Comparison of Energy Storage Technologies for a Notional, Isolated Community Microgrid

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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 this 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 four BESS technologies are analyzed in two parts: (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; and (b) 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.

Keywords:

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

1. Introduction

In the World Energy Outlook 2018, the International Energy Agency (IEA) 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 [1]. 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 allowing nighttime activities [2]. The problem is especially acute for poor, remote communities which are disconnected from the main power grid. In recent years, cost reductions have resulted in far more access to renewable energy production, even for poorer communities [3]. 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. 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 farmworkers are back in their homes. 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, which allows the rural user to use the stored energy produced during daylight hours upon returning home after working outdoors during the day.

Today, pumped storage hydropower (PSH) is by far the predominant technology accounting for about 98% of worldwide energy storage. However, 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 [4]. This study focuses on four battery technologies where PSH would not be viable: the lead-acid battery, the liquid electrolyte lithium-ion battery (LIB), the solid-state LIB, and the vanadium redox flow battery (VRFB). These four technologies are analyzed against two sets of evaluation criteria. The first set centers on an overall cost analysis, which includes analysis factors that are direct inputs into the cost calculations: (a) depth of discharge (DOD) limits, (b) efficiency, and (c) capacity fade, all three of which determine initial battery sizing; (d) battery life, which affects replacement frequency; and (e) operations and maintenance (O&M) costs. The second set of criteria includes four analysis factors that have cost implications but were not used as inputs into this study's cost analysis, although they are still significant factors to consider: energy density, operating temperature limits, safety issues, and environmental concerns.

To support the cost analysis, the BESS technologies were evaluated in an analysis scenario based on a notional rural village that is disconnected from the main power grid and supported by a village microgrid primarily powered by a photovoltaic (PV) source and featuring a BESS which allows for 24-hour electrical power. The details for this notional village microgrid are provided in Section 3 below.

2. BESS Technologies

Until recently, the most common battery energy storage system (BESS) for this application has been a lead-acid battery-based system, which is included in this study to provide a baseline comparison against the newer battery technologies as it is still a widely used battery type in poorer communities. For the renewable energy storage application relevant to this study, three types of deep cycle lead-acid battery technologies predominate: (a) flooded, (b) gel, and (c) absorbent glass mat (AGM).

In recent years, liquid electrolyte LIB energy storage systems (ESS) have experienced dramatic cost reductions and performance improvements and are now the predominant choice in developed countries, despite several inherent shortcomings. One key LIB disadvantage is the formation of the solid electrolyte interphase (SEI), a passive layer of decomposition products which form over the surface of the anode during cycling resulting in eventual irreversible charge loss, shortening battery life [5]. Another liquid electrolyte LIB disadvantage is the formation of metallic lithium deposits, known as dendrites, on the anode. Dendrites can grow over multiple charges and discharge cycles until they breach the separator and 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 [6]. This becomes a safety issue as thermal runaway propagates to surrounding cells, causing a chain-reaction, which can lead to catastrophic battery failure.

Research in lithium-ion solid-state battery (SSB) technologies has accelerated in recent years to address the shortcoming of liquid electrolyte LIBs by providing a safer energy storage solution. The solid electrolyte allows the use of metal lithium instead of carbon as an anode material, resulting in theoretical gravimetric energy several times higher than non-lithium anode liquid electrolyte LIBs [7], and volumetric energy densities up to 70% higher [8]. Also, solid-state electrolytes deter dendrite growth as the solid nature of the electrolyte blocks dendrites from establishing the unwanted connection by providing a physical barrier [9]. Although several large companies are investing heavily in SSB development, projections place full SSB development and commercialization at least a decade away [10].

The VRFB is an energy storage solution which features its own set of advantages over the other technologies and is in widespread use today. A VRFB stores its electrolytes in external tanks separate from the battery cell itself, where the vanadium ions exist in four different oxidation states in the system. The electrolytes are pumped through their separate half-cells, returning to their respective storage tanks for recirculation. The redox reactions of the vanadium ions cause hydrogen (H^+) ions to diffuse through the stack's 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. The reaction occurs in reverse during charging. A unique characteristic of VRFBs is that its energy storage capacity 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 [11]. 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 [12], a significant advantage of VRFBs.

