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Long-life Nickel Iron Battery Functionality / Cost Comparison for Peak Demand SWER Network Voltage Support Application

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Abstract—SWER line voltage sags, if network upgrade is not possible, eventually require active power injection as one of the intervention technologies. Active power support can be provided by many technologies, and some of these involve battery energy storage. Nickel-iron Edison batteries are an often little known or understood battery. Compared to three other commonly available industrial batteries, and despite their design being over 100 years old, they are a still a long-life contender for large stationary battery energy storage systems. Continuing research into their design may even further improve their performance.

Keywords— Nickel-iron battery, life costs, SWER line.

I. INTRODUCTION

Battery technology continues to be challenged by modern applications such as voltage regulation support by active power injection during peak load demand periods for single wire earth return (SWER) rural power. The requirements for these applications are deep discharge capability and rates with a long cycle life to minimise costs. Battery types with high recharge rate and a lack of sensitivity to overcharge or undercharge are also an advantage. As a background to SWER network application, in both developed and developing nations, typically they trend in time from initial light loads for lighting and small enterprise, gradually growing in demand for opportunistic rural development for irrigation automation and on farm post-harvest crop processing (milling, refrigeration, washing / packing lines etc.). SWER networks normally radiate out from populous centres to sparse rural settlement areas to provide cost effective power for development opportunities in agri-business. Quite often during a SWER asset's half-life of 40 – 60 years of age, the annual load demand increases (for example, in rural Australia being 2.2% to 3% per annum) compounds to cause voltage sags to occur for back end line customers during peak load demand periods. Overcoming this by network upgrades to a heavier SWER conductor, or ultimately to a two wire single phase or three phase network is very capital intensive. Published submissions [1] and reports from the Victorian Black Friday Royal Commission [2] into SWER line contribution to bush-fire spread provides the means to calculate the cheapest upgrade for a portion of a SWER network backbone line from 3/2.75 SC/GZ to 3/4/2.5 ACSR/GZ as being \$18,000 per km or more. It is difficult to justify high cost capital investment for a very sparsely distributed SWER network customers in developed

nations, and impossible to do so in developing nations. There are many options for intervention to support voltage regulation during peak load periods in SWER networks, each with advantages and disadvantages in regard to initial investment and life cycle replacement. These options include series HV auto-transformer voltage regulators, HV supply side static or switched capacitive or reactive compensators, LV inverter compensators to balance the reactive p.f. load component, or LV customer load side voltage regulators. In spite of the advantages to SWER customers' voltage regulation, these tend to substantially increase upstream series network resistive losses. It is inevitable, if the network cannot be economically upgraded, that active power injection along the network will be required to support voltage regulation. Correctly placed active power injection supports voltage during peak demand periods by reducing electrically far LV network loads and providing significant upstream series HV network line loss relief. In doing so, it reduces the SWER network's high resistive component losses, particularly on light SWER lines (such as the galvanised steel wire and lighter aluminium clad conductor types) that have above unity R/X ratios, or higher R/X ratios of 5 or above. Active power sources are traditionally fossil fuel IC engine or gas turbines powered alternators, sustainable solar, wind and geothermal energy supplies, which may include battery storage for time-shifting energy to peak demand periods. An alternative to these is a large battery array using off-peak base load supply for charging. This latter option is only possible where there is reserve off-peak SWER network capacity. This paper compares the current solar deep discharge nickel-iron Edison battery with three other industrially manufactured battery types readily available for application for active power injection to support SWER voltage regulation during peak periods. As a historical perspective Junger in Europe first discovered and built the nickel-iron battery 1899 before choosing the nickel cadmium battery for patented development. Edison on the other hand chose to patent the nickel iron battery in the USA during 1901. Nickel-iron batteries nearly disappeared from technology use in the 1970's and are now sometimes little known in many engineering disciplines. (*Note: For this study, Nickel-cadmium batteries were excluded due to the heavy metal cadmium issue that currently often limits these to special applications; Nickel Metal Hydride battery was excluded for large remote battery arrays as these have temperature performance sensitivity*

above 25°C necessitating prevention of thermal runaway damage by significant cooling intervention. Similarly, also the review of the recent DOE/EPRI 2103 Electricity Storage Handbook, Chapter 2 [11], (while noting its disclaimer on accuracy or completeness of information), has prompted exclusion of high temperature batteries such as the Sodium-sulphur and Sodium-nickel-chloride batteries on the basis of increased risk of bushfire ignition for very remote installation in the event of accident. The Zinc-Air battery is excluded due to its air electrode's sensitivity to inlet air temperature and humidity changes and de-activation by CO₂. High

temperature / humidity changes and the prevalence of dust storms or bush fire with air-borne particles and CO₂ emission are normal remote Australian conditions. These ambient conditions pose problems for the Zinc-air battery remote operation and performance. The Vanadium Redox and Iron-chromium Redox batteries are not included in this study, as the Zinc Bromide battery as it has an Australian manufacturer, is considered a reasonable representative for this type of storage.)

