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TECHNICAL AND ECONOMIC CHALLENGES OF FLOW BATTERIES IN GRID SCALE ENERGY STORAGE

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Abstract

In present, where machines are evolving their energy needs from carbon-emitting fossil fuels to electrochemically generated provisions for portable electronics, electric vehicles (EV) and even large grid-scale applications. With the rapid need of electric storage devices, the academia and industries are continuously improving their research and development in energy materials, durability, and reliability. Here energy storage devices are portioned into two broad categories: lithium-ion and flow batteries. Lithium-ion batteries (LIB) are overly praised by generalizing its application as universal and are continuously underestimating the flow batteries behind which can have better performance for some large-scale applications. This makes LIB production as a global threat for other batteries which are evaluated in term of their fundamental construction, technical and economic analysis.

Keywords: electric vehicles, flow batteries, grid-scale energy storage, industrialization, lithium-ion, renewable intermittency

1. INTRODUCTION

The technologies of the world have been rampantly evolving with its fastest speed ever. In this speed life seems to be battery powered – every accessory either necessary or auxiliary is running through batteries which includes a household electronic device to vehicles for daily transport [1,2]. In this situation where traditional engineering is changing from carbon-emitting fossil fuels to renewable energy [3], a plethora of improvements is evidently acknowledged in recent decades. However, with this adoption of renewable energy have also introduced new issues at their grid-scale application [4,5] including intermittency of energy due to unpredictable behavior of renewables nature. This issue has been retorted by integration of grid-scale energy storage devices which work as shock-absorbers between renewables and grid [5] – presently, this concept is known as peak shaving (frequency regulation) in smart grids. With the increased number of electric vehicles have changed the dynamics of batteries in terms of their usage and the materials those construct them [6]. This has rampant the scarcity of some materials with aggressively high rate including cobalt for LIBs [7]. LIB has been considered a remedy of all energy issues including for automobiles, electronics and even in grid storage [8] it is undoubtedly true that some application like electronics and automobiles are thankful of LIB for providing portability and fuel-independence, whereas parallel to this, the use of LIB is unfit for the application of grid storage [9].

In this regard, there are many other batteries with the same potential as LIB and can outperform in their suitable applications. Due to overly admired LIBs around the world causing great damage to other batteries. Research and development on batteries other than LIB are less fortunate for having good funding opportunities because of their less demand in the industry. In doing so, newly-ignited researchers unluckily shifting their research interest into the celebrity LIBs and we are ultimately creating a vacuum for other batteries technology versus LIB and one day we will have realized that we have gone far ahead and leaving behind these batteries which could serve us well or even better. In addition to this, geographically, there has been an extensive increase in some materials use in LIBs a recent research of the European Union has computing resources use in the framework [10].

Previous studies have provided specific case analysis on chemistries, the criterion for a specific metal's use, life-cycle assessments focused on analyses of issues surrounding their end of life (EoL). A great attention is caretaken for battery's materials, however, a slight of importance is realized after they are used or discarded. It turns out, the discard batteries materials are highly hazardous for the environment by recent study focused on toxic gas emission from damage LIBs and other batteries [9]. Lastly, the study of MIT shared that China has emerged as biggest LIB manufacturer in the world and creating international pressure even in United States' native companies are facing difficulties to survive due to high influence of China [11], which promotes the dangerously accelerating use of LIB in the world.

The intended research work is provided to explore new dimensions for flow batteries for their suitable application, i.e. grid-scale storage. Here LIBs are discussed as a direct competitor for flow batteries. Moreover, this paper provides to contribute for flow batteries to widen the horizon of energy storage devices by the promotion of new batteries not only in laboratory uses but also helps them industrialized.

Section II covers construction of LIBs and RFBs. section III discusses the technical and economic aspects of flow battery and finally, this paper is concluded in section IV.

2. CONSTRUCTION OF BATTERIES

Here rudimentary materials are discussed from literature for the construction of batteries mainly lithium-ion (Li-ion) and redox flow batteries (RFBs). This construction of batteries provides basic functionality for their comprehensive analysis. Here, this paper has not included various equivalent models of batteries by keeping the scope of this paper limited to challenges and their research improvements for grid-scale applications.

2.1 Li-ion Battery

The Li-ion battery considered as an advanced rechargeable battery (first time developed by Sony for commercial purposes) in the early 1990s. In their charging period, Li-ions are introduced to negative electrodes and de-inserted from the positive electrode. Lithium positive ion (Li^+) is deintercalated from the cathode oxide compound and then introduced into the lattice of anode [1]. The cathode of LIB has high potential and poor lithium (Li) state. In contrary, the anode has low potential and rich Li state. This process is reversed when the battery is discharging. In the fig.1. The construction of Li-ion is shown with a graphite anode and layered oxide compound as a cathode.