3. Methodology

The evaluation of the four different BESS technologies was conducted in two parts:

(a) cost analysis, including factors which directly affect the overall lifecycle cost estimate: DOD limits, efficiency, capacity fade, battery life, O&M requirements.

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

To provide a common set of evaluation criteria, an analysis scenario was developed which features a notional village microgrid whose characteristics were based on real world studies by Nandi and Ghosh [13] of the Sitakunda upazila in Bangladesh, Patel and Singal [14] of the village of Khatisitara in India, and Ma et al. [15] of a small remote island in Hong Kong. Based on a blending of characteristics from these locations, a notional village was defined, supported by a renewable energy-based microgrid with the following features: (a) disconnected from the main grid, (b) 125 households supported, (c) 250 kWh/day and 200 kW power output, (d) 605 kWh BESS capacity, (e) 20 year system lifetime.

The cost analysis used a methodology from Mongird et al. which characterized energy storage technologies and costs [16]. Mongird's framework provided a cost methodology for 11 different energy storage system technologies, including lead-acid batteries, liquid electrolyte LIBs, and VRFBs. Mongird did not include lithium-ion SSBs since they are not yet in production, so cost data does not yet exist. Therefore, SSBs are also not evaluated in this study's cost analysis. For systems based on the different BESS technologies, the methodology calculates total project cost based on the sum of capital cost, power conversion system (PCS) cost, the balance of plant (BOP) cost, and construction and commissioning (C&C) costs. In addition, fixed and variable O&M costs are also calculated.

Capital cost (expressed in $/kWh) pertains to the procurement of the DC energy storage unit, basically the battery itself. A major capital cost driver is the initial capacity rating of the battery bank, which is affected by DOD operating limits, DC round-trip efficiency, and capacity fade over the life of the battery. Each of these factors requires the initial BESS capacity rating to be scaled up to still provide the scenario's 605 kWh of useful storage at battery end of life (or just prior to replacement). Battery life is another cost driver as it determines how often the battery bank must be replaced during the 20 year scenario lifespan. Battery life estimates from manufacturers' data was used to determine how often and when batteries would be replaced as part of capital cost.

PCS costs (mainly the inverter) and BOP costs (wiring, transformers, other ancillary equipment) were estimated using the power output of the BESS in kW (200 kW for the analysis scenario). Mongird [16] 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. 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 then equals the sum of capital cost, PCS, BOP, and C&C costs.

The British Standards Institute [17] 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 [16] 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. [18,19] which show O&M costs to be roughly equal for all BESS, Mongird [16] assumes the same factors for all three technologies.

Table 1 displays the cost factors used in the cost analysis. Note that a cost analysis was not done for SSBs as that technology is still as much as a decade away from commercialization.

Table 1 Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type [adapted from 16].

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-year)	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					

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

2 Annual cost reduction data from Mongird [16] (2.35%) applied to actual costs for out years

4. Cost Analysis Results

4.1 Lead-Acid Battery Cost Analysis Results

When deep cycle lead-acid batteries are used for the BESS application, battery life is significantly affected by DOD. Commonly, lead-acid battery manufacturers and vendors recommend a 50% DOD [20, 21], which means that only half the rated capacity is useful. This results in needing an initial installation of twice the required battery storage when designing a lead-acid battery bank. Combining this factor with a typical 85% DC round trip efficiency [22], and a capacity degradation to 80% of initial capacity at the end of life [23], an installed rating of 1780 kWh is required to deliver 605 kWh of usable energy storage for the village scenario. Several factors, including DOD, operating temperature, and overcharging and undercharging [24], significantly affect lead-acid battery life. Assuming correct battery operation and maintenance, the analysis determined flooded lead-acid battery lifetime expectancy at 5.5 years, gel at 3 years, and AGM at 4.5 years. For the 20 year scenario, this drives the requirements for the flooded type battery bank to be replaced three times in years 6, 11, and 16; the gel type seven times in years 3, 5, 8, 10, 13, 15, and 18; and the AGM type four times in years 5, 9, 13, and 17. Procurement costs for lead-acid batteries were determined by averaging cost data from five independent Internet-based vendors [25-29] for 116 different battery models from four different manufacturers. The total project cost was then calculated using assumptions from Mongird [16], based on a lead-acid battery bank with the aforementioned initial capacity of 1780 kWh. Procurement costs were reduced by 3.26% annually on a linear scale using Mongird's [16] extrapolated cost reduction assumptions. The resulting capital cost estimates for the three lead-acid types and the average are shown in Table 2.