II. BATTERY ENVIRONMENTAL AND SAFETY IMPACTS

TABLE 1: SUMMARY RISK ASSESSMENT FOR VRLA, LITHIUM-ION, NICKEL-IRON AND ZINC-BROMIDE REDOX FLOW BATTERIES [3] - [10]

Risk Assessment Deep Discharge > 5kWh Storage Battery Bank Type				
Characteristic	Valve Regulated Lead Acid (VRLA)	Lithium-Ion	Nickel-iron (Edison pocket plate)	Zinc-Bromide Redox Flow
Fire ignition risk	Minimal	Thermal proximity to another fire source will cause internal thermal run-away	Minimal	<i>Electrolyte if heated may release toxic and highly corrosive hydrogen bromide and bromine fumes that will react directly with combustible materials causing their self ignition with many organic compounds and hydrogen burn in bromine gas.</i>
Self-ignition risk	Minimal	<i>Thermal run-away due to overcharge, excessive charge rate in cold conditions, >65°C temperature while charging. Thermal runaway can begin at 80°C, self combustion at 135°C.</i>	Nil	Minimal
Fire personnel fighting precaution requirements	Protection from acid burns and breathing apparatus to prevent fumes acid, lead/antimony/arsenic dust/fumes from inhalation.	<i>Full protection against explosion using full self-extinguishing fire suits and self powered self-contained breathing apparatus.</i>	Face shield, breathing mask and body protection suit for protection against alkaline air borne mist.	<i>Bromine impervious facemask, neoprene based gloves and suit, special bromine proof respirator or self contained breathing apparatus. Safety shower after, and not to eat or drink until showered and full change of clothes.</i>
Fire Extinguishment requirements	<u>CO₂, dry chemical or foam</u>	<i>Halon, copper based, or powder based</i>	<u>Secondary fire of battery container - use water, foam, BCF or powder type extinguishers.</u>	Neutralise with potassium carbonate solution, Cool surrounding areas with water to prevent thermal transfer to electrolyte. Use sand or vermiculite in a fire situation to safely absorb any liquid electrolyte.
Fire Extinguishment risks	Never use Water	<i>NEVER USE WATER, FOAM OR CO₂ DIRECTLY ON BURNING LI-Ion batteries as these are combustible in the presence of lithium, adding to fire severity.</i>	Nil	<i>Do not use CO₂ or any organic based foam extinguishers if bromide (brown vapour) or hydrogen bromide are present from fire.</i>
Environmental hazards	<i>Lead, antimony and arsenic are toxic heavy metals in animals, marine life and insects.</i>	<i>Hydrogen Fluoride (HF) and fluorine based compounds from combustion of electrolyte are hazardous and damaging to the environment.</i>	<u>No long term hazard, localised immediate damage due to electrolyte alkalinity that can be quickly neutralised.</u>	<i>Zinc-bromide electrolyte is classed a long-term water based pollutant and is recognised toxic agent to marine and aquatic life.</i>
Persistence in environment	<i>Regulated waste due to heavy metal toxicity persistence.</i>	<i>Not established - under consideration at present due to presence of fluorine in electrolyte.</i>	Nil	
Human general risk	<i>Lead, antimony and arsenic are airborne / ingestible cancer agents, mutagens, and are highly toxic. Lead inhalation or ingestion at sufficient levels is a neuro-toxin.</i>	<i>Lithium is a psychoactive agent, inhalation of combustion gases or ingestion are to be avoided by use of self contained breathing apparatus.</i>	<u>Nil to minor nickel allergy. Caustic mist from vented gas can cause lung irritation, eye damage if direct or skin irritation or burns.</u>	<i>Hydrogen bromide and bromine gas aggressively attack eye, skin, lung and internal body membranes.</i>
Human toxicity		<i>Fluorine based flame products from electrolyte combustion are destructively reactive to mucous membranes of eye, lungs and skin.</i>	<u>Nickel compounds are skin / lung irritants to approximately 10% of human population. Nickel toxicity is minimal, requiring ingestion of high doses of nickel based dust to act as a minor carcinogen agent.</u>	<i>Chronic toxicity effects include significant mental ability loss, slurred speech, poor memory, apathy, anorexia, drowsiness and sensitivity to touch and pain. Bromine is also a mutagenic agent to bone marrow.</i>
Recycling legal requirements	<i>Heavy metal - reportable and traceable legal requirement.</i>	<i>Not established - currently under review due to presence of fluorine in electrolyte. Lithium ion batteries require traceability in recycling.</i>	Nil	<i>Zinc-bromide is a reportable and traceable marine and biological agent.</i>
Overall environmental and safety risk assessment.	Medium to High	High	Low	Very High
KEY	Indicates nil or minimal hazard			
	<u>Indicates hazard requires risk management</u>			
	Indicates significant hazard requiring specific risk management responses			
	<i>Indicates dangerous hazards requiring detailed risk assessment and hazard management in design, operation and disposal.</i>			

