Battery Technologies for Unattended Monitoring Systems

Recommendations for current and future systems

Chemical Sciences and Engineering Division

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EXECUTIVE SUMMARY

A review of battery technologies was undertaken to identify those that could be used as part of the Uninterrupted Power Supply (UPS) for an Unattended Monitoring System (UMS). The costs associated with servicing and replacing batteries is a significant contribution to overall IAEA expenses. The current suite of batteries in use must be replaced every 2 years; this adds effort, shipping and disposal costs. An extension of the battery lifetime by a factor of at least three would reduce costs and allow for expanded UMS deployment. The results of this study clearly show that this is possible for some batteries.

<i>Characteristic</i>	<i>Lithium</i>	<i>NiMH</i>	<i>Tesla</i>
Direct DC	Possible	Yes	Yes
Expected Lifetime	12 y	5-10 y	10 y

Two different battery chemistries were evaluated: lithium based batteries and nickel metal hydrides. Each battery has various advantages and drawbacks. Lithium ion, while having a higher energy density and limited availability as a UPS, has additional shipping regulations that can complicate logistics. NiMH are ubiquitous worldwide but are generally heavier and exist as battery packs rather than as a UPS. While neither system can cover the entire mission space, a combination of the two technologies can provide ample coverage. Larger UMS systems may benefit from the increased stability of NiMH if shipping regulations become too burdensome. However, the higher density of lithium-ion products is more suitable for small form factor operations (i.e., Seals such as: EOSS, RMSA).

Finally, a new concept was explored based on the commercially available Tesla Powerwall. The concept is to provide a centralized UPS for multiple UMSs within a single facility. This removes the need to replace UPS systems in each of the individual cabinets (for large systems) or to provide reliable power to seals when in a defined storage space (to prevent discharge of the backup battery). This type of installation can reduce the amount of time spent replacing batteries by centralizing the operation.

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ACRONYMS AND INITIALISMS

ANL	Argonne National Laboratory
ARC	Accelerated Rate Calorimetry
BMS	Battery Management System
BNL	Brookhaven National Laboratory
COTS	Commercial off The Shelf
EOSS	Electronic Optical Sealing System
IAEA	International Atomic Energy Agency
Li	Lithium
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
MNC	Lithium Nickel Manganese Cobalt Oxide
MUND	Mobile Unit Neutron Detector
NCA	Lithium Nickel Cobalt Aluminum Oxide
NDV	Negative Delta Value
NGAM	Next Generation Adam Module
NGSS	Next Generation Surveillance System
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
OLEM	Online Enrichment Monitor
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RMSA	Remote Monitoring Sealing Array
SOC	State of Charge
TCO	Total Cost of Ownership
UMS	Unattended Monitoring System
UPS	Uninterrupted Power Source
VPN	Virtual Private Network
VRLA	Valve-Regulated Lead Acid

1 INTRODUCTION

1.1 NEED FOR BATTERY TECHNOLOGY

As of 2014, over 150 unattended monitoring systems (UMS) and 1300 cameras are currently deployed and play a critical role in the ability of the International Atomic Energy Agency (IAEA) to draw efficient and effective safeguards conclusions on nuclear material. The battery systems are required to maintain capability during facility mains power outages and transients. While the IAEA negotiates that their systems receive mains power that is backed up by uninterruptible power supplies using batteries and/or diesel generators, situations still arise where power is interrupted. The IAEA has stated that battery replacement in UMS is a driving factor in the cost of maintenance and has requested battery solutions that are intrinsically safe, and that reduce the cost of logistics and disposal, especially airline regulations [1]. These factors indicated that a review of current and near-to-market battery solutions must be undertaken.

1.1.1 COST DRIVERS

Battery maintenance is a heavy economic burden on the IAEA UMS team. Most industrial batteries used by the UMS are only guaranteed for two years. Since these systems are located around the world, battery replacement travel costs are expensive. Battery life extension is an important contributor to reduced operational costs.

1.1.2 SAFETY DRIVERS

In addition to the cost of constantly replacing lead-acid based batteries, there is the added hazard of working with the batteries themselves. Under normal circumstances, the batteries are a known and easily handled item. However, they are heavy, contain toxic and regulated material (lead), and contain large amounts of acid if depleted. Replacement with lighter, longer lasting materials is therefore not only a cost but also a safety consideration. The replacement devices should be intrinsically safe for operation and shipping as well as for extended operation in highly regulated nuclear facilities.

1.2 METHODOLOGY

Prior to examining the battery technologies that can replace traditional battery backup systems, a survey of current safeguards technology was completed. This survey paid particular attention to system power requirements and any existing battery systems. This was followed by reviews of Commercial off the Shelf (COTS) technologies that could address the power needs in the event of a total mains power loss. The current specification for lifetime to maintain a UMS is targeted at 48 hours. Any extension of this time is also a benefit to maintain robustness of these monitoring systems

1.2.1 BATTERY NEEDS FOR CURRENT UMS SYSTEMS

A review of safeguards technology was completed by Pacific Northwest National Laboratory (PNNL) with input on power specifics from the other study participants. This study was focused on equipment that support the main UMS device (camera, detector, etc.) as well as the device. A standard UMS cabinet will include a mains feed with breaker, data generators (number

dependent on need), collection computer, watchdog, the uninterruptible power supply (UPS), and virtual private network (VPN) adapter. Table 1 provides a list of the current UPS modules employed by the IAEA. Table 2 lists the power requirements for current UMS hardware. The operating voltage, current draw and backup power timeframe will narrow the options in selecting COTS batteries.

Table 1 - Technical specifications for current UPS used by the IAEA

<i>Equipment</i>	<i>Voltage</i>	<i>Current</i>	<i>Power</i>	<i>Capacity</i>
NGSS UPS Module	12 VDC output	2.5 A		5.4 Ah
APC 2200	140-230 VAC		2200 W	
APC 2200 APCRBC117				600 Ah
APC 1500	160-286 VAC		1500 W	
APC 1500 APCRBC115				300 Ah
APC 750	151-302 VAC		750 W	
APC 750 APCRBC116				312 Ah

A review of the power and battery requirements for UMS was completed to capture all relevant power information as a full unattended system employs several pieces of equipment. To better understand the battery capacity requirements, consider three examples; a system of eight MiniGRANDs, the ATPM, and a NGSS installation with four cameras. Using the calculated battery capacity requirements in Table 1, we can determine the total battery backup capacity needed to run the entire system.

1. A system consisting of eight MiniGRANDs would also include one PIP10, one GBS Watchdog and one Juniper VPN. The total required battery capacity for this system is approximately 1,600 Wh or 156 Ah at 12 VDC.
2. The ATPM consists of 2 DF868 flow meters, one NetScreen VPN, and one PIP10 (as placeholder for industrial computer and RAID) requires approximately 3300 Wh or 315 Ah.
3. A NGSS with four cameras includes four DCM-C5 cameras, four DCIs, and one NGSS data consolidator. Thus, the total required battery capacity for such a system is approximately 6,600 Wh, or 550 Ah at 12 VDC.

