Economical Comparison among Rechargeable Batteries for Integrating Renewable Energy into Electrical Grids

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ABSTRACT

In this paper, economical comparison is conducted among non-toxic, non-flammable rechargeable batteries for integrating renewable energy into electrical grids. Two types of recently developed non-toxic aqueous batteries, “flow assisted Zn/NiOOH battery” and “half capacitor - half battery” (AC/NiOOH and AC/NaMnO$_2$, AC denotes activated carbon. The AC electrode can be considered “a half capacitor,” and the NiOOH or NaMnO$_2$ electrode can be considered “a half battery”), are introduced and analyzed. These newly developed energy storage devices offer less expensive solutions for large scale energy storage than conventional batteries such as lithium-ion batteries, lead-acid batteries, vanadium redox flow batteries, and nickel metal hydride batteries. A newly started aqueous battery development, flow-assist-free Zn/NiOOH battery is also presented.

Keyword: Battery, Renewable Energy, Solar and Wind Energy, Electrical Grid

1. Introduction

The renewable energy, such as sunlight and wind, has been given attention recently. Photovoltaics capacity worldwide had reached 139 gigawatt (GW, 10^9 W) at the end of 2013 [European Photovoltaic Industry Association (EPIA), 2014], and an estimated 45-50 GW was installed in 2014 [International Energy Agency (IEA), 2014], i.e. about 179-189 GW in total. Wind power capacity worldwide reached about 370 gigawatts (GW) at the end of 2014 [Global Wind Energy Council (GWEC), 2015]. The electricity consumption worldwide reaches about 19,320,361 gigawatt hour (GWh) per year (52,932 GWh per day) [The World Factbook, Country comparison: Electricity - Consumption.

Kazakhstan has huge renewable energy potential, such as sunlight and wind; however, Kazakhstan’s power generation (93,000 GWh in total in 2013, 2.7% increase compared with that in 2012 [The World Factbook, Country comparison: Electricity -

Production]) has been supplied by coal-fired plants (85.5%), hydroelectric sources (8.7%), and oil- or gas-fired plants. Kazakhstan consumes around 89,000 GWh in total (1.0% increase compared with that in 2012 [The World Factbook, Country comparison: Electricity - Consumption]). The generated power is partially exported to Russia or China etc. The Government of Kazakhstan aims to increase the supply of electricity generated from renewable energy up to 1% by 2016, 5% by 2024, and 11% by 2030 [United Nations Development Programme (UNDP) in Kazakhstan, 2014]. Total yearly electricity generation is expected to be increased up to 150,000 GWh by 2030; therefore, 16,500 GWh is expected to be supplied by renewable energy in 2030. There is a possibility to install several to several dozens of GW-class wind farms. A 2-GW solar plant construction has started in 2013. Kazakhstan is one of the world's biggest uranium producers and has the second largest reserves of uranium trailing Australia; the government of Kazakhstan aims that 1.5 GW power generation will come from nuclear power plant by 2030.

Further application of renewable energy needs the energy storage systems: renewable energy sources are intermittent sources and can cause the fluctuation of electricity supply when being directly integrated to electric grids without using energy storage systems such as rechargeable batteries; or the renewable energy sources have to be often connected/disconnected depending on the fluctuating electricity demand/supply balance. Of course there are many other energy storage means besides rechargeable electrochemical batteries, such as hydroelectric and air-compression; however, rechargeable batteries can be installed in a more flexible manner than hydroelectric facilities or air-compressors.

Conventional rechargeable batteries have offered unsatisfactory cost-performance ratio and/or potential safety issues so far as follows.

(1) The cost per 25 years of lithium-ion batteries (LIBs), lead-acid batteries (LABs), and vanadium redox-flow batteries (VRFBs) are, e.g., 1,830/kWh▪25-year (USD600/kWh, every 8.2 years), e.g., USD731-938/kWh▪25-year (USD120/kWh, every 3.2-4.1 years), and e.g., ≤ USD925/kWh▪25-year (USD1,000/kWh, ≥ every 27 years [Jia H., Fu Y., Zhang Y., He W., 2010]), respectively (APPENDIX).

(2) These batteries have considerable safety issues, e.g., LIBs use flammable electrolyte solutions, LABs use toxic lead and aggressive sulfuric acid, and VRFBs use lethally toxic vanadium and aggressive sulfuric acid. Therefore, the development of safe (non-flammable and non-toxic) batteries at a low life cycle cost is crucial.

