

Energy Storage for Oil & Gas Production at Deep Ocean Sites

*Joseph Farmer¹, Richard Haut², Ginny Jahn², John Goldman², John Colvin²,
Alexander Karpinski³, Arthur Doble³, Jeff Halfinger⁴, Scott Nagley⁴, Kevin Wolf⁵,
Andrew Shapiro⁶, Paul Doucette, Paul Hansen⁷, Akinsowon Oke⁷, Dewey Compton⁷,
Michelle Cobb⁷, Richard Kopps⁷, Jim Chitwood⁷, Wayne Spence⁸, Philippe Remacle⁹,
Cornelia Noel¹⁰, John Vicic¹⁰ and Ron Dee¹⁰*

*¹Lawrence Livermore National Laboratory, ²Houston Advanced Research Center, ³Yardney
Technical Products, ⁴Babcock & Wilcox, ⁵Naval Facilities Engineering Service Center,
⁶General Electric Global Research, ⁷Chevron Energy Technology Company, ⁸Curtiss-
Wright Electro-Mechanical Corporation, ⁹Total Exploration & Production USA LLC,
¹⁰Shell Oil Company*

Table of Contents

Table of Contents 2

Summary of Tables and Figures 3

Abstract 4

Background 5

Lead-Acid Batteries 5

Silver Zinc Batteries..... 5

Sodium-Sulfur Batteries 6

ZEBRA Batteries..... 6

Lithium Ion Batteries..... 7

Regenerative Fuel Cells..... 7

Hybrid Energy Conversion and Storage Systems 8

Summary 8

References 9

Acknowledgements..... 11

Tables & Figures 12

Summary of Tables and Figures

Table 1 – A comparison of energy storage technologies considered for RPSEA hybrid system..... 12

Figure 1 – Range of cell voltages for energy storage technologies considered for the various hybrid energy conversion and storage systems, ranging from the open circuit voltage (OCV) to the minimum operating voltage 13

Figure 2 – Range of operating temperatures possible with the energy storage technologies considered for the various hybrid energy conversion and storage systems..... 13

Figure 3 – A comparison of the specific energies and energy densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems..... 13

Figure 4 – A comparison of the specific powers and power densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems 14

Figure 5 – A comparison of the charge-discharge cycle lives for the energy storage technologies considered for the various hybrid energy conversion and storage systems 14

Figure 6 – A comparison of the cost of energy storage for each of the technologies considered for the various hybrid energy conversion and storage systems..... 14

Subsurface Hybrid Power Options for Oil & Gas Production at Deep Ocean Sites

Joseph Farmer¹, Richard Haut², Ginny Jahn², John Goldman², John Colvin², Alexander Karpinski³, Arthur Doble³, Jeff Halfinger⁴, Scott Nagley⁴, Kevin Wolf⁵, Andrew Shapiro⁶, Paul Doucette, Paul Hansen⁷, Akinsowon Oke⁷, Dewey Compton⁷, Michelle Cobb⁷, Richard Kopps⁷, Jim Chitwood⁷, Wayne Spence⁸, Philippe Remacle⁹, Cornelia Noel¹⁰, John Vicic¹⁰ and Ron Dee¹⁰

¹Lawrence Livermore National Laboratory, ²Houston Advanced Research Center, ³Yardney Technical Products, ⁴Babcock & Wilcox, ⁵Naval Facilities Engineering Service Center, ⁶General Electric Global Research, ⁷Chevron Energy Technology Company, ⁸Curtiss-Wright Electro-Mechanical Corporation, ⁹Total Exploration & Production USA LLC, ¹⁰Shell Oil Company

Abstract

By combining the availability and power density of an energy conversion component with the reliability, continuity and storage capability of an energy storage component, hybrid systems can be built for continuous operation, with the characteristics of high power and energy densities, as well as outstanding reliability. Such systems could be built with the capability of providing a constant source of electrical power for pumps, drill motors, and other equipment. For example, turbines driven by fluctuating currents of wind and ocean will produce unsteady current that will have to be rectified and used to charge batteries, which in turn can be used as a steady source of electrical power for pumps and motors. In the event of a failure of a primary power generation system, such as a small modular reactor, a proton exchange membrane fuel cell or engine being powered with natural gas from subsea well-heads, there must be enough stored electrical energy to enable continued operation of sensor, control, and communications networks, to enable a gradual and graceful shutdown of operations.