Table 2 - Technical specifications for current UMS hardware

Equipment	Voltage	Current	Power	Required Battery	Capacity¹
NGAM	85-240 VAC 12 VDC	10 mA		6 Wh	0.5 Ah
Neumann DCI	11-24 VDC	~360 mA @ 12 VDC	4.3 W Max	206 Wh Max	17 Ah
DCM-C5	85-240 VAC 9-36 VDC	~1.25 A @ 12 VDC	15 W Max	720 Wh Max	60 Ah
NGSS Data Consolidator	110-220 VAC	5.0 A Max		2880 Wh Max	
MiniGRAND	5 VDC	90 mA		22 Wh	4 Ah
MiniGRAND LVPS	115-230 VAC 12.3 VDC	34 mA		20 Wh	2 Ah
MUND	12 VDC	10 mA		6 Wh	0.5 Ah
ATPM DF868	100-130/200-265 VAC 12-28 VDC	~1.67 A @ 12 VDC	20 W Max	960 Wh Max	80 Ah
OLEM Collection Node	24 VDC	~1 A	25 W	1200 Wh	50 Ah
EOSS	5-18 VDC	6 mA		144 Wh	12 Ah
RMSA	5-18 VDC	6 mA		144 Wh	12 Ah
Netscreen 5XP/XT	5 VDC		7.5 W	360 Wh	72 Ah
Juniper SSG5 ³	12 VDC	0.5 A		346 Wh	24 Ah
MPL PIP10	8-28 VDC	~1.67 A @ 12 VDC	20 W	960 Wh	80 Ah
GBS Elektronik	10-15 VDC	100 mA		58 Wh	5 Ah
Watchdog	20-28 VDC	50 mA			2 Ah

¹ Over 48-hour period unless otherwise indicated

² Over 2000-hour period

³ As measured by Jim Garner and Jim Younkin, personal communication

1.2.2 REVIEW OF COMMERCIAL TECHNOLOGY

This report will look at two different battery chemistries (NiMH and Lithium) as well as a new application for commercially available, large-scale batteries. Each technology will be evaluated with respect to the energy density of the battery, general battery characteristics and reliability, and will conclude with a recommended technology (or application set in the case of the Tesla system).

2 NICKEL METAL HYDRIDE TECHNOLOGY

2.1 OVERVIEW

Nickel Metal Hydride (NiMH) batteries are a ubiquitous battery design that have been used in applications ranging from solar-powered yard lights to electric and hybrid vehicles. It is a chemistry that offers many advantages over competing chemistries along with a few disadvantages.

The primary chemistry of the positive electrode is a derivation from the well-known NiCd batteries and is usually a Ni-foam paste. The negative electrode utilizes Hydrogen absorbing alloys that contribute to their high energy density, higher capacity and longer service life. NiMH cells are designed with an oxygen-recombination mechanism that slows the buildup of pressure caused by overcharging. The discharge characteristics depend on factors such as capacity, voltage, and discharge rate, discharge termination, matching of cells in the battery pack, internal resistance and temperature. When testing NiMH battery packs, the results can change dramatically with variations in temperature, charge rate, discharge rate and number of cells in the pack. Increased capacity increases the demand for faster charging and leads to higher charge rates. Care must be taken to ensure a complete charge but minimize the potential damage due to overcharging. Charge control requires proper charge termination using time, voltage or temperature. NiMH batteries must be properly stored to minimize the self-discharge effects of unused batteries. This requires both temperature control and inventory management. A fully discharged battery will last in storage as long as a fully charged battery so they can be stored in any state of charge. Properly storing NiMH batteries requires practicing good inventory management including inventory rotation, temperature and humidity control. [2] [3]

Table 3 - NiMH Battery characteristics

Advantages	Disadvantages
<ul style="list-style-type: none">- Desirable power density- High relative capacity- Heat tolerant- Safe- Thermally stable (does not catch fire if overheated or overcharged)- Do not require safety systems- Low toxicity- Environmentally friendly- Less expensive than Li-Ion- Can be stored in any state of charge- Nickel content makes recycling profitable	<ul style="list-style-type: none">- Possibly susceptible to memory effect- High self-discharge rate- Must incorporate safety vents for gas generation- Less energy storage- Degradation in excessive heat- Inability to be used at temperatures below 14°F (-10°C)

2.2 ENERGY DENSITY

The specific energy density for NiMH material is approximately 70 Wh/kg (250 kJ/kg), with a volumetric energy density of approximately 300 Wh/L (360 MJ/m³). This is about 50% better than NiCd, but only about 60% the density of Lithium ion. Figure 1 is a comparison chart that illustrates the volumetric and gravimetric energy densities based on bare battery cells [4].

The chemical company BASF through its efforts claims to have improved NiMH batteries and as of 2015 had been able to double the amount of energy the batteries can store, making them comparable to Li-Ion batteries. Current research may improve these batteries to increase energy storage by an additional eight times. [5] [6].

Figure 1 - Battery energy density comparison.

2.3 CHARACTERISTICS

One of the more important characteristics of NiMH is that they are safer than Li-Ion cells because they do not contain flammable liquids that can catch fire if they are overcharged thereby eliminating the need for Li-Ion type safety systems. Like most battery types, these batteries must be protected from heat extremes to prolong their service life.

Most commercial NiMH batteries have a nominal terminal voltage of 1.25V during operation. Full charge, no load terminal voltage can range from 1.4-1.5V depending on manufacturer and slowly falls off during discharge until it drops precipitously around 1.1V [7] [8].

NiMH batteries are shipped uncharged and must be charged and conditioned prior to their first use. A fully discharged battery will last in storage as long as a fully charged battery. Therefore, it can be stored at any state of charge. Proper storage of NiMH batteries requires both temperature control and inventory management. [2] [7] [8].

NiMH batteries can be damaged by overcharging which can generate oxygen and hydrogen. There are vents built in to the top of NiMH batteries that are used to relieve the pressure of these gases. The vent is resealable and will close when the pressure returns to normal.

The so-called “memory effect” seen in NiCd batteries causes a decrease in the terminal voltage of the battery if charged from a partial-charge state due to issues with the cadmium electrode. This does not always affect NiMH batteries.

The typical number of recharges available vary greatly from application to application and manufacturer to manufacturer. There are usually several hundred cycles available.

Over-discharge can lead to severe battery degradation. This is where one or both electrodes are so deeply discharged that the electrode voltage reverses polarity that causes the battery to exhibit a reversed terminal voltage. Shutdown of the instrument needs to occur prior to this state being reached [7].

