Energy Storage Options for Environment Monitoring Wireless Sensor Networks in Rural Africa

Maximus Byamukama[1], Roseline Akol[1,] Geofrey Bakkabulindi[1], Björn Pehrson[2], Robert Olsson[2],
Julianne Sansa-Otim[3]

[1]College of Engineering, Design, Art and Technology, Makerere University, Uganda

[2]KTH Royal Institute of Technology, Sweden

[3]College of Computing and Information Sciences, Makerere University, Uganda

***Abstract*—This paper explores various traditional and emerging battery technologies available for deployments of automated environment monitoring devices using Wireless Sensor Networks (WSNs) in Africa and the considerations designers must take into account when implementing these systems.**

Environment-monitoring applications of WSNs are focusing more on reducing power consumption and optimizing data transmission and less on the constraints that their applications and deployment environments put on the energy storage device.

We describe the various properties of energy storage devices and, for each, we highlight the requirements to be met for environment monitoring applications, especially in remote areas in Africa. We evaluate the performance of some of these energy storage options against the requirements using three use cases. We indicate the technologies that have shown reliability for each use case.

We show that emerging battery technologies, such as Lithium Ion Capacitors are well suited for long-life low power deployments while the options for high-power deployments depend on the constraints faced by the designers, such as the power consumption of the sensor network components sand environment temperature range of the deployment environment.

Keywords—Environment Monitoring; Automatic Weather Station; Battery; Energy Storage; Wireless Sensor Network

I. INTRODUCTION

Automated Environment Monitoring in Africa largely utilizes industrial devices , called Automatic Weather Stations (AWS), from a number of commercial manufacturers, which are typically deployed as-is regardless of the characteristics of the deployment environment. Most of these systems employ a centralized wired topology with respect to the energy storage unit and typically comprise a single battery powering the sensors and main processor unit. For these commercial manufacturers, we believe that design and manufacturing decisions are made in the context of a business environment aiming for profit maximization, which makes frequent re-engineering challenging and expensive. As such, it is difficult for them to modify existing designs to keep at par with emerging technologies or to adapt them to where they will be deployed. Some examples are ADCON Telemetry whose A733 GPRS Terminal Unit running on Ni-MH batteries has been on the market since 2006 [1] and DAVIS Instruments which has sold its Vantage Pro2 console, that runs on Type-C 1.5V dry cells, since 2004 [2].

Recently, some research projects in the East African Region, like the WIMEA-ICT project [3], inter-agency partnerships in Malawi [4] and Kenya [5] have pioneered the design and implementation of automated environment monitoring systems based on Wireless Sensor Networks. The penetration of these WSN-based devices introduces new challenges. One of these is selection of the optimal battery to power the various types of nodes in the WSN. In remote deployments especially, such as rural Africa, the ideal battery technologies are those with a relatively high power density in proportion with the consumption of the sensor nodes and a high number of recharge cycles, which would lead to longer life-time and reduce the need for maintenance effort from the concerned meteorological departments. Considerations of the ideal energy storage option is especially important, because the consequences of a failed battery unit are immediate and grave.

The selection criteria for an optimal battery technology in these networks depends on specific needs and requirements, the power consumption of the environment-monitoring device, the nature of the deployment environment among other factors.

The rest of this paper is organized as follows. In Section II, we review the related work in this area. Section III addresses the needs and requirements that need to be considered for optimizing energy storage in WSN-based environment monitoring systems. In Section IV, We analyze the performance of several energy storage options based on three use cases in actual deployment and in Section V, we give conclusions and recommendations for further work.