The energy storage technologies that were explored included: mechanical flywheels; compressed-gas storage; liquid red-ox batteries; lead-acid batteries; silver-zinc batteries; sodium-beta batteries; lithium-ion batteries; regenerative fuel cells. Of these, only the lead-acid, sodium-beta and lithium ion batteries were carried forward for consideration as energy storage options for the deep ocean hybrid energy conversion and storage systems being evaluated.

Background

The energy storage technologies that were explored for the deep ocean hybrid energy conversion and storage system included: mechanical flywheels; compressed-gas storage; liquid red-ox batteries; lead-acid batteries; silver-zinc batteries; sodium-beta batteries; lithium-ion batteries; regenerative fuel cells. From this list of options, only the rechargeable batteries and the regenerative fuel cell were evaluated in detail. By combining the power density of the energy conversion component with the energy storage and reliability of the energy storage component, hybrid systems can be built with high power and energy densities, as well as outstanding reliability. A summary of key attributes of energy storage options used to assess hybrid system options is presented in Table 1 and Figures 1 through 6.

Lead-Acid Batteries

The lead-acid battery has a metallic anode made of a lead alloy, a lead-oxide cathode, a porous polyethylene separator, and an electrolyte of concentrated sulfuric acid. This battery can operate from -20 to +60°C. The open-circuit voltage is 2.1 V, with operation between 2.0 and 1.75 V. The specific power, power density, specific energy and energy density are 20 W/kg, 51 W/L, 20-35 Wh/kg, and 50-90 Wh/L, respectively. The cycle life of a typical lead acid battery can be as long as 1100 cycles (to 80% of the original capacity). The cost of energy storage is approximately \$150 per kilowatt-hour. In summary, lead-acid batteries are proven technology, with a long history of sub-surface application in submarines. The lead-acid battery is relatively heavy, but is relatively inexpensive and should therefore be considered for the RPSEA application.

Silver Zinc Batteries

The silver-zinc battery has a metallic anode made of a zinc alloy, a silver-oxide cathode, a cellophane separator, and an electrolyte of 40% potassium hydroxide. This battery can operate from -20 to +60°C. The open-circuit voltage is 1.86 V, with operation between 1.7 and 1.3 V. The specific power, power density, specific energy and energy density are 5560-1470 W/kg, 9530-2520 W/L, 105-110 Wh/kg, and 180-300 Wh/L, respectively. The cycle life of a typical silver-zinc battery is limited, with a maximum live of approximately 250 cycles (to 80% of the original capacity). The cost of energy storage is approximately \$600 per kilowatt-hour, which reflects the high cost of the silver used in the cathode. In summary, silver-zinc batteries are proven technology, with a long history of sub-surface application in torpedoes and other sub-surface vehicles. The silver-zinc battery is relatively expensive, suffers from short cycle life, but has exceptional specific power and power density, and specific energy and energy density rivaling that possible with state-of-the-art (SOA) lithium-ion batteries. The limited cycle life prevents it from be a good candidate for RPSEA applications.

Sodium-Sulfur Batteries

The sodium-sulfur battery is categorized as a sodium-beta battery. It has a molten sodium anode, a β'' - Al_2O_3 ceramic separator, which also serves as the solid-state, Na^+ -conductive electrolyte, and a molten sulfur cathode. This battery is challenged by the need for a relatively high operating temperature of 290 to 390°C. The open-circuit voltage is 2.08 V, with operation between 1.95 and 1.78 V. The specific power, power density, specific energy and energy density are 390-250 W/kg, 604-386 W/L, 117-226 Wh/kg, and 147-370 Wh/L, respectively. The sodium-sulfur battery has exceptional cycle life, with a maximum life of approximately 2,250 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. Despite the use of molten alkali electrodes, which can react with air and water, this battery has a very good safety record. No gaseous reaction products are formed during overcharge, and the separator tends to be self-healing. The cost of energy storage is approximately \$300 per kilowatt-hour, which is modest. In summary, sodium-sulfur batteries are proven technology, with a solid history of applications in grid-storage (NGK Corporation of Japan). The sodium-sulfur battery is a reasonable contender for RPSEA sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy [Reference: Joseph C. Farmer, Lawrence Livermore National Laboratory, 2009].