Aqueous rechargeable batteries that use non-flammable water-based electrolyte solutions instead of flammable organic electrolyte solutions are preferable to circumvent catching a fire since batteries that store the excess energy produced by power plants (especially intermittent power from solar and wind farms) should be sited anywhere. Aqueous nickel metal hydride (NiMH) batteries have an advantage compared with LABs and VRFBs since NiMH batteries do not use any toxic materials; however, the life cycle cost, e.g., > USD1,098/kWh▪25-year (materials cost = USD360/kWh, every 8.2 years) (APPENDIX), is not satisfactory. NiMH battery for large scale energy storage, e.g., GIGACELL (Kawasaki Heavy Industry, Japan) (http://www.khi.co.jp/english/gigacell/index.html) is available at a higher cost, USD2,500/kWh▪25-year (USD3,000/kWh, every 30 years).

Recently, many types of non-toxic aqueous batteries have shown progresses on life cycle cost. In this paper, some of them that seem the most promising are comparatively analyzed and one more candidate is introduced from our research group.

2. Comparative Analyses on Recently Reported Advanced Aqueous Batteries

2.1 Flow assisted (-) Zn || NiOOH (+) battery

Zinc (Zn) is the negative electrode material that can offer the most negative half-cell potential in aqueous electrolyte solutions leading to a high output voltage of a battery; therefore, many aqueous batteries adopt this negative electrode material including manganese primary (non-rechargeable) battery (Zn/MnO_2 battery) and alkaline manganese primary battery (Zn/MnO_2 battery). Furthermore, zinc is not toxic and cheap. The problem to use zinc for rechargeable batteries is that zinc forms dendrites (multi-branching tree-like crystal) during charging that can penetrate separators resulting in internal short-circuit failure; therefore, the use of zinc for rechargeable batteries had been difficult [Minakshi M., Appadoo D., and Martin E. D., 2010; Miyazaki K., Lee S. S., Fukutsuka T., and Abe T., 2012; Koda R., Fukami K., Sakka T., and Ogata Y. H., 2013].

NiOOH is a positive electrode material that can offer the most positive half-cell potential in aqueous electrolyte solutions leading to a high output voltage of a battery. Furthermore, this material can offer a long cycle life and not toxic.

Even though Zn/NiOOH battery can offer a good initial cost performance (USD300/kWh), the realization of Zn/NiOOH battery had remained difficult because of its short life resulting from zinc dendrite formation [Jindra J., 2000; Geng M. and Northwood D. O., 2003; Iwakura C., Murakami H., Nohara S., Furukawa N., and Inoue H., 2005; Yuan Y. F., Tu J. P., Wu H. M., Li Y., Shi D. Q., and Zhao X. B., 2006; Yuan Y. F., Tu J. P., Wu H. M., Yang Y. Z., Shi D. Q., and Zhao X. B., 2006; Ma M., Tu J. P., Yuan Y. F., Wang X. L., Li K. F., Mao F., and Zeng Z. Y., 2008; Lee S.-H., Kim K., and Yi C.-W., 2013].

However, a new technology, flow-assisted Zn/NiOOH battery, has recently been suggested by a research group of the City College of New York (CUNY) [Ito Y., Nyce M., Plivelich R., Klein M., Steingart D., and Banerjee S., 2011; Turney D. E., Shmukler M., Galloway K., Klein M., Ito Y., Scolklapper T., Gallaway J. W., Nyce M., and Banerjee S., 2014]: by circulating the electrolyte solution via pump system, they have succeeded in suppressing the short-circuit failure resulting from Zn dendrite growth. The cost per 25 years of flow-assisted Zn/NiOOH battery is about > USD377/kWh▪25-year (materials cost + direct labor cost = USD407/kWh, ≥ every 27 years). Furthermore, this battery does not use any toxic materials. A problem is that during the period when there is no sun shine or wind, the circulation system consumes electricity.

2.2 Half capacitor – half battery

ELIT (Russia) and ESMA (Russia) are commercially supplying (-) AC || NiOOH (+) energy storage device. Since zinc is a problematic material for rechargeable batteries, activated carbon (AC) has been used for an alternative to zinc. Activated carbon (AC) is usually used for electrical double layer capacitor (EDLC) that can supply a higher current in a short time than batteries, and can offer a longer life than batteries: since energy can be stored/supplied only through adsorption/desorption of ions in electrolyte solutions onto AC surface; it can offer better kinetics thereby higher current supply in a short time, and less chemical degradation of materials and thereby longer life than batteries. A problem is that the energy density becomes lower than those of batteries (about 1/30 of batteries with zinc anodes) since this type of energy storage device uses AC for the negative electrode.