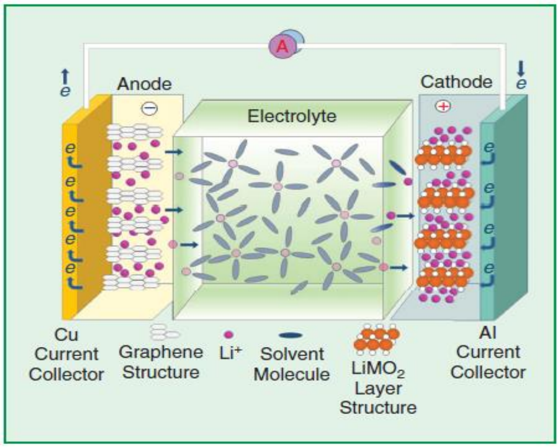

Fig.1. A schematic representation of LIB during discharging, here Al, Cu and $LiMO_2$ is Aluminum, Copper and Lithium Metal Oxide respectively [1].

In Comparison to other batteries e.g., NiCd, lead acid, NIMH, LIB has better characteristics as shown in table no.1. This table includes different features on which any battery is ranked recording to U.S. Advanced Battery Consortium (USABC) which includes energy density (Wh/kg, defines the capacity of battery in terms of size versus energy carrying capacity), Power density (W/kg), Cycle-life (usable period of battery), cost (US$/ kWh), and maturity in terms of commercially availability[1].

Table 1. The prominent features of various LIBs [12].

Type	LMO	LFP	LNMC	LTO	Li-S
Energy density (Wh/kg)	160	120	200	70	500
Power density (W/kg)	200	200	200	1,000	-
Cycle life	≥2,000	≥2,500	≥2,000	≥10,000	~100
Cost	~360	~360	~360	~860	-
Maturity	Com	Com	Com	Demo	R&D
LMO: Lithium Manganese Oxide; LFP: Lithium Iron Phosphate; LNMC: Lithium Nickel Manganese Cobalt; LTO: Lithium Titanate; Li-S: Lithium-Sulfur; Com: commercial; Demo: demonstration; R&D: research and development					

Here is the list of materials used in various LIBs which is shown in table 2. This table depicts natural elements which are used in the formation of LIB including manganese, phosphorous, nickel, cobalt, titanate and sulfur respectively.

Table 2. Element requirement for Li-ion (kg/kWh) [7].

	Li	Ni	Co	Mn	C
LCO	0.113	0	0.959	0	~1.2

NCA	0.112	0.759	0.143	0	
NMC-111	0.139	0.392	0.394	0.367	
NMC-622	0.126	0.641	0.214	0.200	
NMC-811	0.111	0.750	0.094	0.088	
C: Carbon; LCO: Lithium Cobalt Oxide; NCA: Lithium Nickel Cobalt Aluminum; NiCd: Nickel Cadmium; NMC: Lithium Nickel Manganese Cobalt Oxide					

2.2. Redox Flow Battery (RFB)

Literature covers various flow batteries since the 1970s to present (first developed by U.S National Aeronautics and Space Administration) which was iron – chromium RFB. Due to cross-contamination of an active ion between positive and negative solutions [13], which generates excessive hydrogen in the negative electrode during charging cycles. with this evolution of time and experiments, various types of RFBs have been developed and helped to achieve optimal one: vanadium [14] has shown promising performance due to two reasons. Firstly, in VRBs the positive and negative electrolytes use the same element, i.e., vanadium and secondly, by coupling negative electrode (redox standard potential) increases the hydrogen development potentials, therefore, no extra hydrogen is generated.

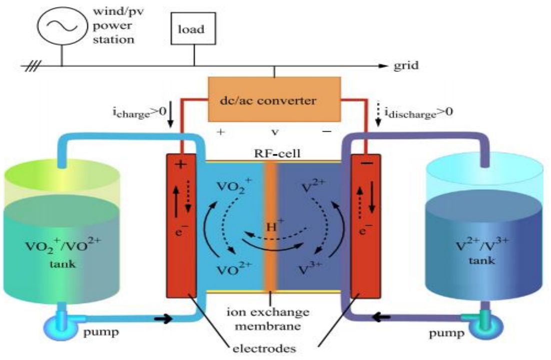

Fig.3. A grid with renewable resources (wind or solar) connected with RFB schematic – including chemical flows [15].

Mechanical and electrochemical are two main parts which make an RFB. The mechanical part consists of a pump which performs chemical and electrical conversions of energies. The pump is associated with stacks which are multiple cells containing a liquid electrolyte. When this liquid electrolyte is pumped to half, cells the energy conversion from chemical to electrical occurs as explained by Eq. (1). In fig.3 the RFB battery setup connected with grid has been shown. This is one of application of RFB with the integration of renewables (wind/PV). Here the RFB are acting as frequency/voltage regulator tolerating variation in both sides, i.e., load demand variation or renewable intermittency. Lastly, fig.4 shows the charging and discharging voltage curve with respect to time.