ZEBRA Batteries

The ZEBRA battery is also categorized as a sodium-beta battery, like the sodium-sulfur battery. The ZEBRA also has a molten sodium anode and a β'' - Al_2O_3 ceramic separator, which also serves as the solid-state, Na^+ -conductive electrolyte, but has a Ni/NiCl₂ cathode with a secondary NaAlCl₄ electrolyte, instead of the sulfur-based cathode used in the sodium-sulfur battery. This battery is also challenged by the need for a relatively high operating temperature of 220 to 450°C. The open-circuit voltage is approximately 2.58 V, with operation believed to occur between 2.25 and 1.72 V, slightly higher than the terminal voltage of the sodium-sulfur battery. The specific power, power density, specific energy and energy density are 171-169 W/kg, 265-261 W/L, 94-119 Wh/kg, and 148-183 Wh/L, respectively, lower than that possible with sodium-sulfur technology. The ZEBRA battery has exceptional cycle life, even better than that achieved with the sodium-sulfur battery, with a maximum life of approximately 3,500 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. The cost of energy storage is only \$220 per kilowatt-hour, which is less than that for the sodium-sulfur battery. In summary, sodium-sulfur batteries are proven technology, with a solid history of applications in transportation (electrical school buses for the Sacramento Utility District, and delivery vans in Europe), grid-storage (Canada), and deep-ocean applications (NATO DSRV, or deep-sea rescue vehicle). The ZEBRA battery is a reasonable contender for RPSEA sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy [Reference: Joseph C. Farmer, Lawrence Livermore National Laboratory, 2009].

Lithium Ion Batteries

The modern lithium-ion battery has: an anode that consists of a graphite-based active material (Li-C6) with carbon filler and PVDF binder coated onto a copper foil current collector; a cathode that consists of a transition metal oxide or iron phosphate (Li-NiO₂, Li-CoO₂, Li-MnO₂, or Li-FePO₄) active material with a PVDF binder coated onto an aluminum foil current collector; a microporous porous polyethylene separator, and an electrolyte consisting of a mixed organic carbonate solvent (EC:DMC:DEC) and LiPF₆ salt. Of course, more advanced materials are evolving, such as the lithium titanate anode (Li-Ti₂O₄) and solid state electrolytes such as LiPONTM. The liquid cylindrical or prismatic cells are contained in a hermetically sealed metal can, while polymer-gel cells are contained in a soft aluminum-polyethylene laminate package, with thermally laminated seams. In the case of the polymer-gel cell, the polyethylene separator is usually coated on both sides with porous PVDF layers. This battery can operate from -40 to +60°C. The open-circuit voltage is 4.1 V, with operation between 4.0 and 3.0 V (possibly as low as 2.8 V). The specific power, power density, specific energy and energy density are 1100-74 W/kg, 2270-147 W/L, 75-182 Wh/kg, and 139-359 Wh/L, respectively. The cycle life of the best state-of-the-art lithium-ion batteries can be as great as 1500 cycles (to 80% of the original capacity). However, poorly constructed cells can have much shorter lives (300 cycles representing poorer cells). Based upon published data, the cost of energy storage is believed to be approximately \$300 per kilowatt-hour (though some quote \$1000 per kilowatt-hour). In summary, lithium-ion batteries are proven technology, and are leading candidates for terrestrial electric vehicles. This technology has also enjoyed limited but successful use in autonomous underwater vehicles used for oceanographic research. Unfortunately, lithium ion batteries have been plagued by a history of significant safety incidents, with some causing serious human injury and property damage (loss of commercial cargo plane, for example). The lithium-ion battery may prove to be relatively expensive, has safety issues that must be dealt with, but has exceptional performance characteristics, that make it a leading candidate for consideration. Designs would have to emphasize safety, thermal management during charge and discharge, and enhanced battery management systems.