The four readily available industrial battery types for deep cycle discharge considered in this review will be valve-regulated lead acid batteries (VRLA) (with the flat plate low maintenance gel batteries as an industry benchmark for low cost deep discharge batteries), the new advanced VRLA AGM glassmat types, lithium-ion (polymer type), nickel-iron (Edison type) and zinc-bromide flow battery. These industrially manufactured batteries are cost effective in regards for large battery arrays. The risk assessment for these is found in table 1. With regard to risk, each battery technology has various levels of environmental and operational handling risks. Lead acid and zinc-bromide batteries have specific toxic material risk to environment and personnel [12] - [15]. VRLA battery recycled materials are generally 20 - 30% dearer than the new component costs, and vary within this region of on-costs dependant on base metal prices, container and separator costs at any given time. Large lithium-ion batteries have high fire risk associated with its operation [5], particularly if thermal run-away occurs during charging or operation or battery safety management / cooling systems fail [11]. Fire breach of this battery will also release toxic lithium and fluorine compounds [5]. In comparison, the nickel-iron Edison battery has minimal toxic material risk from the active material components (noting only a small part of the population have minor allergic reactions to dermal contact with nickel compounds). Its electrolyte, in common with many batteries, is a corrosive alkaline type that can cause dermal burns if leakage occurs during handling. But environmentally, there is no significant disposal or handling issues. Physical dissection and investigation of the Edison nickel-iron battery in this project found it could be easily rebuilt by replacement of the negative iron electrode provided the cell has not been left in circuit for long periods when fully discharged. Its electrolyte can also be reprocessed, re-used or re-vitalised. However, by comparison there are only a few lithium-ion battery reprocessing recycling plants world-wide, and they generally require energy intensive cryogenic conditions [16]. There are traceability requirements for component recycling or disposal of the VRLA battery (that is, lead & alloy elements) and for the lithium-ion battery lithium compounds and electrolyte fluorine. Similarly environmental and personnel risk exists with bromide leakage from the Zn-Br flow battery, and this battery requires the active material interface in each cell replaced as a matter of course about every 5 years [13]. The Nickel Iron Edison battery construction is comparatively environmentally friendly, easily reprocessed, and utilizes naturally abundant material elements readily and cheaply available. It has the lowest environmental impact and risk factor during operation.

III. BATTERY PERFORMANCE

For SWER active power injection application during peak load periods, the discharge rate will normally fall within the C(2_{hr}) and C(3_{hr}) discharge rate. Generally in Australian SWER applications there is the single evening peak that causes the most significant voltage sags. However in other cultures and developing nations, there can be two or more peak demand periods per day depending on the rural

enterprise operation and local cultural practices of time use. Table 2 gives the comparative characteristics extracted from manufacturer's publicly released information for the battery types under study for this discharge rate. In terms of battery performance the main draw-backs of the nickel-iron battery, in comparison to the peak performing lithium-ion battery, are its 1.1V cell voltage and the turn-around efficiency (i.e. 62% compared to 80%). But on the other hand nickel-iron batteries have significant advantages of long cycle life in the face of deep discharge, with the ability to withstand overcharge (and could actually store significant overcharge for short periods). Similarly major advantage is to the nickel-iron battery that it is not damaged by undercharge, and has no cumulative corrosion fatigue provided its alkaline electrolyte pH remains above 9.5 [3], noting its normal pH is above 11. The nickel-iron's high self-discharge rate (measured in weeks) is not a disadvantage in this daily cycle discharge application.

For large battery array development, coupling of nickel-iron battery with auto-watering, or recombinant hydrogen and oxygen technology cell caps, would produce a very long life low maintenance energy storage array. Unlike other batteries, occasional full discharges and low state of charge, do not impact on cycle life. The electro-chemistry of the nickel-iron battery gives these characteristics and life cycle advantages. Like the nickel-cadmium batteries they also have a very slow decline in capacity, and do not fade rapidly at around 80% state of capacity. Lead acid and lithium-ion batteries normally begin rapid capacity fading below 80% capacity due to

TABLE 2: COMPARISON OF OPERATIONAL CHARACTERISTICS OF VRLA, LITHIUM-IRON, NICKEL IRON (EDISON) AND ZINC BROMIDE FLOW BATTERIES. [13] [14] [15] [17] [18] [19] [20] [21] [22] [23]