2.4 CHARGING REGIMEN

NiMH batteries require more attention when charging than NiCd batteries but are easier and safer than Li-Ion [7] [8] [9]. In general, a NiMH charger can safely charge a NiCd battery but a NiCd charger will overcharge a NiMH battery. The battery remains cool and charge efficiency is nearly 100% up to approximately 70% charge after which its temperature begins to rise to the full 100% charge. Rapid charging is a broad term that typically means charging at a rate equal to the amp-hour rating of the battery. For example, if the battery were a 2.5A-H device, the charging would require a 2.5A input and would be charged in approximately 1-1.5 hour. The battery would receive this charge up to a predetermined point (perhaps 70-80% charge) after which a more gradual charge with a different algorithm would be employed.

Multiple rapid charging algorithms are employed to determine the battery state and the end-of-charge. The best and most reliable approach, referred to as the negative delta V (NDV) approach, is to monitor the terminal voltage throughout the charge (which should be continually increasing) and to begin a termination procedure when the voltage begins to decline instead of increase. NDV can be used with a NiCd in a relatively straightforward manner as the signal change (5mV or less per cell) is readable at a charge rate of 0.3C or above. It will terminate at approximately 85-95% of full charge but does not work as well with the NiMH at lower charge rates (since the NDV signature is not as strong and must be employed at 0.5C or greater).

Another rapid charging approach is to utilize the rate of internal battery temperature rise (or $\Delta T/\Delta t$). This is safer and more accurate than simply looking at the actual temperature since the temperature is higher in the core of the battery than on the sides and usually some combination of these are used in so-called ‘smart’ chargers.

After rapid charging is terminated, trickle charging, while not recommended, can be employed but must be carefully controlled in NiMH batteries because the battery can deteriorate due to the excess charge. The trickle charge current needs to be reduced to less than 0.05C or else the battery temperature will increase and cause battery deterioration. Ultimately, the trickle must be shut off within 10-20 hours to ensure no battery damage. A preferred method is to utilize intermittent timer charging which monitors the terminal voltage and starts charging at 0.1C when a lower set point is reached. It then stops when a higher set point is reached.

2.5 CURRENT NiMH BATTERY MARKET

Panasonic offers a variety of back-up batteries for emergency use or back-up use, and a pair for infrastructure. The emergency use / back-up series batteries come in standard battery sizes, AAA, AA, A and C, and the capacity ranges from approximately 0.5 Ah to 3.7 Ah at 1.2 V. This type has been designed for an extended battery life, up to 10 years, and can operate in temperatures as high as 60°C. As these batteries supply a smaller nominal voltage and current, several would need to be combined into a battery pack to fulfill the instrument backup power needs. The infrastructure batteries both have a 90 Ah capacity, but have different footprints and nominal voltage; either 1.2 V or 12 V. The latter could be used as a drop-in replacement for current lead-acid batteries. [10]

Energizer also offers rechargeable NiMH batteries in standard battery sizes under the Recharge® product line. The PowerPlus models provide approximately 0.7 Ah at 1.2 V in a AAA battery up to 2.5 Ah capacity at 1.2 V in a D-sized battery. However, these have a limited lifetime – up to 5 years. Again, these batteries would need to be used in a battery pack to provide the instrument backup power.

2.6 RECOMMENDED TECHNOLOGIES

It is recommended to investigate the use of the Panasonic NiMH batteries as they would provide a better return on investment given their longer life span. The emergency-use batteries would be used in a battery pack for smaller instruments. The infrastructure battery could be used for high current equipment or groups of instruments placed near one another.

3 LITHIUM TECHNOLOGY

In this section, we will compare lithium ion batteries with the commonly used traditional valve-regulated lead acid (VRLA) batteries for UPS or UMS. Many factors of the two types of batteries have been studied and compared in the literature. A comparison of the two types of batteries in energy density, charge/discharge capabilities at different temperatures, calendar life, energy efficiency, self-discharge rate, hazard assessment and cost will be presented.

3.1 OVERVIEW OF LI-ION BATTERIES

Li-ion batteries have been used commercially for more than 20 years in various applications such as cell phones, laptops and electric vehicles. Like all batteries, a lithium ion battery consists of a positive electrode (cathode) and a negative electrode (anode). In between the electrodes, the electrolyte is used to shuttle the lithium ions during charge and discharge. Unlike VRLA batteries and nickel metal hydride batteries, which are water-based systems, li-ion batteries utilize organic solvents for electrolytes, which provide a larger voltage window, which enables increased energy density, but at the same time also raise concerns on the safety of the li-ion batteries due to their flammable nature.

It should also be noted that unlike VRLA batteries, which utilize lead/lead oxide (in aqueous sulfuric acid) as the electrode material, different li-ion batteries utilize different materials in the electrodes in order to achieve the optimal performance for a certain application. For example, the most common materials used in the cathode of li-ion batteries include lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) and lithium nickel cobalt aluminum oxide (NCA). The common materials used in the anode of li-ion batteries include graphite and lithium titanate (LTO). Therefore, when li-ion batteries and VRLA batteries are compared below, the material chemistry type of the li-ion batteries will be specified.

3.2 ENERGY DENSITY

Table 4 compares the technology between VRLA batteries and li-ion batteries (NMC/LMO blend as the cathode) for UPS application [11]. Additional comparisons on typical performance ranges of li-ion battery cells and VRLA battery cells being used in UPS applications can be found in Donovan [12].

One thing to notice is the much higher energy density that can be provided by the li-ion batteries. According to Table 4, the volumetric energy density of li-ion batteries of choice (NMC/LMO blend as the cathode) is 2.5 times the energy density of VRLA batteries. The gravimetric energy density of the chosen type of li-ion batteries is more than 3 times that of VRLA batteries. This much higher volumetric energy density indicates that a lot less volume is required for li-ion batteries to accommodate the same energy needed in comparable VRLA batteries. The re-claimed space can be used towards other more productive uses. The much higher gravimetric energy density indicates that a lot less mass is required for li-ion batteries to accommodate the same energy. The less mass reduces the requirement to the floor loading capacity and reduces the need to reinforce the battery room [11].

In general, li-ion batteries offer higher voltages per cell (2.7-4.2 V) than a VRLA battery (1.7-2.4 V), as shown in Table 4. This higher and broader voltage range can decrease the number of cells required to configure a single string so that point of failure can be reduced.

Due to the high energy density of li-ion batteries, another advantage of li-ion batteries is that they can be designed as power cells or energy cells, whereas VRLA batteries can only be designed as energy cells due to the limitation of the battery chemistry and technology [13]. A power cell is designed to provide a large amount of power in a short amount of time during which time most of the capacity of the battery is used. An energy cell is designed to provide a relatively small amount of power over a long time.