AQUION ENERGY (USA) has recently started supplying the prototype of (-) AC || $NaMnO_2$ (+) energy storage device that was first reported by Qu Q.T., Shi Y., Tian S., Chen Y.H., Wu Y.P., and Holze R. [2009]. However, $NaMnO_2$ offers less capacity (100-150 mAh/g) than NiOOH (292 mAh/g). Even though $NaMnO_2$ was expected to be mass-produced at a cheaper cost than NiOOH, the durability of $NaMnO_2$ is still problematic: probably, $NaMnO_2$ with a dopant such as Bi^{3+} is required because of the multi-valency of manganese that can cause the dissolution of manganese ion into electrolyte solutions if the crystal structure of manganese oxide is not stabilized by a dopant. The doping can result in the cost increase.

The cost per 25 years of the half capacitor - half battery is about USD547/kWh▪25-year (USD300/kWh, every 13.7 years).

2.3 Life cycle cost comparison

Table I summarizes life cycle cost comparison among various types of conventional batteries and recently developed ones. As shown in Table I, recently developed batteries such as flow-assisted Zn/NiOOH battery and half capacitor - half battery (activated carbon/NiOOH, activated carbon/$NaMnO_2$) offer less expensive life cycle cost than conventional batteries (lithium-ion batteries, lead-acid batteries, vanadium redox-flow batteries, and nickel metal hydride batteries).

Table I. Life cycle cost comparison (assuming 365 cycles per year).

Battery type	Life cycle cost (USD/kWh▪25-year)	Initial cost (USD/kWh)	Life (year)	Flammability, toxicity etc.
Lithium-ion	1,830	600	8.2	Flammable
Lead-acid	731-938	120	3.2-4.1	Toxic
Vanadium redox-flow	≤ 925	1,000	≥ 27.0	Toxic
Nickel metal hydride	1,110	364	8.2	Self discharge
Flow-assisted Zn/NiOOH	> 377	> 407	≥ 27.0	
Half capacitor – half battery	547	300	13.7	

3. Newly Started Aqueous Battery Development Project

A new aqueous battery development project has been implemented at the Institute of Batteries LLC (IoB) (Kazakhstan). Compared with the earlier mentioned flow-assisted Zn/NiOOH batteries, the IoB's flow-assist-free Zn/NiOOH battery does not need the implementation cost for an electrolyte solution circulation system that is used for the flow-assisted Zn/NiOOH batteries.

The key technologies for the suppression against Zn whisker growth are (1) the morphology control of Zn anode crystals via use of a special deposition technique and (2) Zn whisker growth suppressor coated onto the Zn, and (3) the morphology control of NiOOH or $Ni(OH)_2$ (reduced form of NiOOH) crystals via use of a special deposition technique etc. As suggested by Parker et al., the following strategy: (i) facilitating long-range electronic conductivity through the inner core of zinc electrode, (ii) amplification of electrified interfaces to distribute current uniformly throughout the electrode structure, and (iii) forming partially confined void volume elements within the interior of the porous zinc anode that expedite dissolution/deposition can suppress Zn dendrite formation [Parker J. F., Chervin C. N., Nelson E. S., Rolison D. R., Long J. W., 2014; Parker J. F., Nelson E. S., Wattendorf M. D., Chervin C. N., Long J. W., Rolison D. R., 2014].

The merits of this new battery is low materials cost (USD103/kWh without current collectors, Table II.) and low direct labor cost (USD24/kWh, Table III). Currently, we use expensive current collectors; however, the total materials cost of USD131-331/kWh is possible in the near future (Table IV), resulting in the total cost of USD155-355/kWh that is less expensive than the earlier mentioned flow-assisted Zn/NiOOH battery. The durability of the flow-assist-free Zn/NiOOH battery has not been confirmed since the project has just started. However, as mentioned earlier, newly implemented technologies, such as (1) the morphology control of Zn anode crystals using a special deposition technique and (2) Zn whisker growth suppressor (polymer) coating onto the Zn anode crystals, are expected to improve the durability of the battery. This battery uses separator: even when a thick separator (e.g., 3 mm) is used, the battery can offer a higher volumetric energy density than the flow-assisted Zn/NiOOH battery. The flow-assist-free Zn/NiOOH is more reliable during the period when there is no sun shine or wind (flow-assist one needs electricity supply in order to circulate the electrolyte solution).

