their batteries. But their custom built nature and large size variation makes analysis at this level difficult.

Liquid electrolyte LIB energy density analysis results

As with lead-acid battery banks, the total enclosure size of an integrated LIB grid storage system is more applicable to our analysis than the energy density in the stand-alone LIB unit. And as there are several liquid electrolyte LIB ESS commercially available from a variety of manufacturers, analysis at this level is practical. LG Chem boasts that their M48218P5B Energy Storage System provides the highest energy density of any currently available LIB-based containerized energy storage system with a 6.8MWh capacity packaged in a standard 40-ft High Cube (HC) enclosure [112]. Samsung SDI offers a similar product in their 6 MWh system in the same 40-ft. HC enclosure [113]. These products provide the highest energy densities of the integrated products at close to 80 Wh/liter but are of higher capacity than our scenario requires. Smaller integrated systems more applicable to our scenario are typically packaged in standard ISO 20-ft. containers, such as the 1187 kWh Aggreko Y.Cube 60, the 780 kWh Saft Intensium Max

IM+ 20P1, and the 1000 kWh Fluence Energy Edge The popular BYD grid-scale ESS also delivers 1000 kWh but in an ISO standard 40-ft container. Results from the container-level energy density analysis for these four liquid electrolyte LIB ESSs are presented in Table 14

Table 14 Containerized liquid electrolyte LIB systems energy density summary

Manufacturer Name	**Model Name**	**Container Type (ISO)**	**Volume (m^3)**	**Energy Density (Wh/liter)**	**Ref.**
Aggreko	Y.Cube 60	20ft HC	43.0	27.6	[114]
Fluence	EnergyEdge	custom 20 ft	57.8	17.3	[115]
Saft	Intensium Max	20ft HC	43.0	18.1	[116]
BYD	ESS	40 ft	77.0	13.0	[117]

Solid-state LIB energy density analysis results

As described in Section 2.4, when using lithium metal as the anode (along with sulfur as the cathode), solid electrolyte LIBs can achieve a theoretical gravimetric energy several times higher than non-lithium anode liquid electrolyte LIBs [118], and volumetric energy densities up to 70% higher [119]. Takada [120] describes how SSBs do not suffer from the limitation in liquid electrolyte LIBs which experience oxidative decomposition of the electrolyte at high voltages, thus limiting their practical capacity to half of the potential capacity. In March 2020, Samsung [121] announced their “groundbreaking” SSB prototype using a silver-carbon composite layer as the anode, which suppresses dendrite formation while increasing energy density to 900 Wh/liter. In late 2019, the Deakin's Institute for Frontier Materials [122] made similar claims of an SSB prototype at twice the energy density of current liquid electrolyte LIBs.

However, a variety of advances must be achieved before full production and commercialization of SSBs, including enhancing Li-ion transport, decreasing boundary resistance at the solid electrolyte-electrode interface, and improving stability [96]. As lithium-based SSBs have not matured to the point where they are being produced commercially, there are no current product specifications to compare to the other technologies. If the promise of higher energy densities is realized, it is safe to assume that future containerized SSB systems would be packed in smaller containers, or containers of the same size as current offerings would be capable of storing more energy.

VRFB energy density analysis results

As with liquid electrolyte LIB systems, the total enclosure size of an integrated VRFB grid storage system is applicable to our analysis. The disassociated nature of ta VRFB's storage components (tanks and piping) and its power-producing stack also makes energy density at a lower level impractical. Table 15 presents the energy density analysis summary for five current integrated containerized VRFB systems.

Table 15 Containerized VRFB systems energy density summary

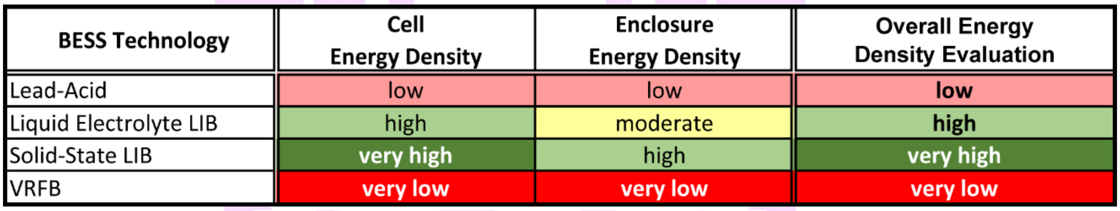
Manufacturer Name	Model Name	Volume (m^3)	Energy Density (Wh/liter)	Ref.
StorEn	ST 50-500	49.0	10.2	[99]
WattJoule	ElectriStor500	38.7	12.9	[61]
Rongke	Vmodule1-A	77.0	8.1	[101]
Sumitomo	AC250kW	179.3	4.2	[102]
Rongke	Vpower1-A	256.0	3.9	[123]

Energy density analysis summary and conclusions

Increasing energy density is a major focus for current battery research, but this priority is largely fueled by commercial competition in the electric vehicle and personal electronics markets. While important for energy storage applications such as residential systems, having smaller footprint systems is generally less important for microgrid storage applications. This is especially true in rural settings where land is plentiful.

LIBs have a clear advantage in energy density over VRFBs, as evidenced by their use in electric vehicles and electronic devices today where this metric is important. But when grid storage LIBs are containerized into integrated systems complete with fire suppression and HVAC subsystems, their footprint versus VRFBs is less significant, providing approximately twice the energy density. Both types of BESS in the 1-MWh range are typically packaged with the necessary supporting systems in a standard 20-ft container. Likewise, our baseline lead-acid battery systems would typically be installed in a battery room of generally the same size for the corresponding storage capacity. Lithium-ion SSBs promise higher energy densities in the future, but again these advantages probably will not outweigh their added cost for quite some time. In cases where a smaller footprint is required, integrated SSB-based BESS should have the advantage of being in smaller footprint enclosures.

Although energy density is not a key metric for the notional analysis scenario microgrid, Figure 4-7 provides the results from a qualitative rubric analysis for the four technologies for cell and enclosure energy density, and an overall evaluation.



BESS Technology	**Cell Energy Density**	**Enclosure Energy Density**	**Overall Energy Density Evaluation**
Lead-Acid	low	low	**low**
Liquid Electrolyte LIB	high	moderate	**high**
Solid-State LIB	**very high**	high	**very high**
VRFB	**very low**	**very low**	**very low**

Figure 31 Energy density qualitative rubric analysis results

Temperature limits analysis results

Lead-acid battery temperature limits analysis results

Guari et al [17] determined that the optimum operating temperature for a lead-acid battery is 30°C; operation above and below this range negatively affects the battery. Trojan [82] recommends the operating temperature range for their flooded and AGM type batteries as -20°C to 50°C and of their gel type batteries as -20 °C to 45 °C, while noting that “heat is an enemy of all lead-acid batteries, flooded, AGM and gel alike and even small increases in temperature will have a major influence on battery life” [67].

For roughly every 10°C increase in operating temperature, a lead-acid battery’s life is reduced by 50%, a significant effect. Internal battery temperature is the key parameter, which is determined by the ambient temperature as well as battery loading and charging conditions [56]. A general rule of thumb is that lead-acid battery life is reduced by 50% for every 15°C above optimal operating temperature [73]. Cold temperatures increase a lead-acid battery's internal resistance and lowers capacity. Typically, a lead-acid battery capable of providing 100% capacity at 27°C will provide about 50% at minus-18°C [124].

The effect of reduced service life is a critical factor in our scenario as cost constraints in replacing the batteries can mean the difference between an operating and non-operating system. For this reason, in hotter climates a cooling system must be provided for the battery enclosure to ensure the lead-acid batteries operate at or near their optimal temperature. The electrical power required to operate these cooling systems will reduce the overall efficiency of the BESS, as some power must be diverted for this purpose. Also, the cooling systems add cost and increase the maintenance demands. Lead-acid battery use in hot climates demands an adequate air circulation system in battery enclosures to work in conjunction with the cooling system. Blue Box Batteries provides the example where lead-acid batteries are mounted in a 6-tier stand over 2 meters high, where there can be a 5ºC difference between the bottom and top of the assembly [125]. As shown above a 5ºC increase can result in reduced battery lifespan. Adequate ventilation is also a requirement to prevent the buildup of hydrogen gas during charging operations of flooded type lead-acid batteries. The air circulation system would be another electrical load lowering the efficiency of the overall system. High temperatures also can prevent charging a lead-acid battery. Trojan [82] recommends that their batteries never be charged when temperatures exceed 50ºC.

Liquid electrolyte LIB temperature effects analysis results

As described previously, integrated liquid electrolyte LIB systems designed for grid energy storage applications all feature thermal controls to maintain temperature within the LIB's operating range. Due to the significant issues with operation at both the low and high end of the operational temperature range [63], the ideal temperature to operate a LIB is generally limited to about 15–35°C [126], which requires the use of a thermal control subsystem, which not only robs the overall system of power and thus lowers overall efficiency, but these HVAC systems also require their own maintenance. Although HVAC maintenance expertise is common even in remote rural areas, this adds to the overall expense and any downtime associated with the HVAC system will also force a downtime on the LIB battery.

At low operating temperatures below 0°C, liquid electrolyte LIB chemical-reaction activity and charge-transfer velocity slows resulting in a decrease of ionic conductivity in the electrolyte which results in a reduction of energy capacity and power, and sometimes performance failure [126]. Figure 4-8 shows this phenomenon.

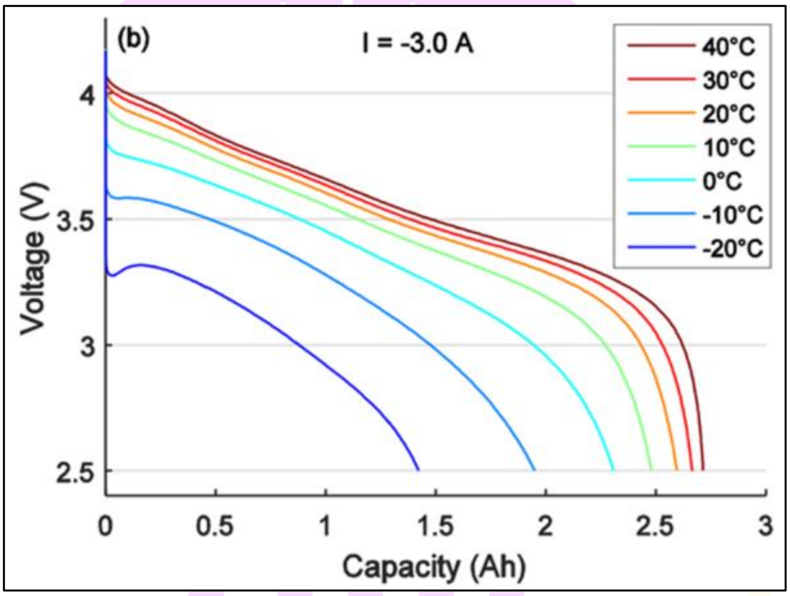


Figure 32 Decreased storage capacity and voltage of an 18650 Li-ion cell as temperature lowers [124]

All containerized LIB systems include HVAC systems to maintain temperatures towards the middle of these ranges. These auxiliary systems allow for operation in extreme hot and cold conditions outside the enclosure, typically about -20°C to +50°C [114-117]. Although this range is wide, the effects of poor performance at the low end and safety issues at the high end need to be considered, especially if the HVAC subsystems become inefficient or inoperative.