Furthermore, these references also indicated that comparative to VRLA batteries, li-ion batteries provide a longer calendar life and need a shorter recharge time.

Table 4 - Technology comparison between VRLA battery and li-ion batteries (NMC/LMO) for UPS applications [11]

<i>Item</i>	<i>Valve Regulated Lead Acid</i>	<i>Lithium Ion Battery (NMC/LMO)</i>	<i>LI/VLRA</i>
Volumetric Energy Density	100 Wh/L	250 Wh/L	250%
Gravimetric Energy Density	40 Wh/kg	150 Wh/kg	375%
Discharge Efficiency	100% @ 20-hr rate	100% @ 20-hr rate	100%
	80% @ 4-hr rate	99% @ 4-hr rate	123%
	60% @ 1-hr rate	95% @ 1-hr rate	158%
Cycle Life	1,000 cycles at 50%	>4,000 cycles at 80%	~400%
Calendar Life	5-7 years	10-15 years	~200%

Figure 2 shows the relationship between energy and power density for different types of batteries [12]. The downward curve for each line shows the limitation of the battery to supply its full energy capacity at shorter runtimes. Comparing the relative positions of li-ion batteries and lead-acid batteries, one can conclude that when high power is needed, li-ion batteries can provide higher powers without sacrificing its full energy capacity. For a UPS system requiring the batteries to supply a high power, using lead-acid batteries may require having an oversized energy battery solution in order to achieve the power output needed, whereas using li-ion batteries may require a “right-sized” power battery solution [12].

Figure 2 - Relationship between energy and power density of different battery types. Reprinted with permission from Gigaom [26]

Figure 3 compares the charge/discharge capabilities of VRLA batteries with two common types of li-ion batteries: LFP/C (lithium iron phosphate as the cathode and carbon-based material as the anode) and LMO/LTO (lithium manganese oxide as the cathode and lithium titanium oxide as the anode) [13]. The normalization was confirmed by considering the capacity measured with 1C-rate at 25°C as the base value for each type of batteries. It can be observed that both LFP/C and LMO/LTO li-ion batteries present very stable capacity independent of the considered C-rate and temperature. On the other hand, VRLA batteries only have good performance in terms of delivered capacity at low C-rates. The effect of temperature on the VRLA batteries are also much more prominent. In conclusion, li-ion batteries are able to provide much more stable capacity at different rates and temperatures.

Figure 3 - Normalized discharged capacity versus current rates for VRLA, LFP and LTO at various working temperatures [13].

3.3 SERVICE LIFE AND CALENDAR LIFE

Service life is the estimated time a battery will last before it reaches 80% of its energy capacity under the real-world conditions it will be used in [12]. Since service life is based on specific conditions the battery will be used in, service life has no real specifications. VRLA batteries have a service life in the range of 3-6 years whereas li-ion batteries can have a service life of up to 10 years [12]. A longer service life for li-ion batteries means less cost for servicing and replacement comparative to VRLA batteries.

Calendar life is the estimated time a battery will last if it were to remain trickle charged for its entire life without power outages at a specific temperature [12]. For UPS applications, batteries will not be charged and discharged at a daily basis but instead are maintained at a high state of charge. Therefore, having a long calendar life at full or close-to full state of charge is very important.

The VRLA batteries are expected to have a calendar lifetime of 5 years at a fully charged state and standard working temperature (25°C) [13]. An increase from the standard working temperature would result in a decrease of the calendar life of VRLA batteries. A rule of thumb for a stationary VRLA battery kept at a constant state of charge (float life) says there is a 50% reduction in life for every 8°C increase in temperature above optimum 25°C [14]. The li-ion batteries show a longer lifetime expectation. For li-ion batteries, the lifetime at 50% state of charge (SOC) and 25°C working temperature is estimated to be 20 years for LFP batteries and 25 years for LTO batteries [13]. The lifetime at fully charged state and the same 25°C working temperature decrease to 12.6 years for LFP batteries and 15.75 years for LTO

batteries [13] [15]. Figure 4 shows another example of how temperature and state of charge affects the calendar life of li-ion batteries (lithium cobalt oxide as the cathode, carbon-based material as the anode) [16]. For 100% state of charge, the calendar life is not significantly affected by the state of charge until the storage temperature reaches 35°C. At lower state of charge, the influence of temperature on the calendar life of the battery is even less. Therefore, in comparison, the calendar life of li-ion batteries at fully charged state is much longer than the calendar life of the VRLA batteries at fully charged state.

As discussed above, the lifetime of both li-ion batteries and VRLA batteries is affected by the operation temperature. The temperature of the VRLA battery is usually specified at 25°C for North America and 20°C for rest of the world [17]. Increasing the temperature by 8°C will result in roughly a 50% reduction in service life of the battery [14]. On the other hand, li-ion batteries in general can tolerate higher ambient temperatures better and li-ion service life is less affected by high temperatures than lead acid batteries. As shown in Figure 4, the capacity fade of an NCA/graphite li-ion battery increases by only less than 5% when the temperature is raised from 25°C to 50°C. Many of the li-ion batteries being used in UPSs are designed for higher average temperatures (e.g. 40°C) and are capable of reaching the specified service life at those higher temperatures [23]. The longer service life and calendar life at full state of charge will reduce the frequency of the batteries to be replaced, therefore reducing replacement costs.

Figure 4 - Capacity fade over storage state of charge for different storage periods of an NCA/graphite lithium-ion battery [16]

3.4 ENERGY EFFICIENCY

The energy efficiency is defined as the ratio of discharge energy to charge energy. Since the batteries of UPS need to be charged at all times, a higher energy efficiency means

less energy is required to keep the batteries charged, and therefore reduces the operating losses (i.e. the energy used to keep the batteries charged).

Figure 5 shows the energy efficiency for VRLA batteries and two types of li-ion batteries, LFP and LTO, at different C-rates (0.25C, 0.5C, 1C, 2C, 3C and 4C) and at 25°C [13]. VRLA batteries have the lowest energy efficiency while LTO li-ion batteries show the highest energy efficiency. Since the energy efficiency of li-ion batteries are higher, less energy is required to keep them charged compared to VRLA batteries.

It should also be noted that although li-ion batteries require less energy to keep charged this advantage might be offset by the need of li-ion batteries to have a battery management system (BMS) to monitor and protect the whole system. The BMS system consumes energy. So overall, the operating losses of li-ion batteries and VRLA batteries may be similar.

Figure 5 - Energy efficiency versus C-rate obtained at 25°C for three batteries (VRLA, LFP, and LTO) under test [13]

3.5 SELF-DISCHARGE RATE

Batteries lose their charge capacity when they are stored due to self-discharge. Faster self-discharge results in faster loss of charge capacity and therefore more operation losses to keep the batteries charged.