4. Conclusion

In this paper, economical comparison has been conducted among non-toxic, non-flammable rechargeable batteries for integrating renewable energy into electrical grids. Two types of recently developed non-toxic aqueous batteries were introduced and analyzed. Flow assisted Zn/NiOOH battery is available at >USD377/kWh▪25-year (materials cost + direct labor cost = USD407/kWh, every 20 years). Half capacitor - half battery, such as AC/NiOOH and AC/NaMnO$_2$ are available at USD547/kWh▪25-year (USD300/kWh, every 13.7 years). These newly developed energy storage devices offer less expensive solutions for large scale energy storage than conventional batteries: lithium-ion batteries (LIBs), USD1,830/kWh▪25-year (USD600/kWh, every 8.2 years); lead-acid batteries (LABs), USD731-938/kWh▪25-year (USD120/kWh, every 3.2-4.1 years); vanadium redox flow batteries (VRFBs), ≤ USD925/kWh▪25-year (USD1,000/kWh, ≥ every 27 years); and nickel metal hydride (NiMH) batteries, USD547/kWh▪25-year (USD300/kWh, every 13.7 years).

A newly started aqueous battery development, flow-assist-free Zn/NiOOH battery is expected to offer further economical solutions, e.g., at the initial cost of USD155-355/kWh. Its life cycle cost depends on the success of the key technologies for suppressing Zn whisker growth, i.e., the morphology control of Zn anode crystals via use of a special deposition technique, and Zn whisker growth suppressor (polymer) coating onto the Zn anode crystals by using self-limited electropolymerization etc.

Table II. Materials cost (without current collectors cost) for one 2 kWh cell.

Item	Cost per unit (USD)	Unit	Unit needed	Item cost (USD)
Cell box (inner space = 40*40*2 cm = 3.2 L)	3.20	1 box	1.00	3.20
Terminal	3.00	1 terminal	2.00	6.00
KOH solution (5 M)	0.88	1 L	2.16	1.90
ZnO powder (30 g/L)	1.83	1 kg	0.06	0.12
Gelating agent (polyacrylamide) (60 g/L)	2.37	1 kg	0.13	0.31
Current collector	0.00	1 collector	92.00	0.00
Separator (Celgard 3501, 0.25-µm-thick)	0.96	1 sheet	162.00	155.52
Zn source ($ZnSO_4$▪H_2O)	0.44	1 kg	2.41	1.06
Zn surface treatment agent	45.50	1 kg	0.01	0.26
Ni source ($NiSO_4$)	4.75	1 kg	7.80	37.04
Total				205.40
			(USD/kWh)	102.7

Table III. Direct labor cost for one 2 kWh cell (labor unit cost = minimum wage in China × 4).

	labor unit cost (USD/h)	hours needed	labor cost (USD)
Mixing electrolyte	8.00	0.50	4.00
Setting (46 substrates)	8.00	0.50	4.00
Anode electrodepositon	8.00	0.50	4.00
Anode rinse & drying (1)	8.00	0.50	4.00
Anode surface treatment	8.00	0.50	4.00
Anode rinse & drying (2)	8.00	0.50	4.00
Cathode setting (46 substrates)	8.00	0.50	4.00
Cathode electrodeposition	8.00	0.50	4.00
Cathode rinse & drying	8.00	0.50	4.00
Cathode annealing	8.00	1.00	8.00
Cell assembly	8.00	0.50	4.00
Total		6.00	48.00
		USD/kWh	24.00

Table IV. Materials cost (with current collectors cost) for one 2 kWh cell.

(a) Current collector: Toray carbon paper, TGP-H-060

Item	Cost per unit (USD)	Unit	Unit needed	Item cost (USD)
Cell box (inner space = 40*40*2 cm = 3.2 L)	3.20	1 box	1.00	3.20
Terminal	3.00	1 terminal	2.00	6.00
KOH solution (5 M)	0.88	1 L	2.16	1.90
ZnO powder (30 g/L)	1.83	1 kg	0.06	0.12
Gelating agent (polyacrylamide) (60 g/L)	2.37	1 kg	0.13	0.31
Current collector (TGP-H-060)	130.00	1 collector	92.00	11960.00
Separator (Celgard 3501, 0.25-µm-thick)	0.96	1 sheet	162.00	155.52
Zn source ($ZnSO_4$▪H_2O)	0.44	1 kg	2.41	1.06
Zn surface treatment agent	45.50	1 kg	0.01	0.26
Ni source ($NiSO_4$)	4.75	1 kg	7.80	37.04
Total				12165.40
			(USD/kWh)	6082.7

Table IV. (continued)