Regenerative Fuel Cells

During discharge, regenerative fuel cells burn stored hydrogen and oxygen, with the production of electricity and water. Due to the energy penalty associated with separating pure water from seawater (theoretical minimum of 2.5 Wh/gal, with actual values of 24-36 Wh/gal required for separation with reverse osmosis), the pure water produced by the oxidation of hydrogen in the fuel cell is stored during discharge. During recharging, this stored water is electrolyzed, with the formation of both hydrogen and oxygen, which is stored. In this case, we assume that the gases would be stored in bottles at a pressure of approximately 10,000 pounds per square inch absolute (psia). Assuming that a proton exchange membrane fuel cell (PEMFC) is used as the basis for this system, the air cathode would consist of a dispersed platinum catalyst on a porous carbon substrate, the hydrogen anode would consist of a dispersed platinum or platinum-ruthenium catalyst on a porous substrate, and the electrolyte is a polymeric cation-exchange membrane made of a material such as NafionTM. The operating temperature of a PEMFC ranges from 30 to 120°C. The open circuit voltage of such a regenerative fuel cell would be approximately 1.2 V, while the expected operating voltage under load would be 0.5-0.7 V. The specific

power and power density of such a system would be approximately 27 W/kg and 17 W/L, while the specific energy and energy density would be approximately 326 Wh/kg and 209 Wh/L, respectively. Such systems provide greater specific energy and energy density than SOA secondary batteries, but have limited power density. The power density dictates the size of such systems in high power applications. Therefore, regenerative fuel cells are not considered good choices for the RPSEA application.

Hybrid Energy Conversion and Storage Systems

Hybrid systems use energy conversion devices with high specific power to efficiently achieve high levels of current, and energy storage devices with high specific energy to enable sustained operation in the event that the primary power generation systems fails. The following combinations of energy conversion and storage devices have been evaluated in this study as candidate hybrid systems for powering subsea oil and gas production operations:

1. PWR = Pressurized-Water Nuclear Reactor + Lead-Acid Battery
2. FC1 = Line for Surface O₂ + Well Head Gas + Reformer + PEMFC + Lead-Acid & Li-Ion Batteries
3. FC2 = Stored O₂ + Well Head Gas + Reformer + Fuel Cell + Lead-Acid & Li-Ion Batteries
4. SV1 = Submersible Vehicle + Stored O₂ + Fuel Cell + Lead-Acid & Li-Ion Batteries
5. SV2 = Submersible Vehicle + Stored O₂ + Engine or Turbine + Lead-Acid & Li-Ion Batteries
6. SV3 = Submersible Vehicle + Charge at Docking Station + ZEBRA & Li-Ion Batteries
7. PWR TEG = PWR + Thermoelectric Generator + Lead-Acid Battery
8. WELL TEG = Thermoelectric Generator + Well Head Waste Heat + Lead-Acid Battery
9. GRID = Floor Electrical Grid + Lead-Acid Battery
10. DOC = Deep Ocean Current + Lead-Acid Battery

Summary

By combining the power density of the energy conversion component with the energy storage and reliability of the energy storage component, hybrid systems can be built with high power and energy densities, as well as outstanding reliability. Such systems must be capable of providing a constant source of electrical power for pumps, drill motors, and other equipment. For example, turbines driven by fluctuating currents of wind and ocean will produce unsteady current, which will have to be rectified and used to charge batteries, which in turn can be used as a steady source of electrical power for pumps and motors. In the event of a failure of a primary power generation system, such as a small modular reactor, a proton exchange membrane fuel cell or engine being powered with natural gas from subsea well-heads, there must be enough stored electrical energy to enable continued operation of sensor, control, and communications networks, to enable a gradual and graceful shutdown of operations.

The energy storage technologies that were explored included: mechanical flywheels; compressed-gas storage; liquid red-ox batteries; lead-acid batteries; silver-zinc batteries; sodium-beta batteries; lithium-ion batteries; regenerative fuel cells. The practicality of compressed-gas storage was site specific, and

not considered viable for most concept-of-operations sites under consideration. The silver-zinc batteries were considered too limited in cycle life and too expensive to include in the final evaluation. Similarly, the regenerative fuel cell was considered too expensive, and had a high level of complexity. Of these, only the lead-acid, sodium-beta and lithium ion batteries were carried forward for consideration as an energy storage option for the deep ocean hybrid energy conversion and storage system.

References

Keith Adendorff, First National Battery, Batteries for Energy Storage (www.battery.co.za), ZEBRA Battery (www.cebi.com), Downloaded August 12, 2009, 40 Slides.

Allen J. Bard, Larry R. Faulkner, Electrochemical Methods, Fundamentals and Applications, Selected Standard Electrode Potentials in Aqueous Solutions at 25°C in V vs. NHE, Table C.1, Appendix C, John Wiley & Sons, New York, New York, 1980, pp. 699-701.