Figure 6 shows the self-discharge for VRLA battery and li-ion batteries when stored in a thermal chamber at 25°C [13]. A typical VRLA battery will experience self-discharge at a

rate of 4% per month (ca. 0.1 V) at 25°C and therefore requires float charging from the UPS system in order to provide full energy when it is in need [18]. In contrast, li-ion batteries show a much lower self-discharge rate. As an example, NMC/LMO (nickel manganese cobalt oxide/lithium manganese oxide blend) li-ion batteries experience a voltage drop of 0.023 V per month at 25°C, thus only requiring intermittent charging [11]. Float charging of li-ion batteries was also studied and showed that life degradation due to float charging was barely distinguishable after 50 weeks of testing period [11].

Figure 6 - Amount of self-discharge for VRLA, LFP, and LTO batteries after 1 day at 25°C [13]

3.6 HAZARD ASSESSMENT AND MITIGATION STRATEGIES

Lead acid batteries and lithium ion batteries are both capable of going into thermal runaway in which the cell rapidly heats up and can emit flames and dangerous fumes [12] [19] [20]. Thermal runaway occurs when the rate of internal heat generation exceeds the rate at which the heat can be dissipated into the environment [20]. Thermal runaway can occur due to many causes including [20] [21]:

- use of batteries in high temperature environment
- external shorts due to faulty wiring
- a defect inside the cell which results in internal short circuit and local heat accumulation at the location of the defect
- mechanical damage to the cell or battery which leads to internal short and heat generation

- improper electrical connection at the tab of a battery

When thermal runaway occurs, flammable gas and excessive amount of energy can be released. Explosion can happen if the gas is ignited. On a cell level, the likelihood of such an event is higher for lithium-ion batteries as it has a higher amount of energy in a smaller volume, and usually contains a flammable electrolyte. However, many efforts can be made to make li-ion battery systems safer.

Since occurrence of such event can be extremely catastrophic for large battery systems, it is very important to assess the risks. In this section, detailed hazard assessment for li-ion batteries will be discussed and compared with lead-acid batteries. Ways to improve safety of li-ion batteries will then be discussed.

3.6.1 HAZARD ASSESSMENT FOR LI-ION BATTERIES VS. VRLA BATTERIES

3.6.1.1 Thermal runaway temperature

Thermal runaway temperature of VRLA batteries happens at lower temperature compared to li-ion batteries. Figure 7 shows the typical thermal behavior of a lead-acid battery. Figure 7a shows the situation where the heat generated is well-balanced by the heat dissipation to its surroundings. In this case the temperature rise is well controlled and stops at a certain moderate temperature. Figure 7b shows the situation that the internal heat generation exceeds the heat dissipation. In this case, the temperature rises dramatically and reaches a temperature above 60°C. At a high temperature of above 60°C and under some critical conditions (such as high floating voltage or electrolyte saturation) the battery can go into thermal runaway.

When it is anticipated that the VRLA batteries will be subjected to elevated temperatures (greater than 92°F) during float charging, the charging voltage should be reduced to minimize the potential for thermal runaway [20].

Figure 7 – Generalized thermal behavior of a lead-acid battery showing the normal, controlled temperature rise (blue) and out of control temperature rise (red) due to insufficient heat dissipation to its surroundings. Data Source: [19]

In the case of li-ion batteries, the thermal runaway happens at higher temperatures.. Figure 8 shows the Accelerated Rate Calorimetry (ARC) test result for a commercial li-ion battery at 4.2 V charged state. At approximately 100°C, the self-heating rate increases dramatically and the cell goes into thermal runaway. The thermal-runaway temperature of Li-ion batteries varies with different choices of the electrode chemistry. The specific thermal-runaway temperature of a Li-ion battery should be verified with the manufacturer.

Figure 8 - Generalized cell temperature for a 18650-type cell when undergoing thermal runaway at 4.2 V. Data Source [27]

3.6.1.2 Gas generation during thermal runaway

Thermal runaway of VRLA batteries occur when the batteries are kept at elevated float voltage or is overcharged in a full recombinant mode in which all of the overcharge energy results in heat [20]. Figure 9 shows the hydrogen gas evolution and the oxygen recombination efficiency (RE) at different cell power. When the float voltage is at 2.65 V, hydrogen gas evolution greatly increases and the recombination efficiency greatly decreases. The generation of more gas with poor recombination efficiency will be accompanied by the generation of significantly more energy, which makes the VRLA batteries more prone to thermal runaway.

In the case of thermal runaway in VRLA batteries, the gas products are hydrogen and oxygen. In some cases, minute amounts of hydrogen mix with electrolyte and form hydrogen sulfide (H_2S). The human nose is very sensitive to hydrogen sulfide, capable of detecting hydrogen sulfide at levels as low as 0.005 to 0.02 parts per million [14]. While there is some evidence of risk from long-term exposure to hydrogen sulfide, there is no evidence of risk from short-term moderate levels of exposure. The biggest concern with thermal runaway of VRLA batteries is the off gassing of hydrogen and oxygen and possible ignition of the gas and explosion. Hydrogen becomes flammable when it reaches the lower explosive level (LEL) at approximately 4% concentration of air. Furthermore, hydrogen gas is very light and always rises, making it difficult to contain. With well-designed power systems and facilities, the accumulation of hydrogen can be prevented. Standard practice is to control accumulation of hydrogen in cabinets or rooms to below 1% concentration. The valves on the VRLA battery itself are designed to prevent flames entering the battery and causing an internal explosion.

Figure 9 – Hydrogen evolution rate (blue, circle) as a function of cell watt output. Cell temperature is indicated next to data points, log-log plot. Hydrogen-Oxygen recombination efficiency (orange, triangles), lin-log plot. Adapted from data in [28].

For li-ion batteries, the cells produce gases (from side reactions) that build up within the cells when thermal runaway occurs. However, since li-ion batteries use organic solvents instead of water (as in lead acid batteries and nickel metal hydride batteries), the composition of the gas generated can be more complicated, containing both toxic and highly flammable gasses. Furthermore, the organic solvents may also be ignited, causing further generation of gas and significant energy.

The amount of gas vented during a thermal runaway event for a 7.7 Wh pouch cell at three different states of charge, with the volume reported in reference to standard atmospheric pressure and temperature (80°F), can vary from 0.10 L/Wh at 50% SOC to 0.78 L/Wh at 150% SOC [21]. It shows that the higher the state of charge, the larger the amount of gases released. The main components of the gases generated during a thermal runaway event of a 7.7 Wh lithium-ion pouch cell was found to be hydrogen gas (~30 vol. %), carbon dioxide (~30 vol. %), and carbon monoxide (~20 vol. %) [21]. The other gases generated were various hydrocarbons (methane, ethylene, propylene, hexanes, ethane, etc.), which are also flammable. In addition, carbon monoxide and some of the hydrocarbons are not only flammable, but also pose significant health hazards. For large battery packs where the battery modules are often contained in an enclosure, an explosion can occur when the uncombusted vented gases mix with remaining air in the enclosure or with fresh air, that enters the enclosure from vents and openings, and the mixture is further ignited by an ignition source such as a failing cell.