Solid-state LIB temperature effects analysis results

Ogawa et al [127] found that SSBs are capable of operating at high temperatures without a significant impact on battery performance or capacity. Their tests were conducted at 180°C, close to the melting point of the lithium metal anode. In fact, research has shown that the performance of SSBs improves with increasing temperatures in the areas of ionic transport and maximum charge and discharge rates. The maximum operating temperature in only limited by the 180°C melting point of lithium metal [98]. SSB microgrid BESSs could therefore be containerized in enclosures without the need for HVAC in hot climates, thus avoiding the efficiency loss and maintenance requirements of these subsystems. At low temperatures Ogawa et al [127] found that battery output was reduced, but not as severely as with liquid electrolyte LIBs where increased viscosity or freezing of the liquid electrolyte occurs. The ability to maintain performance and safety while operating at high and low temperatures is a significant advantage of SSBs over their liquid electrolyte counterparts.

VRFB temperature effects analysis results

WattJoule's ElectriStor system is an example of current VRFB systems that feature a wide operating temperature range of -40ºC to 70ºC, removing the need for any auxiliary thermal control systems which robs the overall system of efficiency [61]. Table 4-9 lists the operating temperatures of some commercially available VRFB systems.

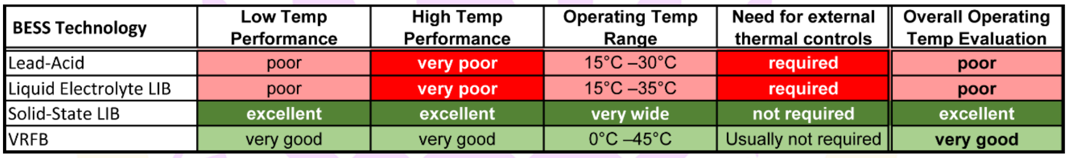
Table 16 Operating temperature range of current VRFB systems

Manufacturer Name	Model Name	Operating Temp Range	Ref.
Storen	ST 50-500	-10°C to +50°C	[99]
WattJoule	ElectriStor500	-40°C to +70°C	[61]
Rongke	Vmodule1-A	0°C to +35°C	[101]
Sumitomo	AC250kW	-5°C to +40°C	[102]
VRB Energy	VRB Gen 3	0°C to 50°C	[123]

Unlike liquid electrolyte LIBs, VRFB do not experience performance losses at the lower or upper end of the range. The broad operating temperature ranges, particularly the maximum limits, is a distinct advantage of VRFBs as it eliminates the need for any cooling systems for the battery enclosure in even the hottest climates, as long as some amount of air circulation is present. This is not only a significant cost reduction in the initial system cost, but it also eliminates another auxiliary system that requires preventative maintenance and can break down requiring costly repairs.

Temperature limits analysis summary and conclusions

The ability to operate at temperature extremes, especially high temperatures which characterize many of the poorer areas of the world, is a significant advantage of SSBs and VRFBs. The necessity of operating HVAC subsystems for lead-acid and liquid electrolyte LIB energy storage systems to maintain temperatures in narrow ranges not only adds cost to the overall integrated system, but also creates additional maintenance demands. Figure 34 provides the results of the rubric analysis for the four technologies.



BESS Technology	Low Temp Performance	High Temp Performance	Operating Temp Range	Need for external thermal controls	Overall Operating Temp Evaluation
Lead-Acid	poor	very poor	15°C –30°C	required	poor
Liquid Electrolyte LIB	poor	very poor	15°C –35°C	required	poor
Solid-State LIB	excellent	excellent	very wide	not required	excellent
VRFB	very good	very good	0°C –45°C	Usually not required	very good

Figure 33 Operating temperature limits rubric analysis results

Safety issues analysis results

Lead-acid battery safety issues analysis results

SafeWork South Australia [128] points out two primary safety concerns with lead-acid batteries: (a) explosions due to ignition of hydrogen gases produced by the battery, and (b) the extremely corrosive (pH<2) sulphuric acid electrolyte causing chemical burns to the skin or eyes. Figure 4-10 from Crown Battery [129] shows some of the safety issues associated with lead acid-batteries.

HEALTH		ENVIRONMENTAL	PHYSICAL
Acute Toxicity (Oral/Dermal/Inhalation)	**Category 4**	Aquatic **Chronic 1** Aquatic **Acute 1**	Explosive Chemical, Division 1.3
Skin Corrosion/Irritation	**Category 1A**		
Eye Damage	**Category 1**		
Reproductive	**Category 1A**		
Carcinogenicity (lead compounds)	**Category 1B**		
Carcinogenicity (arsenic)	**Category 1A**		
Carcinogenicity (acid mist)	**Category 1A**		
Specific Target Organ Toxicity (repeated exposure)	**Category 2**		

***Hazard Statements* – DANGER!**

Harmful if swallowed, inhaled, or in contact with skin.
Acid causes severe skin burns and eye damage.
May damage fertility or the unborn child if ingested or inhaled.
May cause harm to breast-fed children.
May cause cancer if ingested or inhaled.
Causes skin irritation, serious eye damage.
Contact with internal components may cause irritation or severe burns.
Causes damage to central nervous system, blood and kidneys through prolonged or repeated exposure if ingested or inhaled.
Irritating to eyes, respiratory system, and skin.
May form explosive air/gas mixture during charging.
Extremely flammable gas (hydrogen).
Explosive, fire, blast or projection hazard

Precautionary Statements

Obtain special instructions before use.
Do not handle until all safety precautions have been read and understood.
Wash thoroughly after handling.
Do not eat drink or smoke when using this product.
Avoid contact during pregnancy/while nursing.
Wear protective gloves/protective clothing, eye protection/face protection.
Use only outdoors or in a well-ventilated area.
Avoid contact with internal acid.
Do not breathe dust/fume/gas/mist/vapors/spray.
Keep away from heat/sparks/open flames/hot surfaces. No smoking
IF SWALLOWED OR CONSUMED: rinse mouth.
Do NOT induce vomiting. Call a poison center/doctor if you feel unwell.
IF ON CLOTHING OR SKIN (or hair): Remove/Take off immediately all contaminated clothing and wash it before reuse. Rinse skin with water/shower.
IF INHALED: Remove person to fresh air and keep comfortable for breathing.
Immediately call a POISON CENTER or doctor/physician.
IF IN EYES: Rinse cautiously with water for several minutes.
Remove contact lenses, if present and easy to do. Continue rinsing.
If exposed/concerned, or if you feel unwell seek medical attention/advice.
Store locked up, in a well-ventilated area, in accordance with local and national regulation.
Dispose of contents/container in accordance with local and national regulation.
Keep out of reach of children.

Figure 34 Lead-acid battery hazards [129]

During the charging cycle, lead-acid batteries generate hydrogen gas that can be explosive in air at concentrations of 4.1 to 72 percent hydrogen [15]. Flooded type lead-acid batteries are especially vulnerable as the hydrogen gases are vented to the atmosphere via the vent caps by design. This process also involves the continuous loss of electrolyte, so water needs to be added periodically to the battery, increasing the risk of contact with the highly acidic sulphuric acid electrolyte [130], which is also poisonous if swallowed [15]. Sealed type gel and AGM VRLA batteries emit far less hydrogen gas and are spill proof, so are generally safer than flooded type batteries.

The requirement to adequately ventilate a battery rom due to the potential buildup of hydrogen gas adds to the electrical power load, and thus lowers efficiency and adds to overall maintenance requirements. There are also health impacts associated with lead which are discussed in the following section on environmental concerns.

Liquid electrolyte LIB safety issues analysis results

LIB safety is a cause for concern as illustrated by the many safety LIB incidents in recent years, some of which are highlighted here. In January 2013, a faulty LIB caused a fire aboard a Japan Airlines Boeing 787 Dreamliner parked at Boston's Logan's airport. The following week a second LIB fire occurred aboard a Dreamliner in Japan, prompting the U.S. National Transportation Safety Board (NTSB) to temporary ground all Boeing 787s [131]. The damaged battery is shown in Figure 36 The NTSB's [132] subsequent Aircraft Incident Report on the Logan Airport incident cited a long list of issues with LIBs including safety issues related to "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".

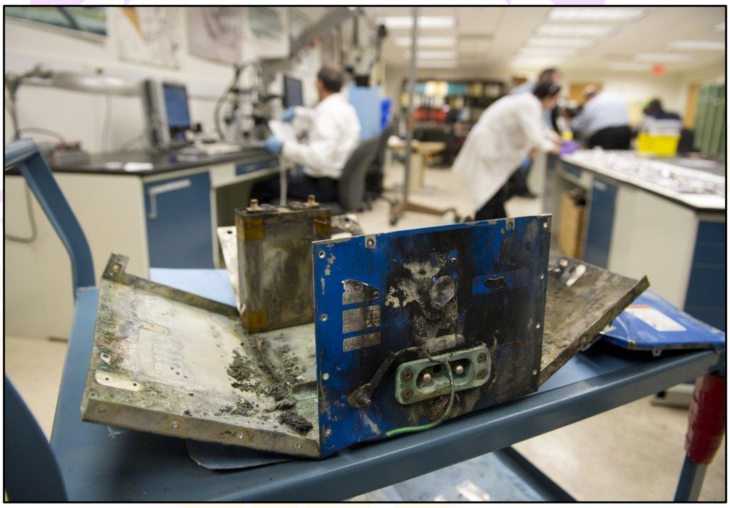


Figure 35 Boeing 787 battery after explosion and fire [131]

Other well publicized aircraft incidents involving passenger-owner products using LIBs include the March 2017 incident of a passenger's LIB-powered noise-cancelling headphones exploding causing burns to her face and head [133]. More famously, in October of

2014, the U.S. Department of Transportation's Federal Aviation Administration (FAA) [134] took the unprecedented step of officially banning all Samsung Galaxy Note 7 mobile phones from all flights in the U.S. due to explosions and fires caused by the Note-7's LIB. A January 2020 FAA [135] report cited 168 air or airport incidents involving LIBs carried as cargo or baggage since January 23, 2006.