Alexander Blake, External Pressure, Chapter 36, Practical Stress Analysis in Engineering Design, 2nd Edition, Revised and Expanded, Marcel Dekker, Incorporated, New York, New York and Basel, Switzerland, Equations 36.20 through 36.23, pp. 513-545.

Jeffrey W. Braithwaite, William L. Auzer, Sodium Beta Batteries, Chapter 40, Handbook of Batteries, 2nd Edition, David Linden, Thomas B. Reddy, Editors, McGraw-Hill, San Francisco, California, 1995, pp. 40.1 through 40.32.

Jeffrey W. Braithwaite, William L. Auzer, Sodium Beta Batteries, Chapter 40, Handbook of Batteries, 3rd Edition, David Linden, Thomas B. Reddy, Editors, McGraw-Hill, San Francisco, California, 2002, pp. 40.1 through 40.31.

Cord-H. Dustmann, ZEBRA Battery Meets USABC Goals, Journal of Power Sources, Volume 72 Issue 1, March 30, 1998, Pages 27-31.

Cord-H. Dustmann, The Swiss ZEBRA Battery System, Presented at EVS-17, Pages 1-17.

K. Fukuda, W. Danker, J. S. Lee, A. Bonne, M. J. Crijns, IAEA Overview of Global Spent Fuel Storage, IAEA-CN-102/60, Department of Energy, International Atomic Energy Agency, Vienna, Austria, Table I.

Doris L. Gonzalez, Abul K. M. Jamaluddin, Schlumberger; Trond Solbakken, Hydro Gulf of Mexico; George J. Hirasaki, Walter G. Chapman, Rice University, Impact of Flow Assurance in the Development of a Deepwater Prospect, SPE 110833, Society of Petroleum Engineers, Incorporated, 10 pages.

Tyler Hamilton, Senior Energy Reporter and Columnist, Toronto Star Newspaper, Canada

Ronald O. Hammel, Alvin J. Salkind, David Linden, Sealed Lead-Acid Batteries, Chapter 25, Handbook of Batteries, 2nd Edition, David Linden, Editor, McGraw-Hill, San Francisco, California, 1995, pp. 25.1 through 25.39.

Sohrab Houssain, Rechargeable Lithium Batteries, Ambient Temperature, Chapter 36, Handbook of Batteries, 2nd Edition, David Linden, Thomas B. Reddy, Editors, McGraw-Hill, San Francisco, California, 1995, pp. 36.1 through 36.77.

Makoto Kamibayashi, Advanced Sodium-Sulfur (NAS) Battery System, Tokoyo Electric Power Company (TEPCO), Tokoyo, Japan, Downloaded August 12, 2009, 19 Slides.

Ramesh Kainthla, Ph.D., Brendan Coffey, Ph.D., RBC Technologies, NASA Aerospace Workshop, Huntsville, AL, Long Life, High Energy Silver/Zinc Batteries, 11/19/2002.

Alexander P. Karpinski, Stephen F. Schiffer, Peter A. Karpinski, Silver Oxide Batteries, Chapter 33, Handbook of Batteries, 3rd Edition, David Linden, Thomas B. Reddy, Editors, McGraw-Hill, San Francisco, California, 2002, pp. 33.1 through 33.30.

A. P. Karpinski, S. J. Russell, J. R. Serenyi, J. P. Murphy, Silver Based Batteries for High Power Applications, Journal of Power Sources, Volume 91, 2000, pp. 77-82.

Edwin C. Kluiters, Dick Schmal, Willem R. ter Veen, Kees J. C. M. Posthumus, Testing of a Sodium/Nickel Chloride (ZEBRA) Battery for Electric Propulsion of Ships and Vehicles, Journal of Power Sources, Volume 80, Issues 1-2, July 1999, Pages 261-264.

David Linden, Sealed Lead-Acid Batteries, Chapter 23, Handbook of Batteries, 2nd Edition, David Linden, Editor, McGraw-Hill, San Francisco, California, 1995, pp. 23.1 through 23.22.

MES-DEA S. A., Divisione Energie Alternative, Via Laveggio, 15 CH-6855 Stabio, Switzerland, Tel. 41 (0) 91 6415392, Fax. 41 (0) 91 6415395, Email. info@mes-dea.ch, Internet www.mes-dea.ch

Benjamin L. Norris, Jeff Newmiller, Georgianne Peek, NAS Battery Demonstration at American Electric Power, A Study for the DOE energy Storage Program, Report SAND2006-6740, Sandia National Laboratory, Albuquerque, New Mexico 87185, Livermore, California 94550, March 2007, 55 Pages.