Table 2 Lead-acid battery capital cost summary.

BatteryType	Cost per kWh	Initial Cost	Replacement Cost	Total Capital Cost	Cost Source
Flooded	145	258,139	612,903	871,042	[25-27]
Gel	258	460,081	2,598,857	3,058,937	[25, 28]
AGM	291	517,540	1,639,956	2,157,496	[25, 26, 29]
Average	231	411,920	1,617,238	2,029,158	

All Costs in US Dollars

20 year total project cost was calculated using total capital costs from Table 2 and PCS, BOP and C&C costs calculated using Mongird's [16] assumptions. Maintenance requirements for lead-acid batteries includes periodic inspections and cleaning as well as watering and freshening charges for flooded type [30]. 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 [9] cost analysis methodology. The overall lead-acid battery cost results presented in Table-3.

Table 3. Lead-acid battery overall cost summary

	Flooded	Gel	AGM	Average
Capital Cost (20 years)	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 years)	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

All Costs in US Dollars

4.2 LIB Cost Analysis Results

Australia's Lithium Ion Battery Test Centre [31] tested six LIBs with manufacturer-recommended DOD limits ranging from 80-95.7%. LIB efficiency typically ranges from 85% to 95% [32]. For this analysis, a 90% DOD operating limit and 90% efficiency were assumed. LIBs also experience capacity degradation to approximately 80% capacity at end of life [33], so the initial LIB must be sized at 125% to ensure sufficient capacity at end of life. These three factors result in the requirement for an initial 934 kWh LIB to provide the scenario's 605 kWh of storage at the end of its 10-year operating life. Mongird [16] determined that with active thermal management, LIBs can be expected to last for 10 years in a grid connected application, which also correlates with several manufacturers' warranties. The implication is that the model should assume a complete LIB replacement at the 10 year point which should then last until the scenario end of life at the 20 year point. As the cost in 10 years can be expected to be much less than today, a 50% cost reduction is assumed for this analysis based on BloombergNEF projections [34].

Although liquid electrolyte LIBs have low maintenance requirements, specialized technicians would usually be required for major maintenance events, such as battery replacement. The travel costs for technicians to visit remote areas, along with the cost of shipping, adds to O&M costs. Integrated containerized LIB systems also have several subsystems that will require periodic maintenance, such as heating, ventilation, and air conditioning (HVAC) and fire suppression systems. While local expertise to maintain and repair these subsystems may exist, this is an added concern for this technology. The scenario cost estimates for the liquid electrolyte LIB are provided in Table 4.

Table 4 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

All Costs in US Dollars

4.3 VRFB Cost Analysis Results

A major advantage of VRFBs is they can be fully discharged to 100% DOD and then restored to a full charge for a large number of cycles over many years and not lose capacity [35]. So initial BESS sizing is not affected by either DOD or capacity fade. VRFB DC round trip efficiency was assumed to be 79% by averaging the efficiency specifications of four VRFB systems appropriate for a microgrid ESS application [36-39]. This results in the requirement for a 765 kWh rated VRFB to provide the usable 605 kWh storage for the scenario. An analysis of five current VRFB ESS suitable for our scenario have system lifetimes ranging from 20 to 30 years, implying that no battery replacement is necessary for the 20 year life of our scenario.

As with the other technologies, Mongird's [16] assumptions are used for PCS, BOP, and C&C costs. Lourenssen [35] 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 VRFBs to have relatively low running and capital costs, especially compared to other emerging energy storage technologies". However, as with LIBs most complex maintenance would require expertise not available in the local village. The fact that VRFBs do not require HVAC and fire suppression systems is another significant O&M savings. The scenario cost estimates for the VRFB are provided in Table 5.

Table 5 VRFB cost summary.

	Year 2018	WattJoule 2020 [36]	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

All Costs in US Dollars

Table 5 includes current costs for the ElectriStor system by the manufacturer, with 2020 factors for PCS and C&C extrapolated linearly from Mongird's 2018 and 2025 values. The ElectriStor BOP cost is included in its capital cost. The ElectriStor costs are in line with Mongird's [16] estimates and actually would be somewhat less, as the included BOP costs are for a 5 MWh system, and the 765 kWh scenario system would require less piping, and smaller tanks, pumps, and stack.