(b) Current collector: Made in China

Item	Cost per unit (USD)	Unit	Unit needed	Item cost (USD)
Cell box (inner space = 40*40*2 cm = 3.2 L)	3.20	1 box	1.00	3.20
Terminal	3.00	1 terminal	2.00	6.00
KOH solution (5 M)	0.88	1 L	2.16	1.90
ZnO powder (30 g/L)	1.83	1 kg	0.06	0.12
Gelating agent (polyacrylamide) (60 g/L)	2.37	1 kg	0.13	0.31
Current collector (Made in China)	0.60	1 collector	92.00	55.20
Separator (Celgard 3501, 0.25-µm-thick)	0.96	1 sheet	162.00	155.52
Zn source (ZnSO4▪H2O)	0.44	1 kg	2.41	1.06
Zn surface treatment agent	45.50	1 kg	0.01	0.26
Ni source (NiSO4)	4.75	1 kg	7.80	37.04
Total				260.60
			(USD/kWh)	130.3

(c) Current collector: Made in China with surface treatment

Item	Cost per unit (USD)	Unit	Unit needed	Item cost (USD)
Cell box (inner space = 40*40*2 cm = 3.2 L)	3.20	1 box	1.00	3.20
Terminal	3.00	1 terminal	2.00	6.00
KOH solution (5 M)	0.88	1 L	2.16	1.90
ZnO powder (30 g/L)	1.83	1 kg	0.06	0.12
Gelating agent (polyacrylamide) (60 g/L)	2.37	1 kg	0.13	0.31
Current collector (Made in China -> surface treatment)	5.00	1 collector	92.00	460.00
Separator (Celgard 3501, 0.25-µm-thick)	0.96	1 sheet	162.00	155.52
Zn source (ZnSO4▪H2O)	0.44	1 kg	2.41	1.06
Zn surface treatment agent	45.50	1 kg	0.01	0.26
Ni source (NiSO4)	4.75	1 kg	7.80	37.04
Total				665.40
			(USD/kWh)	332.7

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APPENDIX

Cost per 25 years

- LIB: 1,830/kWh▪25-year (USD600/kWh, every 8.2 years)

USD600/kWh assuming $LiFePO_4$-based LIBs (one can find similar LIBs for off-grid solar power system at http://www.alibaba.com/ etc.). The cycle life of $LiFePO_4$ cathode is about 3,000 cycles corresponding to 8.2 years assuming 365 cycles per year (http://www.lifepo4-info.com/smith-ev-finds-after-10-years-3000-cycles-lifepo4-batteries-retain-80-percent-capacity/, http://fpotiumby.en.china.cn/selling-leads/detail,1288326618,32V-3000-Cycles-60Ah-LifePO4-Cell-For-Backup-Power-Supply-Solar-Energy.html, http://evlab.co.nz/product/evlab-36v-lifepo4-battery/); the cycle life of graphite or hard carbon anode is at most 1,000 cycles corresponding to 2.7 years; some new anode materials, such as nano-silicon/carbon composites can be used for several thousand cycles. Short cycle-life LIBs, such as a replacement battery for the 2012 Chevy Volt, may be available at a cheaper cost, e.g., USD144/kWh; however, such kind of LiBs, e.g., LIBs with a $Li(Ni,Mn,Co)O_2$-based cathode, can be used only for at most 3.3 years (1,200 cycles).

- LAB: USD731-938/kWh▪25-year (USD120/kWh, every 3.2-4.1 years)

The cycle life of LAB is about 1,150-1,500 cycles at a depth of discharge of 50% (e.g., http://saurorja.org/2011/08/30/lead-acid-is-the-cheapest-battery-conditions-apply/, http://www.mpoweruk.com/life.htm).

- VRFB: ≤ USD925/kWh▪25-year (USD1,000/kWh, ≥ every 27 years) http://energy.gildemeister.com/en/store/cellcube-fb-10-20-30

- NiMH: >USD1,098/kWh▪25-year (materials cost = USD360/kWh, every 8.2 years)

The combination of the materials cost of USD360/kWh and the cycle life of 3,000 cycles corresponding to 8.2 years was chosen from a hybrid-electric-vehicle-use. Short cycle-life NiMHs, such as a battery for small electronic gadgets, may be available at a cheaper cost; however, such kind of NiMHs can be used only for 1.4 years. GIGACELL (Kawasaki Heavy Industry, Japan) is available at USD2,500/kWh▪25-year (USD3,000/kWh, every 30 years) (http://www.khi.co.jp/english/gigacell/index.html). Note that low mass-loading of active materials, employing three-dimensional current collector etc. can improve cycle life but accompanying the increase in the cost.