Perry's Chemical Engineering Handbook, 7th Edition, McGraw Hill, San Francisco, CA, pp. 9-10 to 9-13.

Max Peters, Klaus Timmerhaus, Robert West, Plant Design and Economics, 5th Edition, Chapter 12, 2008, p. 553.

Technology Insights, Overview of NAS Battery for Load Management, California Energy Storage Workshop, February 2005, 22 Pages.

T. M. O'Sullivan, C. M. Bingham, R. E. Clark, Zebra Battery Technologies for All Electric Smart Car, Department of Electronic & Electrical Engineering, University of Sheffield, SPEEDAM 2006. International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Taormina, May 23-26, 2006, Published July 5, 2006, IEEE Xplore, Page S34-6 through S34-11.

Sacramento Municipal Utility District Electric Transportation Department (SMUD), Electric School Bust with ZEBRA Battery and Integrated Fast Charge, FCalifornia Air Resources Board, ICAT Grant #01-1, Final

Technical report, April 30, 2004, Pages 1-37; Table 1, Battery Technology Comparison, Page 7; Table 2, Component Costs for the Prototype Bus, Page 11; Table 3, Life Cycle Cost Input Data, Page 12.

Alvin J. Salkind, John J. Kelly, Anthony G. Cannone, Lead-Acid Batteries, Chapter 24, Handbook of Batteries, 2nd Edition, David Linden, Editor, McGraw-Hill, San Francisco, California, 1995, pp. 24.1 through 25.89.

Stephen F. Schiffer, Peter A. Karpinski, Silver Oxide Batteries, Chapter 31, Handbook of Batteries, 2nd Edition, David Linden, Editor, McGraw-Hill, San Francisco, California, 1995, pp. 31.1 through 31.28.

R. A. A. Schillemans, C.E. Kluiters, Sodium/Sulphur Batteries for Naval Applications, Power Sources 15, A. Attewell and T. Keily, Editors, International Power Sources Symposium Committee, Crowborough UK, 1995 p. 421.

Leslie Smart, Elaine Moore, Solid Electrolytes, Section 5.4, Defects and Non-Stoichiometry, Chapter 5, Solid State Chemistry, 2nd Edition, Stanley Thornes Publishers Ltd., Cheltenham, United Kingdom, 1998, p. 172-184.

Dave Williamson, Neil Benstead, The Installation and Use of ZEBRA Batteries, Submarine and ASW Asia 2006, Defense Directory Com Conferences, 2006.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Work was co-sponsored by the Research Partnership for an Energy Secure America (RPSEA).

Tables & Figures

Table 1 – A comparison of energy storage technologies considered for RPSEA hybrid system