3.6.2 MITIGATION strategies FOR THERMAL RUNAWAY OF LI-ION BATTERIES

3.6.2.1 Choosing the right electrode chemistry type

First, the likelihood of thermal runaway for lithium-ion batteries depends strongly on the choice of electrode materials. As an example, lithium cobalt (and nickel, manganese) oxides are more prone to thermal runaway than lithium iron phosphate (LiFePO₄). Therefore choosing the right electrode material/chemistry type is very important; various chemistries

have different performance metrics. For example, LCO and NCA cells have the best specific energy but LFP has the best specific power [23]. The review by Schneider electric gives several important metrics including a safety analysis, which refers to how resistant the chemistry is naturally to entering an uncontrolled state or thermal runaway situation. On the other hand, even with a material that is more prone to thermal runaway, thermal runaway can be prevented with proper cell packaging, manufacturing quality control, as well as a proper battery management system that will be discussed below.

3.6.2.2 Mitigation technique to mitigate consequences of gas generation

Despite the large presence of carbon dioxide, the combustion properties of the vented gases are similar to typical hydrocarbons. Therefore, mitigation techniques for mitigating consequences of leaks of hydrocarbons used in the oil and gas industry or in the chemical industry could be modified and adapted to mitigate the consequences of gas generation from events of li-ion cell failures.

Furthermore, if the battery cells are enclosed in a casing, such casing can be designed to be able to contain the pressure rise caused by gas generation, and can include vents that open when the pressure rises above a predetermined threshold in order to mitigate the risks of exposure.

3.6.2.3 Using fire retardant in the electrolyte

Adding fire retardant into the electrolyte has also been shown to improve the safety of lithium-ion batteries. Safety tests were performed on a 200 Ah li-ion cell based on the risks that can occur in a cell-phone base station [22]. The results showed that with a flame retardant there was no explosion, ignition, or thermal runaway, proving that 200-Ah cells containing flame-retardants were significantly improved in safety. Although flame-retardants in lithium-ion batteries show some promise, they have not been utilized in most commercial lithium-ion batteries.

3.6.2.4 Battery management systems (BMS)

BMS further improve the safety of li-ion battery systems. Because li-ion battery systems are much more sensitive to how they are charged and discharged, li-ion battery systems usually include a BMS, which consists of microprocessors, sensors, switches and related circuits. It constantly monitors battery temperature, charge level, and charge rate on the cell level to protect against short circuits and overcharging, and provides the UPS and user with accurate information about the battery status, health and available runtime. The system is also instrumental in protecting the cells from damage by preventing the voltage from going too low on discharge. However, the BMS comes with a cost. Although the BMS makes lithium ion battery systems much safer, they add cost to the solution and drain energy from the batteries, which reduces the efficiency advantages they offer compared to VRLA batteries [12].

3.6.3 CONCLUSION

In conclusion, the thermal runaway temperature of li-ion batteries is higher than that of VRLA batteries, making it less likely to run into thermal runaway at elevated temperatures. However, Li-ion batteries contain more energy in a smaller volume and use flammable electrolyte, therefore a more catastrophic result could happen when li-ion batteries go into thermal runaway. By choosing the correct electrode chemistry type and cell design, using fire

retardant in the electrolyte, and using battery management systems to monitor the system closely, the risk of thermal runaway is further reduced and the safety of li-ion battery systems is greatly improved.

3.7 COST

In order to understand its real potential to be applied in UPS, various Total Cost of Ownership (TCO) analyses between VRLA batteries and li-ion batteries have been calculated in literature. Although these calculations are mostly performed for applications in data centers, they still provide very informative understanding for using li-ion batteries in UMS applications. Information at scales that would be encountered for UMS applications is not readily available; the relative costs should scale with the size of the system and can be used to estimate costs at UMS scales. Two analyses are shown below for 10-year 500 kW system and 10-year 1 MW system from different sources.

3.7.1 TCO FOR 10-YEAR 500-KVA SYSTEM

The case study presented in reference [11] is by Samsung SDI for a 500 kVA backup system that provides 15 minutes of backup time for a Tier IV Data Center. The cost consist of capital expense and operational expense. For capital expense, detailed specification for each battery systems are compared in Table 5. The price used at the time (2015) for an 800 Ah VRLA battery system was \$100/kWh, and \$600/kWh for an NMC/LMO li-ion battery, although it is noted that the price is dependent on the total production volume. The li-ion battery price per kWh is 6 times higher, but since it only requires 30% of installed capacity, the price gap has been reduced significantly. Considering that the price of li-ion batteries is decreasing over the years, the capital expense for li-ion batteries may be further decreased in the future.

For the operational expense, the study focused on the cost spent on maintaining the batteries, which include cost for warranty, cooling, and maintenance of operating batteries. For VRLA battery systems, the calculation of the maintenance and service cost assumes a scheduled preventative maintenance once per quarter by 2 workers for 4 hours, and an additional service cost for analyzing defects due to lack of a battery monitoring device. Since li-ion batteries have a built-in battery management system that monitors and protects the system, maintenance of only twice per year is required (2 hours per visit).

Table 5 – Select battery system specifications for the case study [11]

<i>Item</i>	<i>Valve Regulated Lead Acid</i>	<i>Lithium Ion Battery (NMC/LMO)</i>	<i>Li/VRLA</i>
Cell Capacity	800 Ah	60 Ah	7.5%
Nameplate capacity	768 kWh	255 kWh	33%
Total weight including enclosure	29,800 kg	4,480 kg	15%
Total Volume including clearance	33.54 m ³	6.86 m ³	20%
Total footprint	20.35 m ³	3.50 m ³	17%

Two main cases were studied, which are summarized in Table 6.

- Case 1: UPS battery is discharged once per year. (Emphasis on calendar life.)
- Case 2: UPS battery is discharged once per day (15 minutes). (Emphasis on cycle life.)