<u>Reaction on positive electrode</u>:

$$VO^{2+} + H_2O \rightleftharpoons VO^+_2 + 2H^+ + e^-$$

<u>Reaction on negative electrode</u>:

$$V^{3+} + e^- \rightleftharpoons V^{2+} \qquad (1)$$

2.3. Other types of RFB technologies

2.3.1. V-Br cell:

Vanadium bromine (V-Br) has shown improved working in recent years. It has an energy density of 35-70Wh/L and charges potential of 1.3V, however, the generation of bromine vapors makes it dangerous during its production. Energy conversion reactions are shown in Eq. (2).

<u>Reaction on positive electrode:</u>

$$2Br^- + Cl^- \rightleftharpoons ClBr_2^- + 2e^-$$

<u>Reaction on negative electrode:</u>

$$2VBr_3 + 2e^- \rightleftharpoons 2VBr_2 + 2Br^- \qquad (2)$$

2.3.2. V-O₂ cell (VOFC)

In Vanadium-oxygen redox fuel cell (VOFC) is hydride combination of RFB and fuel cell that substitutes the positive half-cell (electrolyte and electrode) with air by reaction in Eq. (3).

<u>Reaction on positive electrode:</u>

$$2H_2O \rightleftharpoons 4H^+ + O_2 + 4e^-$$

<u>Reaction on negative electrode:</u>

$$4V3^+ + 4e^- \rightleftharpoons 4V^{2+} \qquad (3)$$

In Eq. (3) one phenomenon is prominent that it doubles the energy density (E^o =1V.) by saving one electrolyte portion (sub-system).

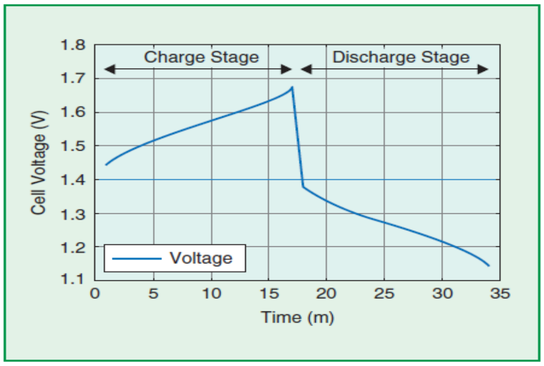

Fig.4. A charging and discharging Trend of RFB in terms of voltage response [1].

3. TECHNICAL AND ECONOMIC ASPECTS OF RFBS

The RFB technology has not matured in real-time and requires Research-oriented programs to promote its commercial potential [16], R&D will help to improve RFBs power density which will ultimately reduce cycle life cost and capital cost respectively. There requires huge improvement in RFBs' cell chemistry including electrochemical reactions of electrodes [17], electrolytes, ion-exchange membranes crossover, charge transport will increase the efficiency of RFB in terms of structure size [13].

With the improvement of electrolytic solutions overall operating temperature limitations will be improved and hence power and energy densities will increase. Recently, experimental VRBs have already demonstrated much higher current and power densities than those are currently available in commercial [18], such breakthroughs advocate RFB use in electric cars by increasing power densities to 120-200 Wh/kg which presently at 30-50 Wh/kg. this current range of power density is not suitable for electric cars and needed to be improved however in future with such ratio of improvement an electric car can provide an average of 100 km.

If improvement will be made in materials which are responsible for ion conduction, then an enormous decrease in cost will be observed. In addition to this, this will also increase the power densities and making system compact (size). In this regard, interdisciplinary collaborative research groups with skill-sets of material sciences, electrical and chemical engineering are needed to foster this domain. In doing so many challenges will be addressed which includes structural, operational and modeling e.g., state-of-charge (SOC), State of health (SOH) and Remaining useful life (RUL) estimation concerns. With the high accuracy in modeling internal reactions can be predicted including, advanced internal flow processes of RFB and will be helpful in system level designing for commercial applications of grid-scale energy storage. This desire can be achieved with the high computational modeling of high orders (defined by equivalent electrical circuits). In addition to this RFB has a silent feature in terms of its construction; power (stack) and energy (electrolytes) capacity are completely independent of each other which makes them easy in their designing for multi-megawatts purposes, moreover in table 2. Various batteries comparison with VRB is shown.

Table 3. shows different technologies in batteries and their standard comparison [12].