Parameter	Units	Pb Acid	AgZn	NaS	ZEBRA	Li-Ion	Regenerative Fuel Cell
Anode	none		Zn	Na	Na	LiC6	PtRu/C
Cathode	none	PbO ₂	AgO/Ag ₂ O	S	NiCl ₂	Li _x (Ni,Co)O ₂	Pt/C
Separator	none	Polyethylene	Cellophane	β"-Al ₂ O ₃	β"-Al ₂ O ₃	Polyethylene	Nafion
Electrolyte Salt	none	H ₂ SO ₄	40% KOH	None	NaAlCl ₄	1M LiPF ₆	None
Electrolyte Solvent	none	H ₂ O	H ₂ O	None	None	EC:DMC:DEC	H ₂ O
Toxic Materials Required	elements	Pb, Sb	None	S	Ni	Ni, Co, LiPF ₆	None
Strategic Materials Required	elements	None	Ag	None	Ni	Ni, Co, LiPF ₆	Pt, Ru
Minimum Operating Temperature	degrees C	-40	-20	290	220	-30	30
Nominal Operating Temperature	degrees C	30	30	310-350	270-350	30	90
Maximum Operating Temperature	degrees C	60	60	390	450	60	120
Minimum Operating Voltage	V	1.75	1.30	1.78	1.72	3.00	0.50
Nominal Operating Voltage	V	1.90	1.50	1.90	2.25	3.80	0.70
Maximum Operating Voltage	V	2.00	1.70	1.95	2.67	4.00	1.20
Open Circuit Voltage	V	2.10	1.86	2.08	2.58	4.10	1.20
Cell Impedance	milliohms	NA	5 to 15	5 to 32	10 to 45	5 to 10	NA
Peak Specific Power	W/kg	210	5560	215-360	250-390	1,100	NA
Specific Power	W/kg	20	5560-1470	390-250	171-169	1100-74	27
Power Density	W/L	51	9530-2520	604-386	265-261	2270-147	17
Specific Energy	Wh/kg	20-35	105-110	117-226	94-119	75-182	326
Energy Density	Wh/L	50-90	180-300	147-370	148-183	139-359	209
Coulombic Efficiency (Ah/Ah)	%	80-90%	90%	89-92%	~100%	99%	90%
Electrical Efficiency (Wh/Wh)	%	70-75%	75%	NA	NA	95%	43%
Self Discharge Rate	% per mo.	< 3	< 3	< 1	< 1	< 2	NA
Minimum Cycle Life	Cycles	200	10	NA	1,300	300	NA
Nominal Cycle Life	Cycles	400	100	2,250	2,500	500	NA
Maximum Cycle Life	Cycles	1,100	250	NA	3,500	1,500	NA
Minimum Calendar Life	years	3.0	0.5	NA	5.0	1.0	NA
Nominal Calendar Life	years	5.5	1.0	7.5	7.0	3.0	NA
Maximum Calendar Life	years	8.0	1.5	15.0	9.0	5.0	NA
Technology Cost	\$/kWh	150	600	300	220	300	NA
Cost Relative to Pb Acid	none	1.0	4.0	1.5	1.5	2.0	NA

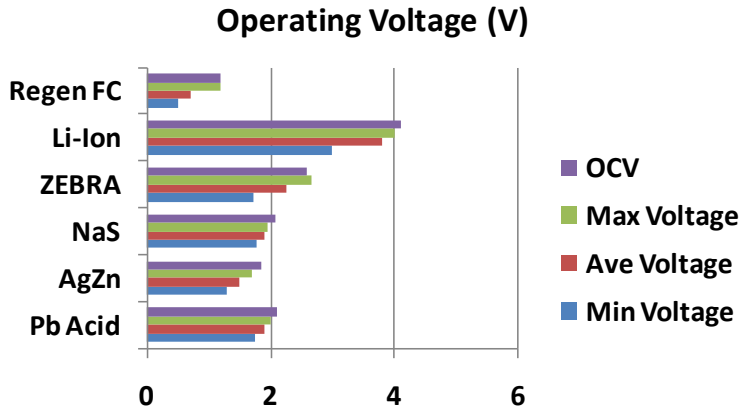


Figure 1 – Range of cell voltages for energy storage technologies considered for the various hybrid energy conversion and storage systems, ranging from the open circuit voltage (OCV) to the minimum operating voltage

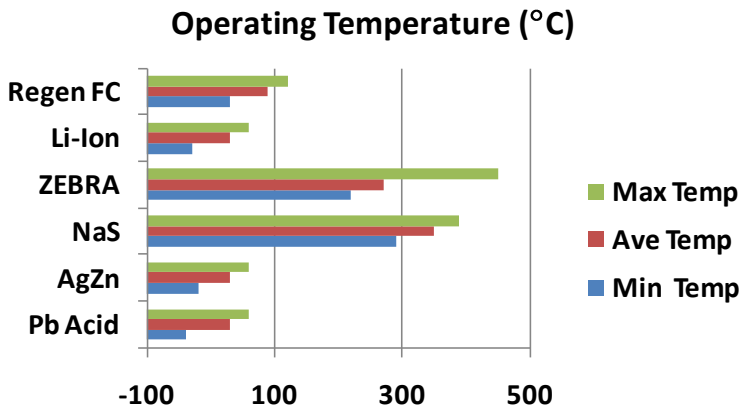


Figure 2 – Range of operating temperatures possible with the energy storage technologies considered for the various hybrid energy conversion and storage systems