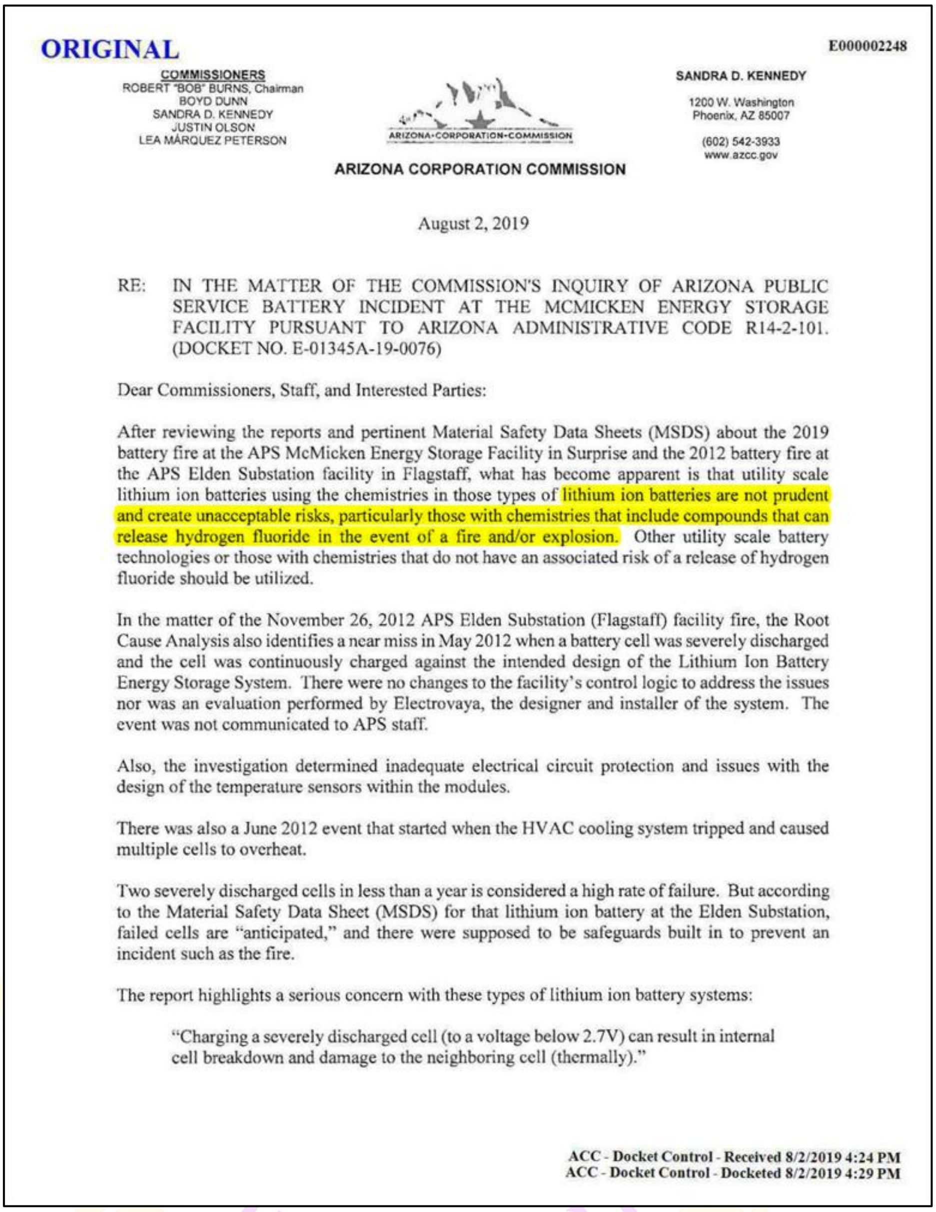
There have also been numerous vehicle-related incidents involving LIBs, where the much larger batteries pose a potential for greater damage. On July 31, 2019, the LIB in a 3-month-old 2019 Hyundai Kona Electric exploded in the owner's garage in Montreal, Canada. The explosion was so violent that it blew the garage roof off and garage door across the street Figure 37 [136]. Several Tesla cars have also recently had their LIBs explode [137].

Figure 36 Hyundai Kova EV explosion [136]

Exploding LIBs have even caused death. In May 2018, a 38-year old Florida man was killed in his home by an exploding e-cigarette when the 18650 drop-in LIB malfunctioned and exploded [138]. Prior to this incident, a 2017 George Mason University [139] study estimated that in the U.S. there were 2035 e-cigarette battery explosions between 2015-2017 that resulted in injuries to the users which required a trip to a hospital emergency room.

These incidents all involved smaller LIBs that would not be used in a microgrid BESS suitable for our scenario, but the LIB technology is the same as in larger containerized LIB systems which have also been involved in recent serious accidents. Toxic gases are emitted in LIB fires, including CO, HF, SO_2, NO_2, NO and HCl, which increase in production with the state of charge of the LIB. In some circumstances, the danger of these toxic gases is far more serious than the fire itself [140], as was the case in the LIB ESS fire in Surprise, Arizona.

In the late afternoon of April 19, 2019, a fire broke out at an AES containerized liquid electrolyte LIB system built by Fluence in Surprise, Arizona, just outside of Phoenix. Firefighters arrived and a hazmat team entered the facility just prior to the battery exploding, causing extensive injuries to eight men with three requiring extended hospital stays. The AES Director of Corporate Safety [141] later stated that the system was equipped with “8 HVAC units, smoke dampers and a fire suppression system”. The 2 MW/2 MWh system is similar in size to an integrated system appropriate for our analysis scenario. An AES [142] investigation found the explosion’s cause was the ignition of a mixture of explosive gases emitted by the burning batteries. The Surprise incident led Arizona regulator Sandra Kennedy [143] to issue an official letter stating that lithium batteries for grid storage “are not prudent and create unacceptable risks” and suggested safer alternatives, such as flow batteries Figure 38.



ORIGINAL

E000002248

COMMISSIONERS
ROBERT "BOB" BURNS, Chairman
BOYD DUNN
SANDRA D. KENNEDY
JUSTIN OLSON
LEA MÁRQUEZ PETERSON

ARIZONA CORPORATION COMMISSION

SANDRA D. KENNEDY

1200 W. Washington
Phoenix, AZ 85007

(602) 542-3933
www.azcc.gov

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

Figure 37 Arizona letter on LIB safety issues [143]

The two Arizona LIB fires highlighted in Kennedy's letter are hardly isolated incidents. There were 17 LIB storage fire incidents at facilities in South Korea alone in an 8 month period in 2018 and 2019 [144] just prior to the Arizona incident, prompting a government investigation [145].

In the US, one issue is that current regulations governing the operation of grid storage batteries are maintained at the state and local level; there is no overarching federal safety law. This issue is worse in poorer countries, where regulations, inspections, and enforcement would tend to be even more lax. And as LIB production increases and installers look for the lowest cost system, manufacturing defects from less expensive batteries can be more prone to failure, making the safety situation worse.

Although safety incidents involving LIBs are cause for concern, the number of installed systems worldwide should also be taken into account. There is certainly a safety risk associated with these systems, but the percentage of systems that have failed, and especially those causing harm, are low when compared to the installed base. But for the remote installations of our scenario, these safety aspects still need to be considered.

Solid-state LIB safety issues analysis results

Safety is one area where SSBs differ from their liquid electrolyte counterparts, as the solid nature of the SSB's electrolyte suppresses dendrite growth. However, studies have still observed the phenomenon where dendrites have progressed through the solid electrolyte matrix and achieved a short circuit condition resulting in melting and burning of the electrolyte. Ma et al [95] note that although the electrolyte is solid, there are still pathways and mechanisms for dendrites to grow and elongate and that short circuit is one of the SSB's serious failure behaviors.

As SSBs are still in the research phase and many different types are under consideration, their failure mechanisms also differ. The inherent nature of a solid electrolyte to significantly limit, if not almost eliminate dendrite growth and also the nonvolatile nature of solid electrolytes should make SSBs inherently safer than liquid electrolyte LIBs, though to what extent remains to be seen.

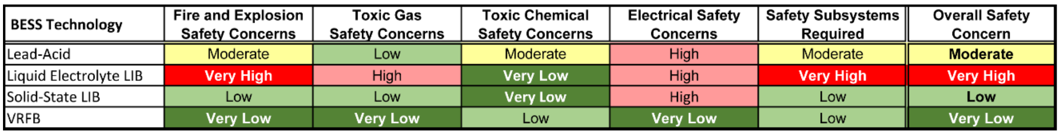
VRFB safety issues analysis results

Safety is another area where VRFBs have an advantage over the other technologies. VRFBs do not present a fire hazard as the vanadium electrolyte is aqueous, incombustible [38], non-reactive, and of low toxicity [65]. Paiss [146] notes another safety feature of VRFBs in that electrical power is only produced when the system is in operation, there is no "stranded energy" as with other battery technologies. When the system is in standby mode (i.e., the pumps are turned off), there is no voltage present at the battery terminals. This is especially important during maintenance as it significantly increases basic electrical safety and contrasts with LIBs which cannot discharge to 0 VDC without risking permanent damage to the battery [147].

Although vanadium in powder form can be toxic, when in solution the VRFB electrolyte can be deemed as non-toxic due to the very low concentration levels of vanadium [146]. Dassisti et al [148] point out that the International Agency for Research on Cancer has determined that vanadium is possibly carcinogenic to humans (U.S. Department of Health and Human Services, 2012). But vanadium is a naturally occurring element that is present in the air, soil, food, and water. They determine that vanadium composites in closed VRFB systems pose a “small risk for injury to human health because electrolytes are incombustible”.

Safety issues analysis summary and conclusions

Battery fires tend to be very intense and difficult to extinguish, sometimes taking days or even weeks to fully put out. They not only present problems due to heat and smoke associated with typical fires, toxic gases are also often an added concern [149]. These issues have been recently highlighted in the many recent LIB ESS fires. Safety issues with traditional lead-acid batteries can be serious, but they are well known, and it can be assumed that community members can safely conduct maintenance and operation. LIBs however present a new set of safety issues which can be a particular concern in a remote village with very limited or no on-site expert monitoring. LIB accidents such as the one in Arizona in 2019 demonstrate the dangers of LIBs. VRFBs provide a much safer alternative, with safety being one of its key advantages over other technologies in virtually every safety category as shown in the rubric analysis summary in Figure 39



BESS Technology	Fire and Explosion Safety Concerns	Toxic Gas Safety Concerns	Toxic Chemical Safety Concerns	Electrical Safety Concerns	Safety Subsystems Required	Overall Safety Concern
Lead-Acid	Moderate	Low	Moderate	High	Moderate	**Moderate**
Liquid Electrolyte LIB	**Very High**	High	**Very Low**	High	**Very High**	**Very High**
Solid-State LIB	Low	Low	**Very Low**	High	Low	**Low**
VRFB	**Very Low**	**Very Low**	Low	**Very Low**	Low	**Very Low**

Figure 38 Safety concerns rubric analysis results

Environmental considerations analysis results

Lead-acid battery environmental considerations analysis results

As a common product, lead-acid batteries are subject to many environmental-related regulations in countries throughout the world. May et al [14] describe how the lead from these batteries is recycled at a >99% rate in the US and European Union via well-established processes and facilities. Other lead-acid battery components such as the polypropylene case and scrap metals such as brass, copper, and antimony are also recovered at a lesser rate.