Battery	**Nominal Voltage (V)**	**Operating voltage (V)**	**Specific Energy (Wh/Kg)**	**Cycle Life (Recharge Cycles at 80% DOD)**	**Self-Discharge (approx. % per month)**
Lead-Acid	2.1	1.8-2.4	33-42	< 350	3-20
Alkaline	1.5	0.9-1.5	85-200	Primary cell (Non-rechargeable)	0.17
Zinc-Carbon	1.5	0.75-1.5	36	Primary cell (Non-rechargeable)	0.32
Nickel Metal Hydride (NiMH)	1.2	0.9-1.2	90-100	300-500	13.9-70.6 (25^{0}C) 36.4–97.8 (45^{0}C) 0.42 (LSD version)
Nickel-Cadmium (NiCd)	1.2	0.9-1.2	30	2000	10
Lithium-ion Cobalt Oxide	3.6	2.7-4.2	100-250	500-1000	1-20% (25^{0}C) 15-35% (60^{0}C)
Lithium Thionyl Chloride (Li-SOCl$_2$)	3.5	3.0-3.5	500-700	Primary cell (Non-rechargeable)	0.08
Lithium Iron Phosphate (LiFePO$_4$)	3.2	2.2-3.6	90-120	1000-2000	4.5
Electrochemical Double Layer Capacitors (EDLCs)	2.7	0-2.7	1.5-3.9	> 1,000,000	~50 to >95% (after 24 hrs, varies with maker)
Polyacene Supercapacitors	3.0	2.5-3.0		> 100,000	~50-100%
Lithium Ion Capacitors (LIC)	3.8	2.2-3.8	10-15	100,000	1.5

Table 1: Properties of common battery technologies for various indoor and outdoor DC applications

II. RELATED WORK

We consulted numerous articles whose subject is in the areas of environment monitoring, wireless sensor networks and energy storage. Selection of appropriate battery technologies for applications appears to be an area of focus majorly for high power applications such as electric vehicles and industrial renewable energy system.

The most relevant works for this paper were those that mentioned the battery technology that was used in their research or application. In [6], [7], [8] and [9], the authors use Lithium-based batteries in their application. In [10], their WSN for Aquatic Environmental Monitoring is designed using NiMH batteries. In [11] and [12], the researchers use battery-supercapacitor hybrids to power WSNs.

The research gap we identified was that while all the cited works acknowledged the use of some form of energy storage in environment monitoring applications, especially employing WSNs similar to our use cases, they do not mention any scientific selection criteria for their battery of choice. Neither is there mention of having done any work that compared the performance of different batteries in any given parameter in their own use cases. We have used some knowledge from these sources, the needs and requirements and the experience from our deployments in Africa [13] to arrive at our analysis and recommendations.

III. ENERGY STORAGE PROPERTIES

There are numerous traditional and emerging energy storage technologies for powering outdoor embedded systems. We have listed the technologies that are most readily available on the market and can be sold directly to consumers. Table 1 shows 11 different battery technologies used in various indoor and outdoor DC applications and their typical electrical properties. These properties have been compiled from [14], [15], [16], [17], [18] and [19]. These electrical properties are what determine the suitability of a given battery technology for a particular use case. We have identified seven properties that we believe are the most important. These properties are the center of the discussion that follows.

A. *Recharge Cycles*

When deployments are going to be remote and with minimum post-deployment human interaction, as is usually the case for rural Africa, the battery must be able to withstand multiple recharge cycles over the lifespan of the environment-monitoring device. These cycles may be deep, due to a lack of opportunity to recharge following limited solar insolation, especially in rainy seasons. It is also necessary that the battery have a low capacity loss—i.e. it does not degrade much following deep discharge, and that it is able to accumulate the same amount of charge in subsequent recharge cycles. A high number of recharge cycles is a major determinant of the life expectancy of the sensor network.

B. *Nominal Voltage*

The battery must have a relatively high nominal voltage in relation to the operating voltage of the sensor nodes and their peripherals. Most microcontrollers and sensors operate in the region of 1.8-5.0V. A relatively high nominal voltage enables direct connection of the battery to the nodes without the need for a boost converter. Batteries with high nominal voltages will ensure that the nodes remain powered as the voltage drops. For example, even at their minimum voltage of 2.7V, most Lithium-based batteries will provide sufficient voltage to sustain operation. A high nominal voltage sustains the operation of the sensors in between charging cycles, even when the battery has a low state of charge.