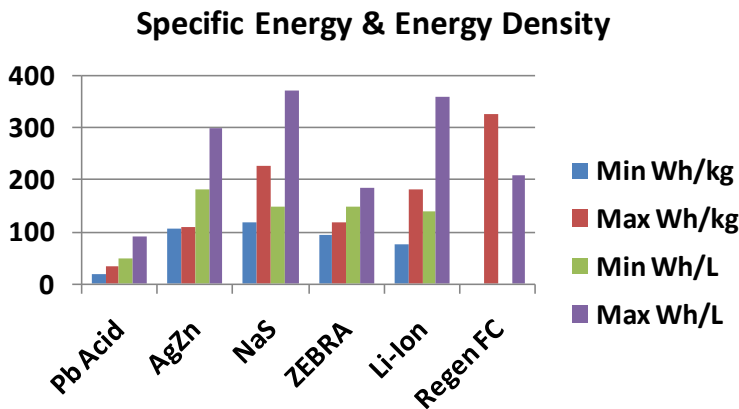


Figure 3 – A comparison of the specific energies and energy densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

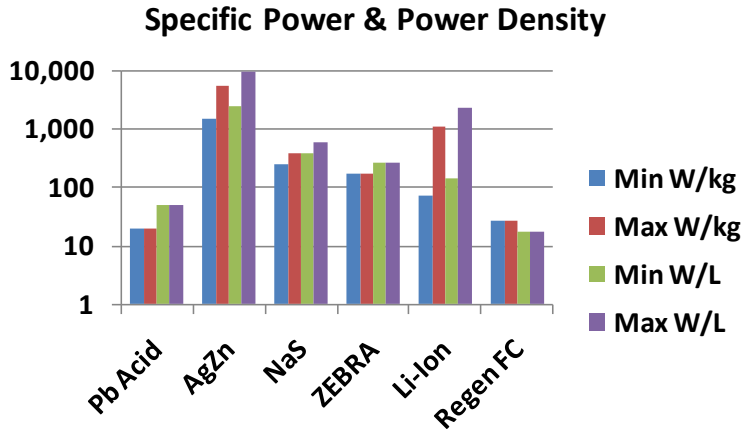


Figure 4 – A comparison of the specific powers and power densities for the energy storage technologies considered for the various hybrid energy conversion and storage systems

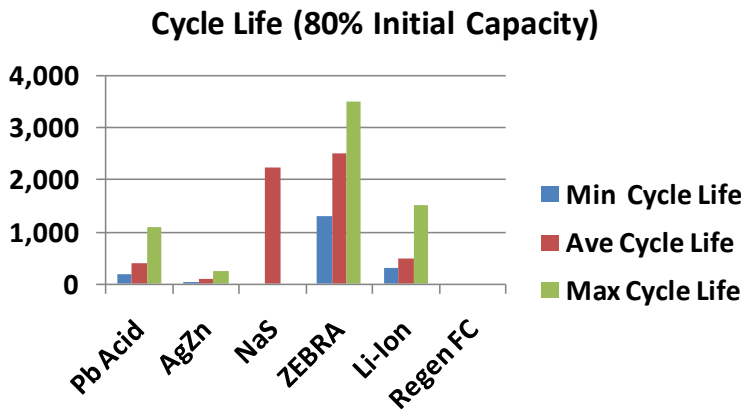


Figure 5 – A comparison of the charge-discharge cycle lives for the energy storage technologies considered for the various hybrid energy conversion and storage systems

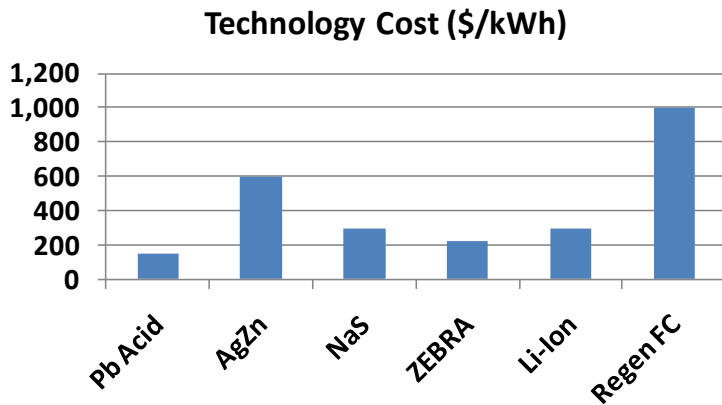


Figure 6 – A comparison of the cost of energy storage for each of the technologies considered for the various hybrid energy conversion and storage systems