Deep Discharge Storage Battery Type @ C(2hr) / C(3hr) Discharge Rates				
Characteristic	Gel/Glassmat VR Lead Acid	Lithium-Ion	Nickel-iron	Zinc-Bromide Redox
Open Circuit Cell Voltage	2.13	3.6 - 3.9 #	1.21 - 1.31 *	1.83
Turn around Efficiency high discharge rate	68%	75%	65%	68%
Cell Voltage at end of High Discharge Rate (C _{2hr}) - (C _{3hr})	1.65 (gel) 1.75(glassmat)	2.45	0.9	1.3
Turn around Efficiency low discharge rate (C _{2hr})	75%	90%	72%	72%
Cell Voltage at end of Low Discharge Rate	1.75 (gel) 1.85(glassmat)	2.75	1	1.3
Watt-hr. / kg	30	150	30	50 - 70
Cycle Life	250 - 1100 (gel)	1000 - 3000	2000 - 9000	2000 - 3000
	3000-4000 (glassmat)			
Recommended DoD	30 - 30% (gel) 40 - 70% (glassmat)	30 - 65%	20 - 90%	20 - 85%
DoD Memory Problems	nil	nil	nil	Nil
Withstand long periods @ low SoC	No	No	Yes	Yes
Suffers from Thermal Run-away	Yes	Yes	No	Needs Heat Exchanger
Maintenance Free	Yes	Yes	No	No
Max. Charge Rate	0.07 x Capacity	0.2 x Capacity	0.2 x Capacity	0.2 - 0.25 x Capacity <i>Battery must disconnect when fully charged.</i>
Tolerance to Over-charge	No Tolerance	No Tolerance	Very Good	
Optimal Depth of Discharge	10 - 30%	25 - 60%	20 - 90%	50 - 80%
Recommended Autonomy Period	To 4 months	To 6 months	14 days	6 months - year
Specific Fire Hazard	Thermal run-away; hydrogen venting necessary	Thermal run-away and self-ignition / explosion.	Hydrogen venting necessary.	Release of bromide
Personal Hazard	Acid electrolyte	Vented lithium gas/coumpounds and flourine gas.	Alkaline electrolyte	Bromide Gas
Environmental hazards	Heavy metal of lead		Almost nil	Bromide / Electrolyte

depends on type of Lithium-Ion Battery
 * As these batteries accept and can store some overcharge - lower voltage is fully charged, upper voltage is retained overcharge voltage
 Indicates desirable characteristic
 Indicates mediocre characteristic
 Indicates non-desirable characteristic

Notes for table 2: (i) These characteristics are for this C(2_{hr}) - C(3_{hr}) as compared to the normal C(10_{hr}) and C(20_{hr}) discharge rating curves generally given for deep discharge batteries. (ii) Zn-Br battery Watt-hr/kg does not include ancillary parts.

corrosion fatigue affects, changes to active materials in electrodes and needle crystal growth that can cause bridging shorting failure through from negative to positive cell electrodes [3], [21]. The Edison battery has its negative electrode made of iron, which has the unique ability to reform its electrode metal crystal structure during charging electrode reduction to its original size and location. Nickel-iron batteries share very similar electro-chemistry as the Ni-CAD battery. Nickel-iron batteries, (in common with nickel-cadmium) are highly alkaline batteries using potassium hydroxide (KOH) and / or lithium hydroxide (LiOH), with a pH >11. While the pH remains above 9.5 in the electrolyte, the entire battery plate's and bus structures are entirely pacified (meaning there is no corrosion) at any of the battery components [3] [24] [25]. As the electrolyte remains very constant in pH during charge and discharge (i.e. very different to the VRLA battery), there is no point at all during normal discharge / recharge of the battery when corrosion can take place. As pointed out by DeMar in "THOMAS EDISON HAD IT RIGHT WHEN HE SAID THAT HIS NICKEL-IRON BATTERIES WOULD LAST 100 YEARS" [26] these batteries only very slowly linearly degrade with usage. This is shared in common again with the nickel-cadmium battery standards [27] that state, "Capacity decreases gradually during the life of the battery, with no sudden capacity loss being encountered under normal operating conditions. Since the rate of capacity loss is dependent upon such factors as operating temperature, electrolyte-specific gravity, and depth and frequency of discharge, an aging factor should be chosen based on the required service life (see IEEE Std 1106-1995)." Review for the nickel-iron battery used in electric vehicle trials by the Department of Energy (DOE) USA [28], and the electro-chemistry research by Demidov, Kokhatskaya and Chervonets [28] revealed capacity loss is via the slow leakage of iron from the negative electrode, and if over-discharged can actually transport iron to the positive nickel oxy-hydride electrode. Normal discharge processes have a small negative electrode underlying loss of iron in the form of magnetite (Fe_3O_4) from the outer edge of the $\text{Fe}(\text{OH})_2 \cdot x\text{H}_2\text{O}$ solgel that forms during negative electrode active material discharge. In a localized depletion lower pH boundary between the solgel and the electrolyte at pH's above 9.5, high rates of discharge or as depth of discharge increases, precipitation of 'black' Fe_3O_4 (a very stable form of iron oxide) results. It is from this outer solgel layer, and particularly as the layer of solgel thickens due to depth of discharge or high rate of discharge, slowing the hydroxyl (OH^-) uptake and passage to combine with the elemental iron in the negative electrode, which promotes this slow loss of iron via the Fe_3O_4 from the negative electrode results. This iron loss is the black magnetite that DeMar [26] refers to removing from the old cells as directed by Edison's manual [30] for these batteries. There are a number of related pathways for iron loss leakage via Fe_3O_4 from the negative plate of the battery [28], and these will be discussed in a later paper. One of the observed issue for depth of discharge and over-discharge in the USA DOE electric vehicle tests [28]. Very severe overcharging splits water into hydrogen and oxygen, providing a remnant oxygen source in the electrolyte. In the presence of oxygen there is a zero energy transformation pathway for formation of from HFeO_2^- , an