Table 6 - Ten-year cost estimate for a data center UPS by Samsung SDI [11]

<i>Expenditure</i>	<i>Case 1</i>		<i>Case 2</i>	
	VRLA	Li-ion	VRLA	Li-ion
Battery Purchase Cost	\$76,800	\$153,000	\$76,800	\$153,000
Installation Cost	\$11,520	\$22,950	\$11,520	\$22,950
Battery Replacement Cost	\$49,920	\$0	\$230,400	\$0
Cooling Cost	\$28,230	\$3,750	\$30,370	\$4,030
Maintenance Cost	\$44,160	\$7,200	\$44,160	\$7,200
Total	\$210,630	\$186,900	\$393,250	\$187,180

No battery replacements are needed for the UPS that used Li-ion since it is assumed to have a 10-year calendar life and 4,000 cycles. Whereas, the VRLA requires one battery replacement for Case 1, and three battery replacements for Case 2 during the 10 year application. In a related study, it was also noted that float charging the UPS that use VRLA batteries adds an additional cost of \$12,300 over the ten years; Li-ion batteries do not require float charging. It can be concluded from Table 6 that considering both capital expense and operational expense, the cost for UPS with li-ion batteries is less than for VRLA batteries for a 10-year 500-kW system.

3.7.2 TCO FOR 10-YEAR 1 MW SYSTEM

Another TCO analysis is shown below by Schneider Electric for a 10-year 1-MW UPS application. Table 7 shows the battery attributes used in the TCO analysis [12].

Table 7 - Battery attributes used in TCO analysis [12]

<i>Battery Attribute</i>	<i>Valve Regulated Lead Acid</i>	<i>Lithium Ion</i>	<i>Li/VRLA</i>
Calendar life at 25°C	5 years	17 years	340%
Battery services life at 25°C	4 years	12 years	300%
Battery footprint	5.4 m ²	2.2 m ²	41%
Battery weight	11,340 kg	2,767 kg	24%
Battery materials cost	\$0.06/W	\$0.12/W	200%

For capital expense, the battery material costs, installation costs, and transportation costs were considered. The operational battery expenses start at year 1 and continue until year 10. Battery maintenance, space lease, and energy costs are incurred every year, while battery refresh costs are incurred at year 4 and 8 (essentially a replacement for VRLA battery). The energy cost in this analysis includes the fixed losses of steady state charging as well as the cooling energy required to reject the heat energy of these losses. Table 8 summarizes these costs for both the VRLA battery and the Li-ion battery. Similar to what was seen in the

previous study by Samsung SDI, the Li-ion battery UPS in this study is the preferred solution over the VRLA battery UPS.

Table 8 - Ten-year cost estimate for a data center UPS by Schneider Electric [12]

<i>Expenditure</i>	<i>VRLA</i>	<i>Li-ion</i>
Battery Material Cost	\$60,000	\$120,000
Installation Cost	\$12,000	\$12,000
Battery Refresh Cost	\$108,790	\$0
Energy Cost	\$26,990	\$13,500
Space Least Cost	\$54,600	\$28,370
Maintenance Cost	\$46,330	\$13,900
Total	\$308,710	\$187,770

3.8 CURRENT LI-ION BATTERY MARKET

Large UPS systems utilizing li-ion batteries that are capable of providing 10-1600 kVA power are already commercially available by Schneider Electric and by Liion for applications such as data centers and facility 3-phase power. In general, these systems are also modular and therefore can be scaled for changing electrical demands. A smaller Li-ion UPS system (500 VA) for office and lab equipment is also available from Schneider Electric.

In conclusion, compared to VRLA batteries, Li-ion batteries show:

1. Increased volumetric and gravimetric energy density, reducing both the space needed and the requirement on floor capacity loading.
2. Better charge/discharge capabilities at various C-rates (especially fast C-rates) and temperatures.
3. Longer service life and calendar life at charged states, reducing the frequency for battery replacement and related battery replacement costs
4. Higher energy efficiency, which reduces the operation losses. However, this benefit may be offset by the energy consumption of the BMS.
5. Lower self-discharge rate, therefore reducing operation losses. Li-ion batteries also do not require float charging since intermittent charging will be sufficient.
6. A higher thermal runaway temperature. Hazard assessment shows that the safety of li-ion batteries can be greatly improved by choosing the appropriate electrode chemistry type, adding fire retardant to the electrolyte as well as monitoring the system with the BMS.
7. A lower 10-year TCO in the case studies for 10-year 500 kW and 10-year 1 MW systems.

4 TESLA POWERWALL™ TECHNOLOGY

We have evaluated the feasibility of the Tesla Powerwall battery system to provide a valid, reliable and sustainable power supply for UMS in safeguards applications. Unattended systems continuously perform a wide variety of qualitative or quantitative measurements of processes throughout the nuclear fuel cycle. As the number of nuclear facilities worldwide continues to increase, the use of UMS to optimize inspection efforts in the field becomes more and more critical. Systems must operate without the loss of safeguards relevant data over extended periods, including at times when the power supply to a facility might be interrupted. As a result, a reliable, sustainable and uninterruptible power supply has become an essential component of most UMS. In this regard, the recently-commercially-available Tesla Powerwall battery system offers a great candidate solution to address the power supply challenges of today's and next-generation UMS.

In this feasibility study, special emphasis was placed on several key parameters: energy density, intrinsic safety, long-term reliability and commercial availability, which are critical criteria for evaluating batteries as the power supply of UMS.

4.1 TESLA POWERWALL SYSTEM

A list of specifications for a Tesla Powerwall is shown in Figure 10 and Table 9. Such a complete system can supply the AC electricity directly to the facility/home during the outage of power supply while the Tesla batteries can be charged by both sunlight and mains grid. A separate battery inverter is not required thanks to the inbuilt DC-AC inverter, simplifying installation and reducing install costs. Furthermore, the Tesla Powerwall is a smart system, which allows the user to monitor the electricity use in real-time from remote computers or hand-held devices. Powerwall can even alert the user when it is preparing for cloudy or severe weather.

Figure 10 - Concept of a Tesla Powerwall 2 system for UMS applications.

Table 9 - Tesla Powerwall 2 AC specifications. [24]

<i>System</i>	<i>Specification</i>
Technology	Rechargeable lithium ion battery with liquid thermal control.
Capacity	13.2 kWh usable capacity (for daily cycle applications)
Warranty	10 years
Efficiency	89% round-trip efficiency
Power	7kW peak / 5kW continuous
Compatibility	Single phase and three phase utility grid compatible.
Grid Frequency	50 and 60 HZ
Operating Temp.	-20°C to 50°C
Ingress Rating	IP67 (Battery & Power Electronics), IP56 (Wiring)
Enclosure	Rated for indoor and outdoor installation
Installation	Wall or floor mount; requires installation by a trained electrician.
Weight	122 kg
Dimensions	1150mm x 755mm x 155mm
Connectivity	Wi-Fi, Ethernet, 3G

4.1.1 ENERGY DENSITY

One of the biggest advantages of Tesla Powerwall is energy density: for a given battery volume, a Powerwall can provide much more power than an equivalent lead-acid battery deployed in current UPS units for UMS. A standard Tesla Powerwall unit can provide the continuous output of 5kW (peak power 7kW) and can power 16 surveillance cameras for around 55 hours in the case of main power outage. That will satisfy the IAEA specification for uninterrupted operation time to maintain a UMS, 48 hours, in the outage of electricity mains. Furthermore, depending on the specific quantities and configuration of the UMS, the Tesla Powerwall battery system can be easily scaled up by connecting multiple Powerwall units together to increase total storage capacity, thanks to Tesla's modular design. It should be mentioned that Tesla recently introduced the second-generation Powerwall 2, which has boosted a further 30% increase in energy density at the battery pack level. Table 10 shows a list of uninterrupted operation time of various UMS equipment, powered by Tesla Powerwall in the event of a mains outage.