However, it is this recycling process, especially in poorer nations, that can cause serious environmental and health damage. Green Cross Switzerland's [150] annual report on the world's worst polluting industries ranks used lead-acid battery recycling as the #1 worst polluting industry in the world, with lead as the #1 toxic threat. Zhang et al [16] estimated that 3 million tons of lead-acid battery waste was generated in 2016 in China alone, with that amount increasing annually.

The World Health Organization [151] describes the many ways in which lead is harmful to humans. Improperly conducted lead-acid battery recycling can release lead into the surrounding ecosystem, eventually finding its way back to humans. Lead builds up in the body, primarily in the bones, and can lead to chronic poisoning affecting almost all body systems. Lead poisoning also disproportionately affects children, causing developmental and neurological problems [150].

Zhang et al [16] also discussed the environmental hazards associated with leakage of the sulfuric acid electrolyte, which is extremely corrosive and can cause serious damage to humans on contact. Although lead-acid battery recycling is highly regulated in developed countries, in low and middle income nations controls are typically more lax, leading to lead contamination in the environment Figure 40.

Figure 39 A man and woman in Tegal, Indonesia use hammers to break up used lead-acid batteries for recycling [from 150]

Used lead-acid batteries pose a significant environmental and health risk in developing countries where these isolated microgrids would often be installed and should be a factor when choosing the battery storage technology.

Liquid electrolyte LIB environmental considerations analysis results

Although spent LIB composition differs between manufacturers and models, they usually contain about 5%–20% cobalt, 5%–10% nickel, 5%–7% lithium, 5%–10% other metals (including copper, aluminum, iron, etc.), 15% organic compounds, and 7% plastic [152]. Mejame et al [153] evaluated the hazardous waste potential of various mobile phone LIB battery models by comparing the amounts of hazardous components against regulatory limits under the California Department of Toxic Substances Control (2004). They found that LIBs should be classified as hazardous waste due to exceeding the limits for cobalt and copper, and in some cases nickel and zinc.

LIB toxicity is problematic due to the current lack of an industrial scale, cost effective process to recycle LIBs after they have reached end of life [154]. With their increasing use and relatively short life, this is a growing environmental issue. Current recycling methods include: (a) mechanical recycling, which involves crushing the discharged battery; (b) pyrometallurgical recycling, where metals are extracted by thermal means; and (c) hydrometallurgical recycling, which uses aqueous processes. After crushing some components are separated but the lithium is recovered by the hydrometallurgical process. This current process also involves the use of dangerous chemicals [152]. The minimal LIB recycling being done today is mostly focused on recovering the cobalt and copper [155].

Researchers are looking into new processes to revive spent cathodes, but these methods are not ready for large scale use as they are not yet cost effective [156]. LIB recycling rates are still very low; both the European Union and United States recycle less than 5% of spent LIBs [157]. For the integrated, containerized grid-scale LIB systems applicable to this study, one should also consider recycling and disposal of the auxiliary components such as the fire suppression systems and forced-air HVAC systems [158].

Solid-state LIB environmental considerations analysis results

With commercialization of solid-state electrolyte SSBs still about a decade away [36], conducting an environmental assessment on future products is difficult due to the lack of real world information and data. It can probably be assumed that SSBs would have many of the same recycling limitations as liquid electrolyte LIBs due to the highly integrated and variable composition of their electrodes [155].

VRFB environmental considerations analysis results

As described in the previous section on safety, VRFB components are relatively benign and their disposal poses much less of an impact on the environment than the other technologies. VRFBs lack toxic metals such as lead, cadmium, zinc, and nickel, which can contaminate the environment. A VRFB's most toxic component is the electrolyte's sulfuric acid, which is only one-third as acidic as that in a lead-acid battery. And as previously described, the vanadium in the electrolyte has low toxicity [65], and VRFBs typically are in enclosures, which would contain any spills [159].

Another key positive factor is that the vanadium electrolyte does not require replacement and can even be reprocessed and reused in new batteries, making disposal unnecessary or at least on the order of several decades [148]. This contrasts with lead-acid batteries which require replacement every few years, or LIB ESS which are replaced about once per decade.

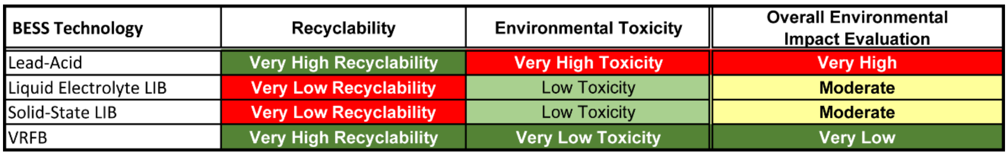
During operation, a VRFB is environmentally friendly because no waste products are produced. At end-of-life, a stack's cell membranes may be highly acidic and should be disposed of properly as a corrosive material [148]. Simon Clarke [159], executive vice president at VRB Power Systems boasts that VRFBs "have the best environmental footprint of any storage technology."

Environmental concerns analysis summary and conclusions

The environmental impact of energy storage systems is a broad topic and has been narrowly addressed here to focus on end of life aspects of the four technologies. Lead-acid battery recycling is a well-established and successful practice where close to 100% of used units are recycled safely in developed countries. However, in lesser developed, poorer areas, recycling can be a cottage industry conducted without environmental and health safeguards. As the analysis scenario is geared towards these types of regions, the end of life environmental impact should be considered a negative for the lead-acid battery technology due to the significant negative health impacts of the recycling process in the developing world.

LIBs also contain some hazardous components, and due to the difficulty and high cost of recycling most used batteries are disposed of rather than recycled, even in developed countries. As solid-state LIBs are not yet in production, it is difficult to project their environmental impact at end of life, but it is practical to assume to be similar to that of liquid electrolyte LIBs. Until a cost effective process is developed and LIBs recycling rates increase, this should also be considered a negative impact for these lithium-ion-based battery technologies.

Of the four technologies, VRFBs cause the least environmental impact at end of life as they are composed of mostly nontoxic components and are highly recyclable. In particular, the somewhat toxic vanadium electrolyte is extremely recyclable and can even be reused after a long 30-year lifespan of a VRFB unit. As shown in the environmental rubric analysis summary in Figure 41, VRFB's low environmental impact is another significant advantage of this technology.



BESS Technology	Recyclability	Environmental Toxicity	Overall Environmental Impact Evaluation
Lead-Acid	Very High Recyclability	Very High Toxicity	Very High
Liquid Electrolyte LIB	Very Low Recyclability	Low Toxicity	Moderate
Solid-State LIB	Very Low Recyclability	Low Toxicity	Moderate
VRFB	Very High Recyclability	Very Low Toxicity	Very Low

Figure 40 Environmental impact rubric analysis results

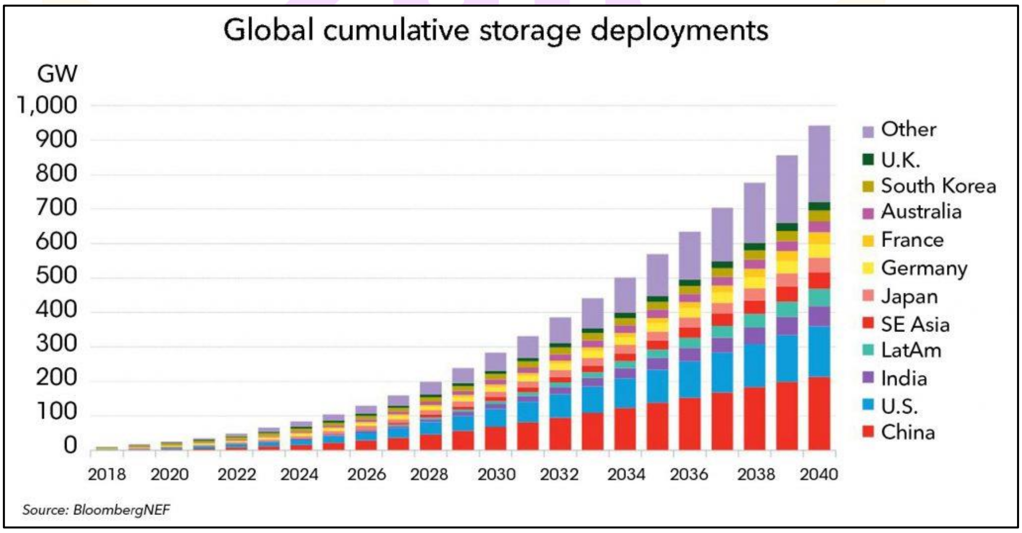
Chapter 5

CONCLUSIONS

Conclusions

This paper compared various battery technologies to support the energy storage requirements for a small renewable energy-based microgrid for a notional, poor community that is disconnected from the main grid. The venerable lead-acid battery is analyzed as a baseline against the current technology leader, the liquid electrolyte LIB, and the VRFB. The solid-state LIB is also investigated as a future technology.

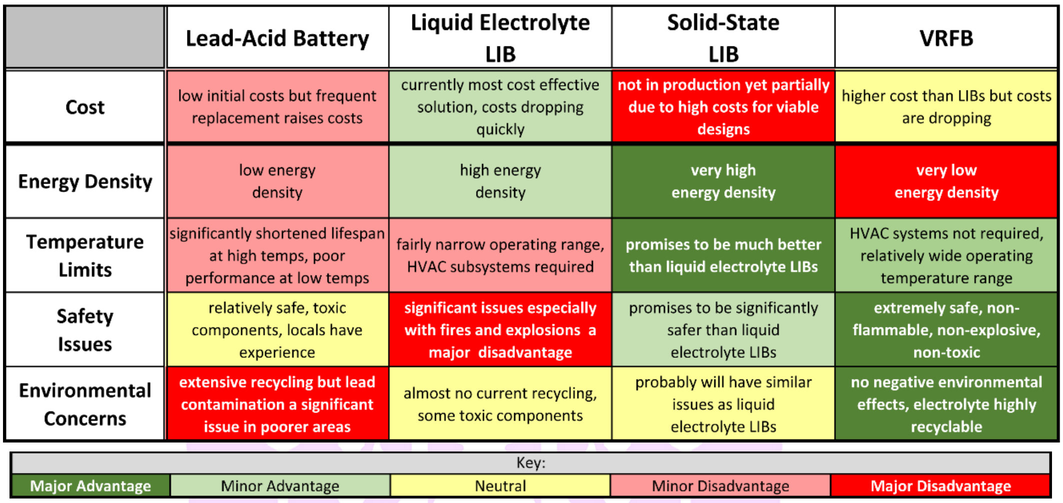
Worldwide grid energy storage is projected to increase significantly over the next two decades Figure 42 [160]. The promise of renewable energy production with storage promises significant advances for poor, disconnected communities similar to our notional scenario village that today remain unelectrified. Indications are that LIBs will maintain their place as the preferred BESS solution, although VRFBs have distinct advantages in several areas including safety and long life.