4.4 Cost Analysis Discussion

Although this cost analysis uses many assumptions and approximations, the results are consistent with current cost generalizations in research and the media. Lead-acid batteries, especially the flooded type, have low initial capital costs but frequent replacement due to their short operating life increases their lifetime costs to well above LIB and VRFB costs. 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 battery ESS applications. However, recent cost reductions of VRFBs are making them cost-competitive with LIBs.

5. Analysis Results of Other Significant Factors

5.1 Energy Density and Capacity Analysis Results

Energy density for the three deep-cycle lead-acid battery types (flooded, gel, AGM) was determined by analyzing data from 142 different lead-acid battery models from 5 leading manufacturers: Trojan, Hoppecke, Crown, Exide, and Hankook [40-46], resulting in an average energy density of 86.3 Wh/liter. Note this energy density only considers the battery itself, not the battery room or enclosure/container that would provide protection from the elements as well as ventilation and cooling. This larger battery room size is more relevant when comparing energy density to integrated containerized LIB and VRFB ESS, which also include the auxiliary subsystems required for their systems.

Integrated LIB ESS applicable to our scenario are typically packaged in standard ISO 20 ft containers. Four of these systems from Aggreko, Fluence, Saft, and BYD [47-50] were analyzed, resulting in energy densities ranging from 13.0 to 27.6 Wh/liter. Five VRFB containerized systems applicable to our scenario from StorEn, WattJoule, Rongke (2 systems), and Sumitomo were analyzed, resulting in energy densities ranging from 3.9 to 12.9 Wh/liter [36-38, 51, 52].

As described, 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 conceivable that future containerized SSB ESS could be in smaller containers.

Increasing energy density is a top priority in current battery research, but this goal is fueled mostly by the electric vehicle and personal electronics markets. System footprint is generally a less important concern for a microgrid BESS, especially in rural settings where land is plentiful. LIBs have a clear advantage in energy density over VRFBs, but when BESS are containerized into integrated systems complete with fire suppression and HVAC subsystems, the footprint versus VRFBs is less significant with both typically packaged in a standard 20 ft container.

5.2 Temperature Limits Analysis Results

Guari et al. [53] determined that the optimal operating temperature for a lead-acid battery is 30°C; operation above and below this range negatively affects the battery. Trojan [54] notes 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". For roughly every 10°C increase in operating temperature, a lead-acid battery's life is reduced by 50%, a significant effect [54].

Integrated liquid electrolyte LIB ESS all feature thermal controls to maintain temperature within operating ranges. Due to significant issues with operation at both the low and high end of the operational temperature range, the ideal temperature to operate a LIB is generally limited to about 15–35 °C [55], 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.

Ogawa et al. [56] found that SSBs are capable of operating at high temperatures without a significant impact on battery performance or capacity, even at 180°C, close to the melting point of the lithium metal anode. At low temperatures, they 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 temperatures is a significant advantage of SSBs over their liquid electrolyte counterparts.

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 would rob the overall system of efficiency [36]. Unlike liquid electrolyte LIBs, VRFB do not experience performance losses at the lower or upper end of the temperature 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.

Many of the poorer areas of the world are in hotter regions here; the effects of high temperatures on energy storage systems must be considered. The ability to operate in a wide temperature range without the requirements of an HVAC subsystem is a significant advantage of some newer VRFBs.

5.3 Safety Issues Analysis Results

SafeWork South Australia [57] 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. There are also health concerns associated with lead which are discussed in the following section on environmental concerns.

LIB safety is a cause for concern as illustrated by many recent incidents, including the 2013 fires aboard two Boeing 787 Dreamliner aircraft, the 2014 banning of all Samsung Galaxy Note 7 mobile phones from flights [58], LIB explosions in electric vehicles [59] and the May 2018 death of a 38-year old Florida man from an exploding e-cigarette LIB [60]. Most applicable to our scenario is the April 2019 fire and explosion at a Fluence built containerized liquid electrolyte LIB ESS near Phoenix, Arizona. The LIB explosion caused extensive injuries to eight men with three requiring extended hospital stays [61]. The 2 MW/2 MWh system is similar in size to an integrated system appropriate for our analysis scenario. This incident led the state of Arizona [62] 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. There were 17 LIB storage fire incidents at facilities in South Korea alone in an 8 month period in 2018 and 2019 [63] just prior to the Arizona incident, prompting a government investigation [64]. For installations in poor remote villages, the safety record of LIB ESSs should be a cause for significant concern.