C. *Temperature of Operation*

Many areas in Africa have hot climates. Juba, for example, and most of the lower Sahara region experience prolonged temperatures in the range of 30^0–40^0C during the hot seasons. While these temperatures are fine for operating most of the technologies listed in Table 1, higher temperatures put a constraint on charging some battery types. Lead-Acid batteries for example must be charged to a lower voltage per cell at higher temperatures and charging must not be done above 50°C. For Lithium batteries with Cobalt Oxide cathodes, the maximum charge storage degrades for every cycle because of the increased degeneration of the cathode during operation at elevated temperatures [20]. Operation at temperatures much higher than typical levels in the open environmental must be considered because most batteries are deployed with the sensor nodes inside some form of air and watertight casing. The lack of ventilation can cause the temperatures inside to rise several degrees higher.

D. *Self-Discharge*

All battery technologies will lose some charge from internal leakage current over time, even when not actively supplying power. This is called self-discharge and reduces the total amount of charge available to do real work. Environment monitoring WSNs are typically inactive networks, with sensor nodes transmitting only a few bytes every few minutes. When not transmitting, which is over 99% of the time in some applications, they are asleep and consuming very little power. For energy storage technologies with high self-discharge, the charge lost during these sleep phases may be of the same or greater degree of magnitude than the actual power used.

E. *Internal resistance*

The main consequence of a battery's internal resistance is its charging speed. A low internal resistance enables batteries to charge very fast. This is beneficial for deployments with intermittent sunlight, as it ensures charge accumulation in the short time that insolation is available. Low internal resistance also permits high discharge currents. Such currents are common when uplink devices on the AWS, such as cellular modems, establish connections to the internet. High internal resistances generate heat during charging and thus put a constraint on the charging temperature.

F. *Specific Energy*

A higher specific energy means more energy is contained in a smaller battery size. Environment monitoring WSNs are typically deployed with a battery in each node because centralizing the battery creates a single point of failure. It is desirable that the battery and node be as portable as possible, and in many cases, the battery is contained in the same enclosure as the node itself. For a given amount of Watt-hours required by a sensor node or gateway device, deployment with batteries with a lower specific energy would take up more space in the enclosure and leave less room for other important peripherals and electronics. Choosing to use larger enclosures instead in such a case would put more constraints on the mechanics of the deployment and would affect the selection of nuts, bolts and hoisting frames.

G. *Cost*

The cost per Wh of batteries varies tremendously. Older chemistries are generally cheaper per Wh than newer ones and larger batteries are more cost-effective than smaller ones of the same type. In Environment monitoring however, the initial cost of purchase is a poor indicator of the actual cost of using a particular battery technology. For example, one main reason why primary batteries cannot be used in remote deployments is the cost of replacement. This maintenance cost will accumulate less from the actual cost of the batteries, as they are very cheap, and more from the travel and labor costs associated with their replacement. Meteorological departments in Africa are often under-funded and this presents a large obstacle.

H. *Other maintenance issues*

There are other maintenance issues that make some battery technologies inconvenient for deployment away from human intervention. Ni-based batteries suffer from crystallization and need to be maintained with periodic deep discharge ("exercise cycles"). Lead-Acid batteries need a minimum floating charge and sometimes a higher voltage to prevent electrode sulphatization. Their charging process is also temperature-dependent and must be monitored.

IV. USE CASES

We have been testing a WSN-based Automatic Weather Station (AWS) in Uganda, South Sudan and Tanzania under the WIMEA-ICT Project for over 12 months. The project plans a mass deployment of 70 AWS units across East Africa. The focus of the testing has been the robustness of the power supply, communication interfaces and general resistance to weather. We have published a full design proposal of this AWS in [21]. At the heart of power system reliability lies the battery technology to use. The Automatic Weather Station consists of independent transmitter nodes and a gateway. Two types of gateways are being tested in the field. One is a Linux-based gateway, the Raspberry Pi with a sink node to receive the data and a 3G USB modem as the uplink device. The other is a very low power gateway, in which the sink node itself implements core functionality of saving data locally and makes it available via a 3G uplink device at predefined intervals.

With the right DC-DC conversion electronics, any battery technology can be used to power any load. In the analysis that follows, we favor technologies that would require minimum or no such electronics as these typically increase the power consumption of the whole set-up [22], as well as adding onto the cost of implementation.