Global cumulative storage deployments

Source: BloombergNEF

Figure 41 Global cumulative energy storage [160]

Figure 42 summarizes the rubric analysis results from the five criteria examined in this study.



	Lead-Acid Battery	Liquid Electrolyte LIB	Solid-State LIB	VRFB
Cost	low initial costs but frequent replacement raises costs	currently most cost effective solution, costs dropping quickly	**not in production yet partially due to high costs for viable designs**	higher cost than LIBs but costs are dropping
Energy Density	low energy density	high energy density	**very high energy density**	**very low energy density**
Temperature Limits	significantly shortened lifespan at high temps, poor performance at low temps	fairly narrow operating range, HVAC subsystems required	**promises to be much better than liquid electrolyte LIBs**	HVAC systems not required, relatively wide operating temperature range
Safety Issues	relatively safe, toxic components, locals have experience	**significant issues especially with fires and explosions a major disadvantage**	promises to be significantly safer than liquid electrolyte LIBs	**extremely safe, non-flammable, non-explosive, non-toxic**
Environmental Concerns	**extensive recycling but lead contamination a significant issue in poorer areas**	almost no current recycling, some toxic components	probably will have similar issues as liquid electrolyte LIBs	**no negative environmental effects, electrolyte highly recyclable**

Key:

Major Advantage	Minor Advantage	Neutral	Minor Disadvantage	Major Disadvantage

Figure 42 Overall rubric analysis summary

Lifecycle cost is usually the ultimate driving factor in technology selection. LIB prices continue to fall, even exceeding projections, and are expected to continue to drop as production ramps up in the coming decade. Current LIB systems offer a significantly lower initial cost, which makes them today's predominate technology choice. Long battery life and the ability to fully discharge without detrimental effects are significant advantages which lower the costs for VRFBs. If VRFBs can achieve further lifecycle cost reductions to achieve more cost parity with LIBs, their other advantages may sway system operators to choose this technology. Short lifespan and frequent replacement drive the lifecycle cost of lead–acid batteries to a point where they are no longer cost competitive with other technologies for these larger BESS applications. O&M requirements are difficult to accurately cost, but both LIBs and VRFB system manufacturers claim low O&M requirements. The main issue with these technologies is the high cost of maintenance when it is required, and the complexity of these systems requiring trained technicians to conduct the maintenance.

Energy density is usually not a major concern for a stationary microgrid ESS, especially in rural areas where space is plentiful. Tolerance for operating at high temperatures is another advantage of VRFBs, as many poor rural areas are located in hotter parts of the world. The ability to operate without a HVAC subsystem removes major components requiring their own maintenance and upkeep. This advantage is shared by both VRFBs and the new SSBs. Safety is another area where VRFBs shine as LIB safety is a major concern in light of many recent incidents. The safety subsystems in containerized LIB systems (mainly fire suppression) add more components requiring their own maintenance. Safety is one of the leading issues against liquid electrolyte LIBs. VRFBs also lead on the environmental front, with a recyclable and nontoxic electrolyte. If LIB recycling can improve, its environmental impact will be lessened. Although liquid electrolyte LIBs are currently the BESS technology of choice, advances in SSB research in the coming decade, along with their eventual commercialization, will also factor into deciding the predominate technology in the future.

Recommendations

BESS performance has been steadily improving while costs have steadily decreased due to research investments. Some areas of further suggested study include following up the technologies several years from now to assess these improvements and assess the accuracy of predicted costs presented in this paper. Another area of interest would be to assess other energy storage system technologies, such as pumped hydro, molten salt batteries, compressed air systems, and flywheels. Other potential study areas are using a more sophisticated energy simulation model such as HOMER for the analysis, and going into further detail in the cost analysis, particularly with O&M costs.

REFERENCES

[1] International Energy Agency. (2018). **World Energy Outlook 2018.** Retrieved May 10, 2019, from https://www.iea.org/weo2018/.

[2] Kim, H. and Jung, T. Y. (2018). Independent solar photovoltaic with Energy Storage Systems (ESS) for rural electrification in Myanmar. **Renewable and Sustainable Energy Reviews,** 82, 1187–1194.

[3] Nam, K.Y., Cham, M.R. and Halili, P.R. (2015). Power Sector Development in Myanmar. Asian Development Bank (ADB). **Economics Working Paper Series,** 460, 1–24.

[4] Chauhan, A., Saini, R.P. (2014). Renewable Energy Based Power Generation for Stand-Alone Applications: A Review. **Renewable and Sustainable Energy Reviews,** 38, 99–120.

[5] Borhanazad, H., Mekhilef, S., Saidur, R. and Boroumandjazi, G. (2013). Potential application of renewable energy for rural electrification in Malaysia, **Renewable Energy**, 59, 210–219.

[6] Yuan, G. (2015). Rural Electrification Goes Local, **IEEE Electrification 1,** 16–24.

[7] Mongird, K., et al. (2019). **U.S. Department of Energy – Energy Storage Technology and Cost Characterization Report, HydroWIRES.** Retrieved May 10, 2019, from https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf.

[8] Connolly, D., Lund, H., Finn, P., Mathiesen, B.V., and Leahy, M. (2011). Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage, **Energy Policy,** 39, 4189–4196.

[9] National Aeronautics and Space Administration (NASA). (n.d.). **Battery Basics.** Retrieved May 10, 2019, from https://ti.arc.nasa.gov/tech/dash/groups/pcoe/battery-prognostics/battery-basics/.

[10] Bates, M. (2012). **How does a battery work? Retrieved.** Retrieved May 10, 2019, from https://engineering.mit.edu/engage/ask-an-engineer/how-does-a-battery-work/.

[11] Bhatt, A., Forsyth, M., Withers, R. and Wang, G. (n.d.). **How a battery works. Australian Academy of Science.** Retrieved May 10, 2019, from https://www.science. org.au/ curious/

technology-future/batteries.

[12] Arora, P. and Zhang, Z. (2004). Battery Separators. **Chemical Reviews,** 104(10), 4419-4462.

[13] Jana, A. and García, R.E. (2017). Lithium dendrite growth mechanisms in liquid electrolytes. **Nano Energy,** 41, 552-565.

[14] May, G.J., Davidson, A. and Monahov, B. (2018). Lead batteries for utility energy storage: A review, **Journal of Energy Storage,** 15, 145-157.

[15] Concordia University Environmental Health and Safety. (2016). **Lead-Acid Batteries.** Retrieved May 10, 2019, from https://www.concordia.ca/content/dam/concordia/services/safety/docs/EHS-DOC-146_LeadAcidBatteries.pdf

[16] Zhang, J., Chen, C., Zhang, X. and Liu, S. (2016). Study on the Environmental Risk Assessment of Lead-Acid Batteries. **Procedia Environmental Sciences**, 3, 873-879.

[17] Gauri, Bisht, M.S., Pant, P.C. and Gairola, R.C. (2018). Effect of temperature on flooded lead-acid battery performance. **International Journal of Advanced Science and Research**, 3(1), 27-29.

[18] MarketsandMarkets™. (2019). Lead Acid Battery Market by Technology (Basic, Advanced Lead Acid), Type (Stationary, Motive), Construction Method (Flooded, VRLA), End-User (Utilities, Transportation. **Industrial, Commercial & Residential), and Region – Global Forecast to 2024.** Retrieved May 10, 2019, from https://www. Markets and markets. com/Market-Reports/lead-acid-battery-market-161171997.html

[19] Burlin, W. (2018). **Lead-Acid Battery Comparison: Flooded vs. Gel & AGM Batteries (Pros & Cons).** Retrieved May 10, 2019, from https://www.wholesalesolar.com/blog/lead-acid-battery-comparison/.

[20] Technician Academy. (2017). **Flooded VS Gel Batteries: What Are the Differences?** Retrieved May 10, 2019, from https://technician.academy/flooded-vs-gel-batteries-what-are-the-differences/.

[21] Battery University. (2017). **BU-201b: Gel Lead Acid Battery.** Retrieved May 10, 2019, from https://batteryuniversity.com/learn/article/bu_201b_gel_lead_acid_battery.

[22] Battery University. (2017). BU-201a: Absorbent Glass Mat (AGM). Retrieved May 10,

2019, from https://batteryuniversity.com/learn/article/absorbent_ glass_mat_agm.

[23] Li, Q., Chen, J., Fan, L., Kong, X. and Lu, Y. (2016). Progress in electrolytes for rechargeable Li-based batteries and beyond. **Green Energy & Environment 1,** (1), 18-42.

[24] Walker, W.Q. (2015). Short Course on Lithium-Ion Batteries – Fundamentals, Thermal Performance and Understanding Thermal Runaway. **NASA Thermal Fluids and Analysis Workshop (TFAWS) 2015.** Retrieved May 10, 2019, from https:// tfaws.nasa.gov/wp-content/uploads/TFAWS2015-SC-Battery-Thermal-Design.pdf

[25] Ulvestad, A. (2018). **A Brief Review of Current Lithium Ion Battery Technology and Potential Solid State Battery Technologies.** Retrieved May 10, 2019, from https://arxiv.org /abs/1803.04317v1.

[26] Battery University. (2019). **BU-205: Types of Lithium-ion.** Retrieved May 10, 2019, from https://batteryuniversity.com/learn/article/types_of_lithium_ion.

[27] Deng, D. (2015). Li-ion batteries: basics, progress, and challenges. **Energy Science and Engineering** 3(5), 385-418.

[28] Nitta, N., Wu, F., Lee, J.T. and Yushin, G. (2015). Li-ion battery materials-present and future. **Materials Today** 18(5), 252-264.

[29] Zhang, X.Q., Zhao, C, Huang, J. and Zhang, Q. (2018). Recent Advances in Energy Chemical Engineering of Next-Generation Lithium Batteries. **Engineering** 4(6), 831-847.

[30] Jones, K.S., Rudawski, N.G., Oladeji, I., Pitts, R. and Fox, R. (2012). The state of solid-state batteries. **American Ceramic Society Bulletin** 91(2), 256-266.

[31] Funke, K. (2013). Solid State Ionics: from Michael Faraday to green energy-the European dimension. **Science and Technology of Advanced Materials** 14(4), 1-50.

[32] Owens, B.B., Munshi, M.Z.A. (1987). **History of Solid State Batteries. Office of Naval Research Technical Report No. 5.** Retrieved May 10, 2019, from https://apps. dtic.mil/dtic/ tr/ fulltext/ u2/ a176283.pdf.

[33] Kim, Y., Lin, X. Abbasalinejad, A., Kim, S.U. and Chung, S.H. (2019). On state estimation of all solid-state batteries. **Electrochimica Acta,** 317, 663-672.