intermediate step in the full hydration of the Fe^{++} ion directly to magnetite during immediate high rates of discharge following an overcharge where dissolved oxygen has not dissipated from the electrolyte. Alternatively this same end effect becomes more dominant for ferrous hydroxide to precipitate magnetite at temperatures above 70°C where the solgel stability changes state, and then results in increasing iron leakage losses coating the separators and battery box surfaces with black Fe_3O_4 . At 120°C the nickel iron battery works as a primary battery instead of a rechargeable secondary battery due to this pathway at elevated temperature. To illustrate this capacity loss and how it relates to depth of discharge, ChangHong NF-S nickel iron battery characteristics show the relationship between depth of charge and life cycle to be below rated 80% capacity in their NF-S battery guide booklet [31] as shown in figure 1. Management of these issues during battery array design and operation provides a very long life for the battery that is only a gradual linear decline in capacity; i.e. it will not suddenly drop off like most other batteries. In fact, when nickel iron batteries reach the standard 80% capacity that is the normal indicative end of life often accepted criteria in international and Australian battery standards, it is possible, and makes economic sense for the 20% of additional capacity of nickel iron batteries to be added to fully replenish the batteries to 100% capacity as a set.

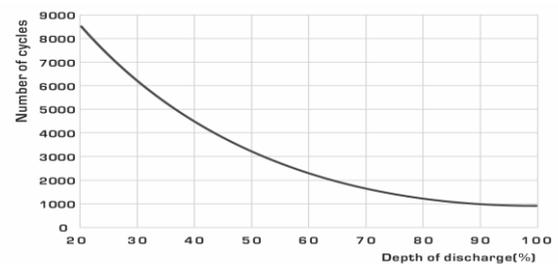


Figure 1: ChangHong NF-S Nickel-Iron Battery Cycle life versus Depth of Discharge (20°C) [31].

Likewise, nickel iron batteries that have reached a residual 50% of the capacity, provided the batteries had not been so completely discharged that iron contamination occurs in the positive electrode, it is possible to just replace the negative iron electrodes to restore battery capacity. Further, the 80% state of life capacity neither provides the end of life state for the nickel iron battery, and re-compensating for lost capacity can be by additional string of new batteries, or overhaul and replacement of the iron electrodes in the cells. Alternatively, if the original nickel iron battery were produced (for such stationary applications like voltage support active power injection for SWER networks) with excess iron to allow for slow dissolution of the iron to magnetite precipitant then any capacity loss would be further significantly delayed.

IV. LIFE COSTS OF LONG-TERM BATTERY ENERGY STORAGE ASSETS

To complete this review of battery technology, a standard 30 year capital cash flow present value (PV) costing with 5% per annum inflation allowance was developed for 5kW-hr battery array block modules. This final study accounted for capital costs, depth of discharge (DoD) on cycle life characteristic, and turn around efficiency. For the

characteristic costs and performance variables, the best compromise was sought for battery size, and DoD effect on cycle life for each type of battery. The discharge rate range of $C(2_{hr})$ to $C(3_{hr})$ {or averaged $C(2.5_{hr})$ } characteristic was used for each type of battery from manufacturers' published data. Table 2 characteristics were accounted for each battery type in this study. For a 30 year capital life period, 1000A-hr battery block units were chosen, and the variables considered for cost, cycle life and disposal were per battery type:

- VRLA gel batteries were costed at \$1,300 per kWh, 70% turn-around efficiency with DoD for 25% = 3.5 year life [18], or alternatively advanced VRLA AGM (glassmat) batteries \$1,400 per kWh 65% turn-around efficiency with DoD of 70% = 10 year life [20] [21].
- Changhong NF-S nickel-iron batteries at \$1,300 per kWh, 50% turn-around efficiency with DoD of 50% = 10.5 year life [30]; with residual capacity at $\geq 80\%$, with the addition of a 20% capacity battery string per 10 years to maintain total system capacity rating. This is permissible due to the unique corrosion pacification of this alkaline battery. (Note – the nickel-iron battery was given a lower turn around efficiency than normal as a worst case to account for any additional charging energy required over the other battery types. The nickel-iron would normally be 60% turn-around efficiency.)
- Lithium-ion at \$1,500 per kWh with 85% turn-around efficiency with DoD of 50% = 6 year life [3].
- Zinc-bromide flow battery at \$1,100 per kWh 73% turn around efficiency with DoD of 78%; including an additional \$2,500 per 10 year intervals for replacing active cell replacement costs (also adjusted in time for inflation) [12] [13] [19].

The 30 year life cycle was chosen as an important milestone for these battery types to be a coupled asset to a large solar array (as a potential active power energy source in SWER networks) that generally has a similar long life cycle. Included was also costing / replacement cycle method are the needed inverter/chargers and disposal costs of batteries requiring replacement during the 30 year battery array life. These costs also include the difference in turn-around efficiency for each battery type as shown in table 2. Taking all of these factors into account, and the specific manufacturer's recommended operating / maintenance practices the resulting capital cost cash flow curves are shown in figure 2 with the VRLA gel-cell option, while figure 3 shows the advanced VRLA glassmat option. Cost values are given in 2011 Australian dollars. As can be seen by figures 2 and 3, the lithium-ion battery has an initial cost advantage up to the 10 year cycle over the nickel-iron battery, even with its absolute worst case turn around efficiency. At 20 years the nickel iron battery costs have reduced below those of the lithium-ion, and at 30 years (to match the life of a large solar array) the nickel-iron battery has a distinct cost advantage over the lithium-ion and the zinc bromide flow battery. From figure 2, the VRLA gel-cell battery is quite expensive as a result of a standard short cycle life even at 25% DoD; resulting in a

nominally twice the capital outlay compared to the other batteries studied.

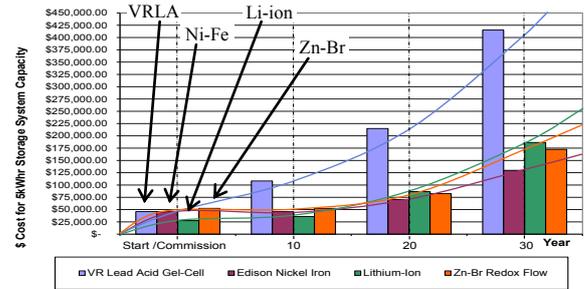


Figure 2: 30 year comparison of capital outlay costs of large production run supply battery production costs of usable 5kWhr modular capacity for VRLA gel-cell, nickel-iron (Edison), lithium-ion and Zn-Br redox flow batteries. (Costs included are inverter / charger costs and disposal / upgrade or replacement capacity costs for each battery life cycle.)

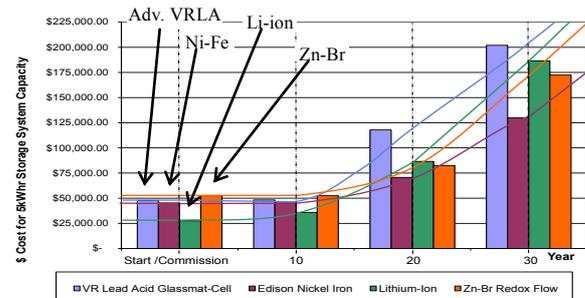


Figure 3: 30 year comparison of capital outlay costs of large production run supply battery production costs of usable 5kWhr modular capacity for advanced VRLA glassmat, Nickel Iron (Edison), Lithium-ion and Zn-Br Redox flow batteries. (Costs include inverter / charger costs, disposal/upgrade/replacement capacity costs for each battery life cycle.)