A. *Transmitter Nodes*

We used the RS2 motes from Radio Sensors AB [22] as the transmitter nodes. The mote is based on the ATMEGA256RFR2 microcontroller. The mote consumes about 100µA in sleep mode and about 17mA during transmissions, which last about 20ms and occur once each minute. The microcontroller can operate at voltages as low as 2.4V. In the experiments in [23], these motes have been shown to transmit for 6 weeks on a single charge of a 270F Lithium-ion capacitor (LIC). This is very low power and both LICs and Li-ion batteries have proven to be reliable in for this application. While all Lithium-based batteries have a high energy density and superior self-discharge characteristics, the LICs have the extra advantage of being able to charge very fast and endure over 100 times more recharge cycles. Unlike the batteries, they do not maintain a constant voltage as they discharge. This, however, is not of major importance because, as stated earlier, the transmitter nodes can operate at voltages near the LIC's minimum voltage of 2.2V. The project has tested LICs in its AWS prototypes for over 2 years and the conclusion is that they are ideal for remote unsupervised deployments in the East African Region.

Related research reveals that Lithium Thionyl Chlrloride (Li-$SOCl_2$) batteries are also optimal for this use case. They are non-rechargeable but their extremely high energy density makes them a suitable contender in very long term, ultra-low power applications. In [6], WSNs running at under 300µW were developed and the battery of choice was an 8.5Ah LiSOCl2 battery that is just 2 inches in height and 1 inch in diameter. The hypothetical lifetime in this use case is over 40 years.

B. *Raspberry-Pi Gateway*

This gateway is composed of an RS2 mote, the same type as the transmitter mote, acting as a sink node and connected to a Raspberry Pi. Internet connection is achieved using a 3G modem. The total consumption of the whole set-up when the modem is active is about 300mA. The operating voltage is 5V— and this is standard across most single-board computers that can be used for this purpose. The mote and modem run on parasitic power from the Raspberry Pi. In a deployment with a typical 45Ah 12V Lead-Acid battery, we have powered the set-up for about 6 days. One advantage is that the battery has enough energy to permit recharge while maintaining operation. Using lithium-ion batteries in such a deployment presents some challenges. First, their nominal voltage is lower than 5V. The solution for this is two-fold. The first way is to use boost converter to bring the voltage to 5V. The challenge with this approach is that current spikes when accessing the cellular network may shoot up to 2A. Most boost converters that can handle such a current, such as the MAX15037, LTC1700, TPS61175, RT8509, LM2587 and others, either have a minimum input voltage that is higher than the minimum voltage of the batteries, in which case some battery charge will be wasted, or they are not readily available as plug-and-play modules. The latter case means designers must invest sufficient development time to create a custom module based on these ICs. The second way is to increase the voltage by using a series connection. The challenge with using this approach is that it requires the two extra electronic devices. The charge-balancing circuit, which is standard when charging a series-connected battery pack, and a buck converter to bring the voltage down to 5V from ~5.4V—8.4V. These issues with Li-ion batteries make it even easier to eliminate any consideration of Nickel-based, Alkaline and Zinc-based batteries, which have lower nominal voltages and fewer recharge cycles.

The Lead-Acid battery requires a buck converter and a charge controller. It must be also kept cool and with a constant charge level. There are also important cost implications. Li-ion batteries cost about \$5/Ah and Lead-Acid batteries cost only about \$1/Ah in East Africa.

Because the set-up is ever on and perpetually connected to the internet, frequent deep discharge is very possible. Using supercapacitors can avoid this and has been tested in [23], with Lead-acid batteries as backup. This approach is rather expensive though. To achieve their ~50Wh supercapacitor battery pack with EDLCs from Maxwell Technologies, a leading manufacturer, will cost about \$1,000 using current pricing [24]. A 270F LIC holds about 0.38Wh and costs \$35. Thus, implementing the same capacity using LICs will cost over \$4,000.

What is clear is that the selection of an energy storage solution for outdoor environment monitoring devices consuming over 1W rests on a number of factors that must be examined on a case-by-case basis. If the fundamental requirement is maximizing on-time at a low cost, then Lead-acid batteries should be used with the necessary optimizations. If cost is not a major obstacle, and focus is on maximizing the operational lifetime of the device then supercapacitors and Li-ion batteries can be considered.