Safety is one area where SSBs differ from their liquid electrolyte counterparts. Ma et al. [65] note although the solid nature of the SSB's electrolyte suppresses dendrite growth, studies have still observed this phenomenon where dendrites have progressed through the solid electrolyte matrix and achieved a short circuit condition resulting in melting and burning of the electrolyte. 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 dendrite growth and also the nonvolatile nature of solid electrolytes should make SSBs inherently safer than liquid electrolyte LIBs.

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 [11], non-reactive, and of low toxicity and when in solution the VRFB electrolyte can be deemed as non-toxic due to the very low concentration levels of vanadium [66]. Generally, vanadium composites in closed VRFB systems pose a "small risk for injury to human health because electrolytes are incombustible" [67].

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 LIBs.

5.4 Environmental Considerations Analysis Results

May et al. [22] describe how the lead from lead-acid batteries is recycled at a >99% rate in the US and European Union via well-established processes and facilities, while other components are also recovered at a lesser rate. However, it is this recycling process, especially in poorer nations, that causes serious environmental and health damage. Green Cross Switzerland's [68] annual report ranked used lead-acid battery recycling as the #1 worst polluting industry in the world, with lead as the #1 toxic threat. The World Health Organization [69] describes how improper lead-acid battery recycling can release lead into the ecosystem, eventually finding its way back to humans, which can lead to chronic poisoning affecting almost all body systems. Although lead-acid battery recycling is highly regulated in developed countries, it poses a significant environmental and health risk in developing countries where regulations and practices are more lax.

LIB waste toxicity from its hazardous materials such as cobalt, copper, nickel, and zinc [70] is problematic due to the current lack of an industrial scale, cost-effective process to recycle LIBs [71]. The minimal LIB recycling being done today is mostly focused on recovering the cobalt and copper [72], but recycling rates are still very low; both the European Union and United States recycle less than 5% of spent LIBs [73]. This environmental impact is a negative factor for LIBs.

With the commercialization of solid-state electrolyte SSBs still about a decade away [10], conducting an environmental assessment on future products is difficult, but it can probably be assumed that SSBs would have many of the same recycling limitations as liquid electrolyte LIBs.

VRFB components are relatively benign and their disposal poses much less of an impact on the environment than the other technologies. A VRFB's most toxic component is the electrolyte's sulfuric acid, which is only one-third as acidic as in a lead-acid battery. Vanadium in the electrolyte has very low toxicity, and VRFBs typically are in enclosures, which would contain any spills [74]. The vanadium electrolyte also 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. During operation, a VRFB is environmentally friendly because no waste products are produced.

The environmental impact of ESS is a broad topic and has been narrowly addressed here to primarily focus on end of life aspects of the four technologies. Lead-acid battery recycling is a well-established and successful practice in developed countries, but in lesser developed areas, recycling can be an unregulated cottage industry fraught with environmental and health issues. 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 the analysis scenario is geared towards less developed regions, the environmental impact should be considered negative for these two 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. As Simon Clarke [74], executive vice president at VRB Power Systems boasts, VRFBs "have the best environmental footprint of any storage technology."

This paper compared various battery technologies to support the energy storage requirements for a small renewable energy-based microgrid for a poor community that is disconnected from the main grid. Worldwide grid energy storage in general is projected to increase significantly over the next two decades [75] and the promise of renewable energy production with storage promises significant advances for poor, disconnected communities that today remain unelectrified. Indications are that LIBs will maintain their place as the preferred battery ESS solution, although VRFBs have distinct advantages in several other areas. For each of the five analysis areas, 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 area, as summarized in Fig. 1.

	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

Fig. 1 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 ability to operate 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 some cost parity with LIBs, their other advantages may sway system designers 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.

6. Conclusions

In summary, energy density is usually not a major concern for a stationary microgrid ESS, especially in rural areas where space is plentiful. O&M requirements are challenging to 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. 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 predominant technology in the future.

Nomenclature

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
ESS	Energy Storage System
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
LIB	Lithium-Ion Battery
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

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