Comparing the figure 2's gel-cell VRLA battery costs to those of the advanced VRLA AGM (glassmat) costs in figure 3 show the reduced costs that innovation in the batteries developed in the past few years by Hitachi [20] and Exide [21]. Particular development in multi-step charging regimes, along with no float charging for this type of battery, have been significant contributors to their life extension to now be 3000 – 4000 discharge / charge cycles at greater than 50% DoD. The VRLA battery also would have the second lowest environmental and operational footprint of the battery types in this study. (For operational safety reasons alone, the newer advanced VRLA AGM battery is still a contender against the lithium-ion technology and zinc-bromide flow battery technologies.) Summarising figure 3 in cost per kWh for each battery type for a 2.5hr nominal discharge is as shown table 3. Comparing these results to the averaged DOE study [10] results for levelled costs of capacity in commercial/ industrial / domestic / distributed supplies, ranks Zinc-bromide flow batteries a cost of \$1033 / kW-Yr for a 3hr discharge rate, advanced VRLA glassmat batteries \$810 / kW-Yr for a 2.6hr discharge rate, and Lithium-ion at \$826 / kW-Yr for a 2hr discharge rate, with each battery technology being costed for a 15 year life. So in scales of relative magnitude, there is agreement of results with the review undertaken.

TABLE 3: \$ COST / KW-HR AT 2.5 HOUR AVE. DISCHARGE RATE

Battery Type	Adv. VRLA	Nickel-Iron	Lithium-Ion	Zinc-Bromide
10 year life	\$1,000	\$840	\$700	\$1,060
20 year life	\$1,200	\$720	\$630	\$800
30 year life	\$1,366	\$840	\$1,100	\$1,146

Regarding bench marking the nickel-iron battery into this study, physical testing [32] for a typical domestic RAPS load profile found that an 85Ahr 11 cell nickel iron NF-S battery can be used, and is lower by 4% using the Net Present Costs (NPC) method, than the comparative 6 cell 225Ahr deep discharge VRLA battery used for this application for a 25 year life cycle. This was also confirmed by HOMER Energy software modelling [32]. So even at these reported comparative costs the nickel-iron battery remains a contender. Further, using larger nickel-iron batteries than the tested 85Ahr cells in this study would increase this advantage, as the cost for nickel iron batteries drops as battery cell capacity increases towards 500Ahr.

V. CONCLUSIONS

With regard to future stationary applications for large battery storage systems, such as needed by SWER line voltage peak period support by active power injection, the Edison type nickel-iron batteries are already worthy of consideration where space footprint is not a problem. Their long cycle life is well matched to suit other 20 – 40 year infrastructure life cycles (e.g. Solar cell or remnant half-life of SWER networks). Of the batteries in this study, they have the highest level of safety for operation, and are the most environmentally friendly over their long asset cycle lives, especially for remote or very remote area deployment. A long term USQ research project continues into modelling nickel-iron battery capacity/fatigue aging processes, its electro-chemistry and physical redesign to electrode structures. Concluding, as the Edison type nickel-iron battery has undergone very little design changes over the past 100 years; it is now timely for detailed design review for further research and development. Areas of current research include reduction in the overall internal impedance of the electrode structures to improve turn-around efficiency and improve the battery's characteristic voltage droop response to high transient load disturbances. This will include the addition super-capacitor carbon electrode structures to the benefit of higher discharge performance as previously reported from USQ research [33]. Research also continues into the battery life degradation modelling and potential for the negative electrode to have excess iron content to extend cycle life to the nominal 80% capacity mark - while still retaining the inherent corrosion resistance and the ability of the iron electrode to reform without distorted metal crystalline structure or micro-needle formation. The nickel-iron battery's highly alkaline iron ferrous hydroxide solgel chemistry is quite unique in battery technology. This provides clues to possible design changes to the original Edison battery structure to further improve its performance.