[34] Braun, P., Uhlmann, C., Weiss, M., Weber, A. and Ivers-Tiffée, E. (2018). Assessment

of all-solid-state lithium-ion batteries. **Journal of Power Sources**, 393, 119–127.

[35] Zheng, F., Kotobuki, M., Song, S., Lai, M.O. and Lu, L. (2018). Review on solid electrolytes for all-solid-state lithium-ion batteries. **Journal of Power Sources**, 389, 198–213.

[36] Sun, C., Liu, J., Gong, Y., Wilkinson, D.P. and Zhang, J. (2017). Recent advances in all-solid-state rechargeable lithium batteries. **Nano Energ,** 33, 363-386.

[37] Lourenssen, K., Williams, J., Ahmadpour, F., Clemmer, R. and Tasnim, S. (2019). Vanadium redox flow batteries: A comprehensive review, **Journal of Energy Storage** 25, 100844.

[38] Shibata, T., Kumamoto, T., Nagaoka, Y., Kawase, K. and Yano, K. (2013). Redox Flow Batteries for the Stable Supply of Renewable Energy, **Sumitomo Electric Industries (SEI) Technical Review** 76, 14-22.

[39] US Department of Energy (DOE). (n.d.). **The Smart Grid.** Retrieved May 10, 2019, from https://www. smartgrid.gov/the_smart_grid/smart_grid.html.

[40] Dan.t.Ton and Merrill A.Smith. (2012). The U.s. Department of Energy's Microgrid Initiative **The Electricity Journal** 25(8), 84-94.

[41] US Department of Energy (DOE). (n.d.). Energy Storage System Firms a Renewable Resource- Successes from PNM's **.(Public Service Company of New Mexico) Smart Grid Demonstration Project.** Retrieved May 10, 2019, from https://www.energy. gov/sites/prod/files/2017/01/ f34/PNM_ Energy-Storage-System-Firms-Renewable-Resource.pdf.

[42] Bush, S.F. (2015). **Smart Grid – Communication-Enabled Intelligence for the Electric Power Grid** Retrieved May 10, 2019, from https://new.siemens.com/global/en/ products/energy/ topics/smart-grid.html

[43] Bowen, T., Chernyakhovskiy, I., Denholm, P. (2019). **Grid-Scale Battery Storage – Frequently Asked Questions. National Renewable Energy Laboratory (NREL).** Retrieved May 10, 2019, from https://www.nrel.gov/docs/fy19osti/74426.pdf.

[44] Schnitzer, D., Lounsbury, D.P., Carvallo, J.P., Deshmukh, R., Apt, J. and Kammen, D.M. (2014). **Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. United Nations Foundation.** Retrieved May 10, 2019, from http:// energyaccess. org/wp-content/uploads/2015/07/Microgrids

ReportFINAL_high.pdf.

[45] Zimmerle, D. and Manning, D.T. (2017). Optimizing Rural Village Microgrids to Provide Affordable and Reliable Electricity in Developing Countries. 2017 **IEEE Global Humanitarian Technology Conference (GHTC),** 4(1),1–6.

[46] MacKay, D.J.C. (2008). **Sustainable Energy – without the hot air. Version 3.5.2.** Retrieved May 10, 2019, from http://www.withouthotair.com/cft.pdf.

[47] MacKay, D.J.C. (2013). Solar energy in the context of energy use, energy transportation and energy storage. Philosophical Transactions of the Royal Society A: Mathematical, **Physical and Engineering Sciences** 371(1996), 1–24.

[48] Bhatia, M and Angelou, N. (2015). **The World Bank Energy Sector Management Assistance Program (ESMAP), Beyond Connections: Energy Access Redefined, Technical Report 008/15.** Retrieved May 10, 2019, from http://hdl. handle.net/ 10986/ 24368.

[49] Nandi, S.K. and Ghosh, H.R. (2009). A wind–PV–battery hybrid power system at Sitakunda in Bangladesh, **Energy Policy**, 37(9), 3659–3664.

[50] Patel, A.M. and Singal, S.K. (2016). Off grid rural electrification using integrated renewable energy system. **2016 IEEE 7th Power India International Conference (PIICON), Bikaner,** 2(1), 1–5.

[51] Rajanna, S., Saini, R.P. (2016). Modeling of integrated renewable energy system for electrification of a remote area in India. **Renewable Energy,** 90, 175–187.

[52] Ma, T., Yang, H., Lu, L. (2014). A feasibility study of a stand–alone hybrid solar–wind–battery system for a remote island. **Applied Energy**, 121, 149–158.

[53] Minke, C., Ledesma, M.A.D. (2019). Impact of cell design and maintenance strategy on life cycle costs of vanadium redox flow batteries. **Journal of Energy Storage,** 21, 571–580.

[54] Aquino, T., Roling, M., Baker, C. and Rowland, L. (2017). **Battery Energy Storage Technology Assessment. Prepared for the Platte River Power Authority by HDR**. Retrieved May 10, 2019, from https://www.prpa.org/wp–content/ uploads/ 2017/10/HDR–Battery–Energy–Storage–Assessment.pdf.

[55] Aquino, T., Zuelch, C. and Koss, C. (2017). **Energy Storage Technology Assessment. Prepared for the Public Service Company of New Mexico by HDR.** Retrieved May 10, 2019, from https://www. pnm.com/documents/396023/1506047/2017+-+HDR+10-30-17+PNM+ Energy+Storage+Report.pdf/a2b7ca65-e1ba-92c8-308a-9a8391a8 7331.

[56] Hutchinson, R. (2004**). Temperature Effects on Sealed Lead Acid Batteries and Charging Techniques to Prolong Cycle Life. Sandia Report SAND2004-3149.** Retrieved May 10, 2019, from https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2004/043149.pdf.

[57] Massachusetts Institute of Technology (MIT) Electric Vehicle Team. (2008). **A Guide to Understanding Battery Specifications.** Retrieved May 10, 2019, from http://web. mit.edu/evt/ summary_battery_specifications.pdf.

[58] Choi, J.W., Aurbach, D. (2016). Promise and reality of post-lithium-ion batteries with high. energy densities. **Nature Review Materials**, 1, 1-16.

[59] Bower, G. (2019). **Tesla Model 3 2170 Energy Density Compared to Bolt, Model S P100D. Inside EVs.** Retrieved May 10, 2019, from https://insideevs.com/news/ 342679/tesla-model-3-2170-energy-density-compared-to-bolt-model-s-p100d.

[60] Li, L., Kim, et al. (2011), A Stable Vanadium Redox-Flow Battery with High Energy Density for Large-Scale Energy Storage. **Advanced Energy Materials**, 1, 394-400.

[61] Gibbard, F and Cipriano, G. (2019). **Watt Joule Company Introduction.** (PowerPoint slides). Retrieved May 10, 2019, from https://flowbatteryforum.com/list-of-papers-2010-2019/.

[62] The World Bank. (2020). **The World by Income, 2020.** Retrieved May 10, 2019, from http://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html.

[63] Liu, G., Ouyang, M., Lu, L., Li, J., and Han, X. (2014). Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors. **Journal of Thermal Analysis and Calorimetry**, 116, 1001-1010.

[64] Zhang, C., Zhao, T.S., Xu, Q., An, L. and Zhao, G. (2015). Effects of operating temperature on the performance of vanadium redox flow batteries. **Applied Energy**, 155, 349-353.

[65] Wang, W. (2012). Vanadium Redox Flow Batteries–Improving the performance and reducing the cost of vanadium redox flow batteries for large–scale energy storage. US Department of Energy (DOE) Energy Storage Program, **Pacific Northwest National Laboratory.** Retrieved May 10, 2019, from https://www.energy.gov/sites/prod/files/ VRB.pdf

[66] Kilfoyle, M. (2019). **How to write a research synthesis report (or how I conquered my batteries mountain.** Retrieved May 10, 2019, from https://blogs.uwe.ac.uk/science–communication/category/publications/

[67] Trojan Battery Company. (2017). **Solar Premium Line Batteries–Product Line Sheet.** Retrieved May 10, 2019, from https://www.trojanbattery.com/pdf/Solar Premium Trojan_ ProductLineSheet.pdf

[68] Trojan Battery Company. (2015). **Deep–Cycle Gel Batteries Product Line Sheet.** Retrieved May 10, 2019, from https://www.trojanbattery.com/pdf/GEL_Trojan_ProductLine Sheet.pdf.

[69] Trojan Battery Company. (2018). **Introducing Solar True Deep–Cycle AGM (flyer).** Retrieved May 10, 2019, from https://www.trojanbattery.com/pdf/TRJN–0255– SOLAR–AGM–Flyer.pdf

[70] Trojan Battery Company. (2015). **Battery Maintenance.** Retrieved May 10, 2019, from https://www.trojanbattery.com/tech–support/battery–maintenance/

[71] Hoppecke Battery. (2013). **Installation, commissioning and operating instructions for valve–regulated stationary lead–acid batteries.** Retrieved May 10, 2019, from https:// www. hoppecke. com/fileadmin/Redakteur/Hoppecke–Main/Products/Downloads/ VRL_ manual _EN.pdf

[72] Connell, J. (2019). 5 lessons you can learn from battery torture tests. **Solar Power World,** Retrieved May 10, 2019, from https://www.solarpowerworldonline.com/ 2019/08/5–lessons–you–can–learn–from–battery–torture–tests

[73] PowerThru. (n.d.). **Lead Acid Battery Working – Lifetime Study (technical paper).** Retrieved May 10, 2019, from http://www.power–thru.com/documents/The%20 Truth%20 About% 20Batteries%20–%20POWERTHRU%20White%20Paper.pdf

[74] Battery University. (2019). **How to Prolong Lead–acid Batteries (BU–804).** Retrieved May 10, 2019, from https://batteryuniversity.com/learn/article/how_to_restore_ and_

prolong_lead_ acid_batteries

[75] Solar Biz. (n.d.). **Trojan solar battery (price list).** Retrieved May 10, 2019, from https://www. thesolarbiz.com

[76] The Powerstore. (n.d.). **Crown battery (price list).** Retrieved May 10, 2019, from https://www. thepowerstore.com

[77] TooSolar. (n.d.). **Exide GNB Classic OPzS Solar Batteries (price list).** Retrieved May 10, 2019, from https://toosolar.it.

[78] FF Solar. (2020). **Public Prices List.** Retrieved May 10, 2019, from http://www.ffsolar.com

[79] Batteries4Pro. (n.d.). **Exide Sonnenschein Solar AGM battery price list.** Retrieved May 10, 2019, from from: https://www.batteries4pro.com.