C. *Ultra-Low Power Gateway*

The challenges with high power gateways have led us to design a very low power gateway implementing only core functionality. The design guidelines to follow when designing such a gateway and a reference implementation have been published in [25]. In this implementation, the sink node is the same RS2 mote and is directly connected to a 3G uplink module. The current implementation consumes ~14mA and lasts about 6 days on a single charge of a typical 18650-type 2200mAh Li-ion battery or a 22650-type 2000mAh $LiFePO_4$ battery. This means that with a properly sized energy-harvesting unit for recharging, the batteries will only partially discharge and there will be more recharge cycles than those specified in Table 1. Using LICs for this use case is possible but expensive. Two 270F LICs in parallel (equaling 0.38Wh x 2) can sustain the deployment for about 24 hours. It is good practice, however, to oversize the storage to account for days with poor sunshine. Using four LICs would cost about \$140, as opposed to \$10 for the Li-ion battery we have tested. We believe that the advantages of LICs do not outweigh the cost in this use case. In hot environments, the self-discharge may go as high as 35% [18] and hence a similar fudge factor should be considered during battery sizing.

V. CONCLUSIONS AND FURTHER WORK

This paper has given a literature and experience-based analysis of factors that must be considered when selecting batteries in Environment Monitoring wireless Sensor Networks, more so in rural African environments. We have shown that engineers must always consider the electrochemical and physical properties of the energy storage options as well as the geographical and human constraints that deployment environments impose on their selection.

There are further research avenues that we are testing. LICs have shown superior self-discharge performance at room temperature, but it is still unknown how high temperatures affect this characteristic. Knowledge of this behavior would provide more insight into their reliability when deployed in very hot areas.

Other emerging technologies, such as the Aluminium-ion battery have been developed [26] are preliminary results show very fast charging speeds, up to 7000 recharge cycles and high gravimetric capacity, which we have shown to all be core for environment monitoring. The authors are interested in active research to test the limits of these emerging technologies when they become available.

REFERENCES

[1] ADCON Telemetry, September 2006. [Online]. Available: http://www.rshydro.co.uk/PDFs/Adcon/A733-manual.pdf. [Accessed 2 October 2017].

[2] DAVIS Instruments, December 2004. [Online]. Available: http://www.davisnet.com/product_documents/weather/manuals/VP2_Updater_UserGd.pdf. [Accessed 2 October 2017].

[3] WIMEA ICT Project, Makerere University, 2013. [Online]. Available: www.wimea.mak.ac.ug.

[4] M. Mafuta, M. Zennaro, A. Bagula, G. Ault, H. Gombachika and T. Chadza, "Successful deployment of a Wireless Sensor Network for precision agriculture in Malawi," in *2012 IEEE 3rd International Conference on Networked Embedded Systems for Every Application (NESEA)*, Liverpool, 2012.

[5] M. MASINDE, A. BAGULA and M. NZIOKA, "SenseWeather: Sensor-Based Weather Monitoring System for Kenya," in *IST-Africa 2013 Conference*, Nairobi, 2013.

[6] T. Torfs, T. Sterken, S. Brebels, J. Santana, R. v. d. Hoven, V. Spiering, N. Bertsch, D. Trapani and D. Zonta, "Low Power Wireless Sensor Network for Building Monitoring," *IEEE SENSORS JOURNAL,* vol. 13, no. 3, pp. 909 - 915, 2013.

[7] M. T. Lazarescu, "Design of a WSN Platform for Long-Term Environmental Monitoring for IoT Applications," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems,* vol. 3, no. 1, pp. 45-54, 2013.

[8] J. Gutiérrez, J. F. Villa-Medina, A. Nieto-Garibay and M. Á. Porta-Gándara, "Automated Irrigation System Using a Wireless Sensor Network and GPRS Module," *IEEE Transactions on Instrumentation and Measurement,* vol. 63, no. 1, pp. 166 - 176, 2014.