REFERENCES

- [1] The NOUS Group, "Rural Electricity Networks National Workshop Appendix C", Melbourne 21 April 2010.
- [2] "Recommendations: Recommendation 33", <http://www.royalcommission.vic.gov.au/Assets/VBRC-Final-Report-Recommendations.pdf> accessed 20th June 2012.
- [3] D. Linden, Ready T B, "HANDBOOK OF BATTERIES", 3rd Edition, (2002).
- [4] Yuasa, "Safety Data Sheet According to Regulation (EC) No 1907/2006 (REACH), Valve regulated Lead Acid Battery", MSCS No. 853023 Revision 08 Dec 2011.
- [5] P. Mikolajczak, M. Kahn, K. White, R. T. Long, "Lithium-Ion Batteries Hazard and use Assessment Final Report", The Protection Research Foundation © 2011.
- [6] Arora A, Harris J, Pinnangudi B, "Lithium Ion Batteries for Stationary Applications: A Safety Perspective", BATCON Conference, Florida 2012.
- [7] Coates D, "SED-WR Program Lithium-ion Battery / EPS Safety plan Document Number SED07-075 prepared for the U.S. Air Force, Air Force Research Laboratory DET1 AFRL/PRKC", Bowling SEC-WR GNC, Release Date 22 August 2007.
- [8] ChangHong ®, "Material Safety Data Sheet for Industrial Nickel-Iron TN and NF-S rechargeable Battery", MSDS No. CHANGHONG 2011.
- [9] ZBB Energy Corporation, "Material Safety Data Sheet for ZBB electrolyte", Revision 3 Issue Date 2nd April 2008.
- [10] CHEMTREC, « Zinc bromide MSDS catalogue code SLZ1012 », CAS# 7699-45-8 issue date 11/01/2010.
- [11] Akhil A. A., Huff G., Currier A. B., Kaun B. C., Rastler D. M., Chen S. B., Cotter A. L., Bradshaw D. T., Gauntlett W. D., "Electricity Storage Handbook in Collaboration with NRECA", SANDIA Report, SAND2013-5131, DOE/EPRI 2013, July 2013.
- [12] www.activepower.com, "Active Power White Paper on Lead Acid Battery disposal Costs", accessed 12/06/2011.
- [13] ZBB Energy Corporation, "White Paper Integrated Power Management & Energy Storage (Integrating Renewables to Reduce Dependence on Diesel Generators and Minimise Fuel Consumption in Off-grid Telecom Applications)", © ZBB Energy Corporation April 2011.
- [14] RedFlow Limited, "An Assessment of the State of the Zinc-Bromide Battery Development Effort by Garth P. Corey", (Energy Storage Systems Engineer) 29th October 2011.
- [15] University of California, "An assessment of Battery and Hydrogen Energy Storage Systems Integrated with Wind Energy Resources in California, California Energy Commission PIER Program Report CEC-500-2005-136", September 2005.
- [16] <http://www.toxco.com/aboutrecycle.html>, accessed 11th May 2011.
- [17] www.ironcorebatteries.com.au, Iron Core Batteries Accessed 15 July 2011.
- [18] <http://www.rpc.com.au>, Rainbow Power Company Website Accessed 15 July 2011.
- [19] <http://www.ritarpower.com>, Ritar Batteries Website Accessed 16 July 2011.
- [20] ZBB Energy Corporation, "White Paper Energy Storage Using Zinc-bromide Flow Batteries as an Alternative to Lead acid (VRLA) Batteries", © ZBB Energy Corporation, April 2011.
- [21] B. Battelle, P. Gorney, B. Hennessey, "Failure Modes & Effects Criticality Analysis of Lithium-Ion Battery Electric and Plug-in Hybrid Vehicles Project Overview", January 26, 2012 Washington Auto Show SAE 2012 Government/Industry Meeting.
- [22] Exide, "Absolyte ® Technology, Battery Energy Storage System (BESS), August 2009.
- [23] AIC Europe, "(Hitachi) Ultra Long Life AVRLA Lead Acid Batteries for Energy Storage Solutions", © 2012 AIC Europe GmbH.
- [24] D. Silverman, "Presence of Solid Fe(OH)₂ in EMF-pH Diagram for Iron", Vol 38, No.8 August 1982, © national Association of Corrosion Engineers.
- [25] D. Silverman, "Revised EMF-pH Diagram for Nickel; 0010-9312/81/00017", © 1981 National Association of Corrosion Engineers.
- [26] P. J. DeMar, "THOMAS EDISON HAD IT RIGHT WHEN HE SAID THAT HIS NICKEL-IRON BATTERIES WOULD LAST 100 YEARS", BATCON 2011, Florida USA.
- [27] IEEE Std 1115™-2000 (R2011), "Sizing Nickel-Cadmium Batteries for Stationary Applications, Sections 6.22 Design Margin and 6.23 Aging factor".
- [28] Argonne National Laboratory for Eaton Corporation and Idaho National Engineering Laboratory for DOE Contract W30-109-Eng 38, "Performance and life Evaluation of Nickel/Iron Battery Technology for Dual Shaft Electric Propulsion Laboratory", May 1990.
- [29] A. Demidov, M. Kokhatskaya, B. Chervonets, "Thermodynamics of Discharge of the Negative Electrode of a Nickel-Iron Battery, ISSN 1070—4272", Russian Journal of Applied Chemistry 2006, Vol. 79, No. 4, pp.677 - 679, Pleiades Publish, Inc., 2006.
- [30] Edison Storage Battery Company, "Bulletin 850X For the Operation and Care of the Edison Alkaline Battery", 1912.
- [31] www.changhongbatteries.com Sichuan Changhong Battery Co., Ltd, "NF-S Series Nickel Iron Batteries for Solar PV Applications", Accessed and downloaded 10-08-2011.
- [32] Helwig, A, Ahfcock T, "Sizing of Nickel-Iron for RAPS systems", Renewable Power Generation (RPG 2011), IET Conference, Edinburgh 2011.
- [33] Helwig, A, Ahfcock T, "Ultra-capacitor assisted battery storage for remote area power supplies: A case study", Adelaide Power engineering Conference, AUPEC 2009.