[80] IEEE Power Engineering Society. (2003l). **IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.** Retrieved May 10, 2019, from http://gost-snip.su/download/ieee_std_ 450_ 2002_ieee_ recommended practice_for_ maintenance

[81] Alcad Standby Batteries. (n.d.). **Lead Acid Battery Operating Instructions, Rev. 0806.** Retrieved May 10, 2019, from https://www.yumpu.com/en/document/view/ 7053869/lead-acid-battery-operating-instructions-alcadcom

[82] Trojan Battery Company. (2019). **User's Guide.** retrieved from: https://www.trojanbattery. com/pdf/TrojanBattery_UsersGuide.pdf

[83] Hesse, H.C., Schimpe, M., Kucevic, D., Jossen, A. (2017). Lithium-Ion Battery Storage for the Grid-A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids. **Energies 2017**, 10(1), 2107.

[84] Soskin, P. (2019). Every charge cycle counts when it comes to battery degradation. **Energy Storage News.** Retrieved May 10, 2019, from https://www.energy-storage. news/blogs/every-charge-cycle-counts-when-it-comes-to-battery-degradation.

[85] Australian Renewable Energy Agency (2017). **Battery Test Centre. Report, 3.** Retrieved May 10, 2019, from https://batterytestcentre.com.au/wp-content/uploads/ 2017/07 /Battery-Testing-Public-Report-3-November-2017.pdf.

[86] Environmental and Energy Study Institute (2019). **Fact Sheet: Energy Storage**

(2019). Retrieved May 10, 2019, from https://www.eesi.org/papers/view/energy-storage-2019.

[87] Xu, B., Oudalov, A., Ulbig, A., Andersson, G., Kirschen, D.S. (2018). Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment. **IEEE Transactions on Smart Grid**, *9(2)*, 1131-1140.

[88] Smith, K., Saxon, A., Keyser, M., Lundstrom, B., Cao, Z., Roc, A. (2017). Life Prediction Model for Grid Connected Li-ion Battery Energy Storage System. **Presented at 2017 American Control Conference, Seattle,** Retrieved May 10, 2019, from: https://www.nrel.gov/ docs/fy17osti/ 67102.pdf.

[89] Balducci, P., et.al., (2017). **The Salem Smart Power Center – An Assessment of Battery Performance and Economic Potential.** Retrieved May 10, 2019, from https://www.pnnl.gov/main/ publications/external/technical_reports/PNNL-26858.pdf.

[90] Goldie-Scot, L. (2019). **A Behind the Scenes Take on Lithium-ion Battery Prices. BloombergNEF.** Retrieved May 10, 2019, from https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/.

[91] St. John, J. (2019). **Report: Levelized Cost of Energy for Lithium-Ion Batteries Is Plummeting. Greentech Media.** Retrieved May 10, 2019, from https://www.greentechmedia.com/articles/ read/report-levelized-cost-of-energy-for-lithium-ion-batteries-bnef.

[92] Henze, V. (2019). Battery Power's Latest Plunge in Costs Threatens Coal, Gas. **BloombergNEF.** Retrieved May 10, 2019, from https://about.bnef.com/blog/battery-powers-latest-plunge-costs-threatens-coal-gas/.

[93] University of Washington Clean Energy Institute (CEI). (n.d.). **Lithium-Ion Battery – What is a lithium-ion battery and how does it work?** Retrieved May 10, 2019, from https://www.cei. washington.edu/education/science-of-solar/battery-technology/.

[94] Colthorpe, A. (2017). O&M in storage: optimisation and maintenance. **PV Tech Power 11,** Retrieved May 10, 2019, from https://www.energy-storage.news/resources/om-in-storage-optimisation-and-maintenance.

[95] Ma, J., Chen, B., Wang, L., Cui, G. (2018). Progress and prospect on failure mechanisms of solid-state lithium batteries. **Journal of Power Sources**, 392, 94-115.

[96] Zhao, W., Yi, J., Zhou, H. (2019). for Solid-State Electrolytes Lithium-Ion Batteries: Fundamentals, Challenges and Perspectives. **Electrochemical Energy Reviews**, 2, 574–605.

[97] Lewis, J.A., Tippens, J., Cortes, F.J.Q., McDowell, M.T. (2019). Chemo-Mechanical Challenges in Solid-State Batteries. **Trends in Chemistry,** 1(9), 845-857.

[98] Taylor, N.J. and Sakamoto, J. (2019). Solid-state batteries: Unlocking lithium's potential with ceramic solid electrolytes. **American Ceramics Society Bulletin** 98(7), 26-31.

[99] StorEn Technologies Inc. (n.d.). **ST 50-500 Energy Storage System (data sheet).** Retrieved May 10, 2019, from https://1a36ec41-0269-46e2-8595-a053c359deb9.filesusr.com/ugd/ 84619e _d2f 2a5b 2a661419f93c4e0ed1962831e.pdf

[100] VRB Energy (n.d.). **VRB Energy-The Most Reliable, Longest-Lasting Vanadium Flow Battery in the World (brochure).** Retrieved May 10, 2019, from https://vrbenergy. com/vrb-energy-commissions-3mw-12mwh-vanadium-redox-battery-energy-storage - system-vrb-ess/.

[101] Dalian Rongke Power Co., Ltd. (n.d.). **Vmodule1-A Product Specification, Version: Rev. 1.** Retrieved May 10, 2019, from http://www.rongkepower.com/chuneng?lang =en.

[102] Sumitomo Electric Industries, Ltd. (n.d.). **Redox Flow Battery (brochure).** Retrieved May 10, 2019, from https://global-sei.com/products/redox/pdf/Container-type.pdf.

[103] redT Energy Storage. (n.d.). **Off-grid energy Secure power, Cut diesel costs, Reduce carbon emissions.** Retrieved May 10, 2019, from https://redtenergy.com/ customers/off-grid-energy/.

[104] Trojan Battery Company. (2019). **Renewable Energy Product Specification Guide (data sheet).** Retrieved May 10, 2019, from https://www.trojanbattery.com/pdf/TrojanBattery_ ProdSpec Guide_RE.pdf.

[105] Crown Battery. (2020). **Renewable Energy on Demand-Renewable Energy Storage Solutions (product brochure).** Retrieved May 10, 2019, from https://www. crownbattery.com/ hubfs/Crown-RenewableEnergyBroch-single%20pgs-web.pdf.

[106] GNB Industrial Power. (n.d.). **Classic Solar (product brochure).** Retrieved May 10, 2019, from http://www2.exide.com/Media/files/GNB_Classic_Solar_NXCSLTEP DF00616.pdf.

[107] Hoppecke Batterien GmbH and Co. KG. (2020). **sunlpower VR L Series OPzV/OPzV bloc-**

valve regulated lead–acid batteries for cyclic operations (product brochure).retrieved May 10, 2019, from https://www.hoppecke.com/fileadmin/Redakteur/Hoppecke–Main/Products–Import/sun_power _vrl_brochure_en.pdf.

[108] AtlasBX. (n.d.). **VGS Premium Liquid Free Sealed Type Battery (product brochure–Korean).** Retrieved May 10, 2019, from https://www.hankook–atlasbx.com/en/ product/industrial/2v–gel.do.

[109] GNB Industrial Power. (n.d.). **Sonnenschein *SOLAR (product brochure).*** Retrieved May 10, 2019, from http://www2.exide.com/Media/files/Downloads/IndustEuro/Sonnenschein_SOLAR_en.pdf.

[110] GNB Industrial Power. (2015). **Absolyte GX (product brochure).** Retrieved May 10, 2019, from http://www2.exide.com/Media/files/Downloads/IndustAmer/Section%2027_10% 202015–03% 20 Absolyte%20GX%20Industrial%20Batteries%20Overview.pdf

[111] Bhatia, A. (n.d.). **Battery Room Ventilation and Safety. CED Engineering.** Retrieved May 10, 2019, from https://www.cedengineering.com/userfiles/Battery%20Room%20Ventilation % 20and %20 Safety.pdf

[112] LG Chem. (2019). **Change Your Energy Charge Your Life – Advanced Batteries for Energy Storage (brochure).** Retrieved May 10, 2019, from http://m.lgchem.com/upload/file/product/ LGChem_Catalog_Global_2018.pdf

[113] Samsung SDI. (2018). **ESS Batteries by Samsung SDI (brochure).** Retrieved May 10, 2019, from http://www.samsungsdi.com/upload/ess_brochure/201803SamsungSDI %20ESS_EN.pdf

[114] Aggreko. (n.d.). **Y.Cube (product guide).** retrieved from: https://www.aggreko. com/en–us/products/energy–storage/ycube

[115] Saft. (2017). **Intensium Max+ 20P (product brochure).** Retrieved May 10, 2019, from https://www.saftbatteries.com/products–solutions/products/intensium%C2%AE–max–megawatt–energy–storage–system

[116] Fluence. (2019). **Fluence EnergyEdge System Spec Sheet.** Retrieved May 10, 2019, from https://aesenergystorage.com/development/wp–content/uploads/2019/04/ Energy Edge–Tech– Spec_Fluence_TS–004–01–EN.pdf

[117] BYD Company Ltd. (2016). **BYD Project Reference (brochure).** Retrieved May 10, 2019, from

https://en.byd.com/wp-content/uploads/2017/06/byd-utility-scale-ess-brochure-v20160520 .pdf

[118] Wang, H.C., Cao, X., Liu, W. and Sun, X. (2019). Research Progress of the Solid State Lithium-Sulfur Batteries. **Frontiers in Energy Research 7.** doi: https://doi.org/10.3389/ fenrg. 2019.00112

[119] Schnella, J., et.al., (2018). All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production. **Journal of Power Sources,** 382, 160-175.

[120] Takada, K. (2018). Progress in solid electrolytes toward realizing solid-state lithium batteries. **Journal of Power Sources**, 394, 74-85.

[121] Samsung. (2020). Samsung Presents Groundbreaking All-Solid-State Battery Technology to 'Nature Energy'. **Samsung Newsroom.** Retrieved May 10, 2019, from https://news. samsung.com/global/samsung-presents-groundbreaking-all-solid-state-battery-technology-to-nature-energy

[122] Blain, L. (2019). Solid state battery breakthrough could double the density of lithium-ion cells. **New Atlas.** retrieved from: https://newatlas.com/science/deakin-solid-state-battery-polymer-electrolyte.

[123] Dalian Rongke Power Co., Ltd. (n.d.). **Vpower1-A Product Specification, Version: Rev. 1.** Retrieved May 10, 2019, from http://www.rongkepower.com/chuneng?lang =en.

[124] Battery University. (2019). **BU-502: Discharging at High and Low Temperatures.** Retrieved May 10, 2019, from https://batteryuniversity.com/learn/article/discharging_at _high _and_low_temperatures.

[125] Blue Box Batteries. (2015). **How Does Temperature Affect Lead Acid Batteries?.** Retrieved May 10, 2019, from https://www.blueboxbatteries.co.uk/blog/how-does-temperature-affect-lead-acid-batteries-30#.Xm2BRKhKiud.

[126] Ma, S., et.al., (2018). Temperature effect and thermal impact in lithium-ion batteries: A review, Progress in Natural Science: **Materials International**, 28(6), 653-666.