[9] V. Jeličić, T. Ražov, D. Oletić, M. Kuri and V. Bilas, "MasliNET: A Wireless Sensor Network based environmental monitoring system," in *2011 Proceedings of the 34th International Convention MIPRO*, Opatija, 2011.

[10] C. Alippi, R. Camplani, C. Galperti and M. Roveri, "A Robust, Adaptive, Solar-Powered WSN Framework for Aquatic Environmental Monitoring," *IEEE Sensors Journal,* vol. 11, no. 1, pp. 45-55, 2010.

[11] W. Wang, N. Wang, E. Jafer, M. Hayes, B. O'Flynn and C. O'Mathuna, "Autonomous wireless sensor network based Building Energy and Environment Monitoring system design," in *2010 International Conference on Environmental Science and Information Application Technology (ESIAT)*, Wuhan, 2010.

[12] F. Ongaro, S. Saggini and P. Mattavelli, "Li-Ion Battery-Supercapacitor Hybrid Storage System for a Long Lifetime, Photovoltaic-Based Wireless Sensor Network," *IEEE Transactions on Power Electronics,* vol. 27, no. 9, pp. 3944 - 3952, 2012.

[13] WIMEA-ICT Project, "WIMEA-ICT Project Data," 2015. [Online]. Available: http://wimea.mak.ac.ug:10004/. [Accessed 30 Jan 2018].

[14] D. Linden and T. B. Reddy, Handbook of Batteries, New York: McGrawHill, 2010.

[15] Taiyo Yuden Co. Ltd, "TAIYO YUDEN Lithium Ion Capacitors," [Online]. Available: https://www.yuden.co.jp/include/english/solutions/lic/LIC_White_Paper_Final.pdf. [Accessed 3 October 2017].

[16] Battery University, "Comparison Table of Secondary Batteries," Cadex Electronics Inc, 11 04 2016. [Online]. Available: http://batteryuniversity.com/learn/article/secondary_batteries. [Accessed 3 October 2017].

[17] Tayio Yuden Co. Ltd, "Cylinder Type PAS Capacitor," Tayio Yuden Co. Ltd, Tokyo, 2012.

[18] Battery University, "Elevating Self-Discharge," [Online]. Available: http://batteryuniversity.com/learn/article/elevating_self_discharge. [Accessed 30 Jan 2018].

[19] Tadiran Batteries, "Compare Lithium Cells," [Online]. Available: http://www.tadiranbat.com/compare-lithium-cells.html. [Accessed 3 October 2017].

[20] F. Leng, C. M. Tan and M. Pecht, "Effect of Temperature on the Aging rate of Li-Ion Battery Operating above Room Temperature," *Nature (Scientific Reports),* no. 5, 5 August 2015.

[21] M. Nsabagwa, M. Byamukama, J. Sansa-Otim and E. Kondela, "Towards a Robust and Low-Cost Automatic Weather Station," *Elsevier Journal of Engineering in Economic Development,* (Accepted), 2017.

[22] Radio Sensors AB, [Online]. Available: www.radio-sensors.com. [Accessed 1 October 2017].

[23] R. Olsson and B. Pehrson, "Powering Devices Using Ultra-capacitor batteries," in *AFRICON2015*, Addis Ababa, 2015.

[24] DigiKey Electronics, "Maxwell Technologies BCAP3000 P270 K04," [Online]. Available: https://www.digikey.com/product-detail/en/maxwell-technologies-inc/BCAP3000-P270-K04/1182-1021-ND/3079285. [Accessed 13 October 2017].

[25] M. Byamukama, J. N. Nannono, K. Ruhinda, B. Pehrson, M. Nsabagwa, R. Akol, R. Olsson, G. Bakkabulindi and E. Kondela, "Design Guidelines for Ultra-low power Gateways in Environment Monitoring Wireless Sensor Networks," in *AFRICON 2017*, Cape Town, 2017.

[26] M.-C. Lin, M. Gong, B. Lu, Y. Wu, D.-Y. Wang, M. Guan, M. Angell, C. Chen, J. Yang, B.-J. Hwang and H. Dai, "An ultrafast rechargeable aluminium-ion battery," *Nature,* no. 520, p. 324–328, 2015.