Type	Lead-Acid	Li-ion	NiMH	NaS	VRB
Cycle life*	200-1,000	1,000-10,000	180-2,000	2,500-4,000	>12,000
Energy-density (Wh/kg)	25-50	75-200	60-120	150-240	10-30
Power-density (W/kg)	75-300	500-2,000	250-1,000	150-230	80-150
Capital cost (US$ kWh)	100-300	300-2,500	900-3,500	300-500	150-1,000
Round-trip efficiency (%)	75-85	85-97	~65	75-90	75-90
Self-discharge	Low	High	Medium	-	Negligible
NiMH: Nickel Metal Hydride; NaS: Sodium Sulfur; VRB: Vanadium Redox Battery					

To reduce non-linearity and multi-physic issues of material behavior advanced computational techniques including machine learning: convolutional neural networks, big data, deep learning can easily resolve the complex numerical problems, parallel to this, control engineering techniques help coping with the automatic chemical rebalancing of electrolyte will promote RFB for remote grid-scale applications. The rate of chemical reactions (flow-rates) highly affects the RFB efficiency. With improved flow-rate pumping power will be reduced. with proper modeling, optimization of RFB electric part can be improved, this includes a proper control system (feedback control). By doing so, RFB will be a key element of the smart grid by ensuring power quality issues mainly peak shaving, frequency control, voltage regulation, load management by leveling and even RFB provide the best solution to renewable intermittent behavior by the adoption of proper converter topologies. The success of such topologies mainly relies on reliable modeling of the system. To achieve this goal, the option of lump model approaches is the outfit.

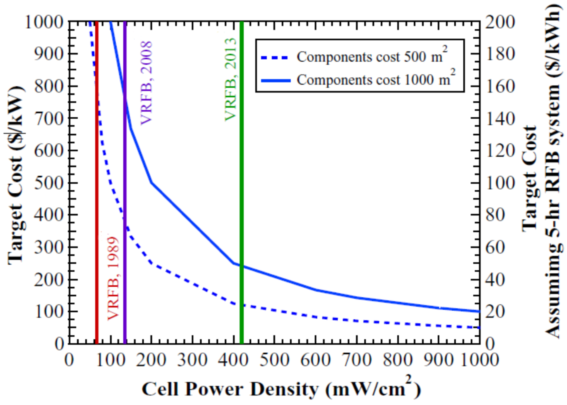

Fig.5. target cost ($/kW) versus cell power density (mW/cm^2) of Vanadium redox flow batteries [19].

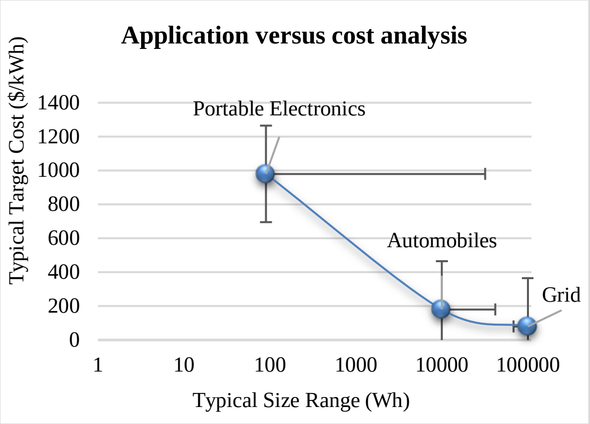

Fig.6. target cost of RFB versus its application: portable Electronics, automobiles and grid-scale energy usage is shown [20].

Economic aspects are in terms of earnings and savings from RFB operations [20]. In fig.5. a target cost ($/kW) versus cell power density (mW/cm^2) is shown and fig.6. shows a direct relationship of cost versus application use of VRBs, with increasing scale of application in terms of power demands cost of VRB decreases drastically. Finally, there is still a need for awareness by taking such topics to the United Nations where proper international policies for materials and their impacts can be addressed. Environmental aspects including carbon dioxide savings are still under discussion towards policy making. In addition to this, many research institute are working on these issues, including Australia, Austria, China, Germany, Ireland, Japan, Netherland UK, US, and now countries like Canada, Korea, Spain, Singapore, and even Pakistan have initiated many research platforms on governmental and private level like USAID are next to do so.

4. CONCLUSION

This paper has established different aspects of RFBs in terms of technical and economic challenges and proposed some real-time improvement which can make RFBs application for their suitable use. Some promising pathways for essentials R&D are required although significant modification in the RFBs have been observed in terms of their cost and performance yet R&D is required. In terms of materials which are directly responsible for the improvement in power densities (W/m^2) and energy densities (Wh/L) require some attention as given to fuel cells and other conventional batteries. In addition to these improvement cost is the main factor in the adoption of any technologies, therefore with lower-cost materials for construction of cell and chemical used for energy conversion requires high R&D – here requires funding for collaborative efforts from multi-disciplinary engineering and sciences academia and research industries including intra-governmental scale policymaking.

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