[127] Ogawa, M., Yoshida, K. and Harada, K., (2012). All-Solid-State Lithium Batteries with Wide Operating Temperature Range, **Sumitomo Electric Industries (SEI) Technical Review,** 74, 88-90. http://global-sei.com/technology/tr/bn74/pdf/74-16.pdf

[128] SafeWork South Australia. (2015). **Lead acid batteries.** Retrieved May 10, 2019, from https://www. safework.sa.gov.au/workplaces/chemicals-substances-and-explosives/ lead-

acid-batteries

[129] Crown Battery. (2019). **Safety Data Sheet (brochure).** Retrieved May 10, 2019, from https://www. crownbattery.com/lp-sds-deep-cycle-batteries.

[130] Canadian Centre for Occupational Health and Safety (CCOHS). (2016). **Battery Charging (fact sheet).** Retrieved May 10, 2019, from https://www.ccohs.ca/oshanswers/safety_haz/battery-charging.html.

[131] Mouawad, J. (2014). Report on Boeing 787 Dreamliner Battery Flaws Finds Lapses at Multiple Points. **New York Times.** Retrieved May 10, 2019, from https://www. nytimes.com/ 2014/ 12/02/business/report-on-boeing-787-dreamliner-batteries-assigns-some-blame-for-flaws.html

[132] U.S. National Transportation Safety Board. (2014). Auxiliary Power Unit Battery Fire Japan Airlines Boeing 787-8, JA829J, Boston, Massachusetts, January 7, 2013. **NTSB Incident Report AIR-NTSB/14/01, PB2014-108867.** Retrieved May 10, 2019, from http://libraryonline. erau.edu/online-full-text/ntsb/miscellaneous-reports/ AIR14-01.pdf.

[133] Guarino, B. (2017). Woman's headphone batteries exploded on flight to Australia, causing burns. **Washington Post.** Retrieved May 10, 2019, from https://www.washingtonpost.com/news/morning-mix/wp/2017/03/15/womans-headphone-batteries-exploded-on-flight-to-australia-causing-burns/?arc404=true.

[134] U.S. Federal Aviation Administration. (2016). Announcement of a Ban on All Samsung Galaxy Note 7 Smartphone Devices from Air Transportation in the United States. **FAA National Part 139 CertAlert.** Retrieved May 10, 2019, from https://www. faa.gov/airports/airport_safety/certalerts/media/part-139-cert-alert-16-08-samsung-galaxy-note-7-ban.pdf.

[135] U.S. Federal Aviation Administration. (2020). Events Involving Smoke, Fire, Extreme Heat or Explosion Involving Lithium Batteries. **FAA Office of Security and Hazardous Materials Safety.** Retrieved May 10, 2019, from https://www.faa.gov/hazmat/ resources/ lithium_batteries/media/ Battery_incident_chart.pdf

[136] Ruffo, G.H. (2019). Hyundai Kona Electric Explodes, Blows Hole in Garage: Cause Unknown. **Inside EVs.** Retrieved May 10, 2019, from https://insideevs.com/news/ 362202/

hyundai-kona-electric-explodes-canada/

[137] Stringer, D., Ma, J. and Hong, J. (2019). **Tesla Fires Sound Alarms About Electric-Car Battery Safety, Bloomberg,** Retrieved May 10, 2019, from https://www.bloomberg.com/news/articles/2019-05-16/tesla-fires-sound-alarms-about-safety-of-electric-car-batteries.

[138] Edwards, E. (2019). The battery behind dangerous and deadly e-cigarette explosions. **NBC News.** Retrieved May 10, 2019, from https://www.nbcnews.com/health/health-news/battery-behind-dangerous-deadly-e-cigarette-explosions-n1032901.

[139] M.E. Rossheim, M.D. Livingston, E.K. Soule and H.A Zeraye, D.L. (2019). Thombs, Electronic cigarette explosion and burn injuries, US Emergency Departments 2015-2017, **Tobacco Control,** 28(4), 472-474.

[140] Peng, Y., et,al. (2020). A comprehensive investigation on the thermal and toxic hazards of large format lithium-ion batteries with LiFePO4 cathode. **Journal of Hazardous Materials** 381, 120916.

[141] Dana, J. and Wilcox, K. (2019). Safety expert emails show APS lacked certain ventilation system in April battery site explosion. **KPNX Channel 12 News (Phoenix, AZ, USA).** Retrieved May 10, 2019, from https://www.12news.com/article/news/investigations/aps-explosion-investigation/ 75- 95590a62-e8ef-46c3-9a89-cf73da298e05

[142] APS. (2019). **McMicken Battery Investigation-November 5, 2019 Update.** Retrieved May 10, 2019, from https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/ McMicken-Investigation-Update-110419.

[143] Arizona Corporation Commission, State of Arizona, USA. (2019). **In the Matter of the Commission's Inquiry of Arizona Public Service Battery Incident at the McMicken Energy Storage Facility Pursuant to Arizona.** Arizona: Administrative.

[144] VRB Energy. (2019). **Energy Storage Safety Monitor (presentation).** Retrieved May 10, 2019, from https://vrbenergy.com/wp-content/uploads/2019/11/Energy-Storage-Safety-Monitor-October-2019.pdf.

[145] Baker, D.R. and Chediak, M. (2020). **Everyone's Favorite Climate Solution Has a Fire Problem, Bloomberg Green.** Retrieved May 10, 2019, from https://www.bloomberg.com/

news/articles/2020-01-28/everyone-s-favorite-climate -solution-has-a-fire-problem.

[146] Paiss, M. (2017). Energy Storage System Safety: Comparing Vanadium Redox Flow and Lithium-Ion Based Systems. **white paper**, Retrieved May 10, 2019, from http://www.energy responsesolutions.com/wp-content/uploads/VRB_Safety Report. pdf.

[147] Daggett, J. (2019). **Can Flow Batteries compete with Li-ion? DNV-GL Energy in Transition.,** Retrieved May 10, 2019, from https://blogs.dnvgl.com/energy/can-flow-batteries-compete-with-li-ion.

[148] Dassisti, M., et,al., (2016). Sustainability of Vanadium Redox Flow Battery. **Reference Module in Materials Science and Materials Engineering (Chapter 4.4).** Retrieved May 10, 2019, from https://doi.org/10.1016/B978-0-12-803581-8.04007-8.

[149] Hesler, P., Travers, K., Warren, S., Anastasia, P. and Chinnock, J. (2018). Lithium-ion Battery Energy Storage Systems - The risks and how to manage them. **AIG Energy Industry Group.** Retrieved May 10, 2019, from https://www.s lipcase.com/view/lithium-ion-battery-energy-storage-systems-the-risks-and-how-to-manage-them.138386?track=0&utm_ medium=email&utm_source=slipcase.

[150] Pure Earth and Green Cross Switzerland (2016). *The Toxics Beneath Our Feet*-World's Worse Pollution Problems. Retrieved May 10, 2019, from https://www.worstpolluted.org/docs/Worlds Worst 2016.pdf.

[151] World Health Organization. (2017). Recycling used lead-acid batteries. **health considerations.** Retrieved May 10, 2019, from https://www.who.int/ipcs/publications/ulab/en/.

[152] Bhatnagar, S. (2020). **Biological Recycling of Lithium Batteries (presentation).** Retrieved May 10, 2019, from doi: 10.13140/RG.2.2.21063.65445.

[153] Paul, P., Mejame, M., Jung, D., Lee, H., Lee, D. and Lim, R. (2020). Effect of technological developments for smartphone lithium battery on metal-derived resource depletion and toxicity potentials. **Resources, Conservation & Recycling**, 158, 104797.

[154] Sloop, S.E., Trevey, J., Gaines, L., Lerner, M.M., Xu, W. (2018). Advances in Direct Recycling of Lithium-Ion Electrode Materials, **Electrochemical Society Transactions MA2018,** 01, 397-403.

[155] European Commission's Directorate-General Environment. (2018). **Towards the**

battery of the future. Future brief 20. Retrieved May 10, 2019, from https://ec.europa.eu/environment/integration/ research/newsalert/pdf/towards_the_battery_of_ the_future_FB20_en.pdf

[156] Harper, G., et.al., (2019). Recycling lithium-ion batteries from electric vehicles. **Nature**, 575, 75-86.

[157] Jacoby, M. (2019). It's time to get serious about recycling lithium-ion batteries. **Chemical & Engineering News 97(28).** Retrieved May 10, 2019, from https://cen.acs.org/materials/ energy-storage/ time-serious-recycling-lithium/97/i28.

[158] Pellow, M.A., Ambrose, H., Mulvaney, D., Betita, R. and Shaw, S. (2020). Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues. **Sustainable Materials and Technologies 23, e00120.** Retrieved May 10, 2019, from doi: https://doi.org/ 10.1016/j. susmat.2019.e00120.

[159] Holzman, D.C. (2007). The Vanadium Advantage: Flow Batteries Put Wind Energy in the Bank, **Environmental Health Perspectives**, 115(7), 115-358.

[160] Henze, V. (2018). Energy Storage is a $620 Billion Investment Opportunity to 2040. **BloombergNEF.** Retrieved May 10, 2019, from https://about.bnef.com/blog/energy-storage-620-billion-investment-opportunity-2040/.

GLOSSARY

GLOSSARY

AC	Alternating Current
AGM	Absorbent Glass Mat
BESS	Battery Energy Storage System
BOP	Balance of Plant
C&C	Construction and Commissioning
DC	Direct Current
DOD	Depth of Discharge
DOE	Department of Energy [USA]
ESMAP	Energy Sector Management Assistance Program [World Bank]
ESS	Energy Storage System
FAA	Federal Aviation Administration [USA]
HC	High Cube
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
LIB	Lithium–Ion Battery
LIPON	Lithium Phosphorus Oxynitride
LISICON	Lithium Super Ionic Conductor
NASICON	Sodium Super Ion Conductor
NGO	Non–Governmental Organization
NTSB	National Transportation Safety Board [USA]
O&M	Operations and Maintenance
PCS	Power Conversion System
PSH	Pumped Storage Hydropower
PV	Photovoltaic
SEI	Solid Electrolyte Interphase
SSB	Solid–State Battery
VRFB	Vanadium Redox Flow Battery
VRLA	Valve Regulated Lead–Acid

VITA

NAME	Paul G. Marshall
DATE OF BIRTH	21 September 1961
PLACE OF BIRTH	Johnson Air Force Base, Japan
INSTITUTIONS ATTENDED	1991 B.S. (Oceanography) United States Naval Academy University of California, San Diego
HOME ADDRESS	645 Front St.1303 San Diego, California 92101 United States of America
PUBLICATION	Paul G. Marshall and Bunyawat Vichanpol (speakers). (28 January 2020). Comparison of Energy Storage Technologies for a Notional, Isolated Community Microgrid Journal of Renewable Energy and Smart Grid Technology, 15(1), (47-60).
AWARD RECEIVED	none