4.1.2 DIRECT DC OUTPUT

A power supply with direct output of Direct Current (DC) is desired by the IAEA since all of their UMS operate on DC. The inverter process from Alternating Current (AC) to DC in the IAEA's current UPS creates an inefficient process that reduces the backup time. In this regard, Tesla Powerwall offers a great fit since it provides excellent DC output directly. The voltage range of Tesla Powerwall's DC output is 350–550 V, while its DC Current is 14.3 A (continuous) and 20 A (peak (10s)). It should be noted that this advantage could further save the cost of inverter if one only uses DC output.

Table 10 - Uninterrupted operation time of various unattended monitoring systems (number of UMS items in parentheses), powered by Tesla Powerwall, in the outage of electricity mains

<i>UMS equipment</i>	<i>Operation time via Powerwall (hours)</i>	<i>UMS equipment</i>	<i>Operation time via Powerwall (hours)</i>
Neumann DCI (16)	190	EOSS (100)	122
OLEM (10)	53	MiniGRAND (6)	4,900
GBS Elektronik Watchdog (10)	470	RMSA (100)	122
ATPM DF868 (2)	660	MPL PIP10 (10)	66
NGSS with DCM-C5 Surveillance Cameras (16)	55		

4.1.3 INTRINSIC SAFETY

The intrinsic safety of Tesla battery is at the top level of the commercial on-the-shelf battery products. The National Fire Protection Association recently tested the Tesla battery and the results are very impressive. The National Fire Protection Association indicates that the Tesla battery cannot start a fire: even in the unlikely event (external fire heating around Tesla Battery) that one or a few cells explode, it will be contained within the pod and will not threaten the entire package.

4.1.4 LONG-TERM RELIABILITY

The Tesla Powerwall battery has advanced control parts embedded and can be seamlessly monitored and automatically managed with the software locally or remotely. It should be noted that the Tesla Powerwall provides a warranty of 10 years, which is 5 times longer than the warranty period of current Lead-Acid battery in UMS system. That means a big saving in maintenance/replacement cost in the whole life cycle.

4.1.5 COMMERCIAL AVAILABILITY

Tesla's Powerwall 2 battery is commercially available since its production in Tesla's Gigafactory in February 2017. IAEA emphasizes to take full advantage of available commercial-off-the-shelf battery and power supply technology for UMS. The use of Tesla Powerwall battery for UMS applications fits into this requirement very well.

There are several other companies that provide similar types of battery systems, most based on Li-ion batteries. These include well-known companies such as LG, Nissan, Mercedes, and BMW. [25] While the attributes listed here are specific to the Tesla product, these other large-scale systems would be as acceptable.

4.2 UMS APPLICATIONS

There are many potential applications for the Tesla Powerwall (or similar large-scale systems). The first application is to use them as a power hub to supply the power to a number of monitoring systems simultaneously. This application makes sense in large facilities with multiple UMS systems in place (e.g., Rokkasho in Japan). Using the NGSS as an example, the initial estimates suggest that a single Powerwall could supply 16 NGSS surveillance cameras for at least 55 hours. This is likely conservative as it is based on the maximum power consumption of the cameras. A NGSS setup with fewer cameras would likely last 60 to 100 hours depending on the actual system configuration.

This configuration saves on the replacement time as well. Rather than supplying each UMS with an individual battery backup, which requires a technician to travel to all of the UMS systems with replacement batteries, several units can be wired to a single battery “substation”. This configuration could then be used multiple times within a facility. Each of these cabinets could be placed in a securable location to prevent tampering. In addition, a pair of systems could be used in tandem to allow one to discharge while the other charges. This would prevent from keeping the system at a high SOC for long time.

An alternate use for this system is to provide backups for centralized data storage and transmission centers on site. The secure storage and transmission could be powered long enough on a single Powerwall to allow for at least safe shutdown as well as some data transmission through hard-wired linkages.

Finally, in smaller facilities where fully conditioned power may not be available, the Powerwall could be used to condition and smooth power for safeguards systems that have their own UPS on-board which will prevent early triggering due to ill-conditioned waveforms. In addition, this backup power could help run critical safeguard systems for longer periods if the power restoration time in the State is longer than the required backup power specification from IAEA.

While there are benefits, there are challenges to this concept as well. The first is the switch from power security at the cabinet to the security of the power network. Measures would have to be installed to ensure that the power to the UMS is connected firmly and cannot be easily disabled or tampered with. As the UMS has been pulled back to near the mains power, simply knowing that the UMS is operating is enough to ensure connectivity but additional anti-tampering provisions may need to be taken.

Another discussion is the merit comparison of centralized backup of power supply versus distributed back up. It is possible that a failure of a UPS of this size, in the event of a total failure during a mains outage, would remove large sections of the UMS surveillance at once. Whereas previous failures may have disabled one camera or one detector, this failure would knock out all of the systems on that UPS. Fortunately, the Powerwall’s capability to integrate seamlessly with solar panels could largely lower the possibility of the total failure of UPS.

5 SUMMARY AND CONCLUSIONS

This work has shown that there are multiple battery chemistries with longer lifetimes and higher power densities than the currently used lead acid batteries for larger UMS applications. Depending on the cost and safety requirements, either lithium or NiMH batteries can be used to provide emergency power in the event of mains power losses. For smaller systems, moving to different chemistries will increase the service lifetimes.

Currently, there are commercially available UPS systems that use lithium ion cells available from multiple vendors (APC, Schneider, Toshiba, etc.). Usually, these are configured for a desktop computer though the available power would be suitable for several larger UMS systems. The ability for these systems to output direct DC voltage is possible. Smaller battery systems for EOSS seal-style applications can be found in multiple form factors commercially; the main issue would be matching the available battery voltage to those systems for long-term use.

NiMH batteries are generally more suited for smaller current applications such as seals. However, larger NiMH batteries can be found on the market for certain applications (e.g., portable power tools) and could be easily modified to operate as a UPS system if the need arose. This would involve a cabinet housing for the control electronics with a set of easily removable battery packs. This system would then be able to serve DC voltage directly, if needed. The infrastructure-sized battery from Panasonic can also be a drop-in replacement for lead-acid batteries.

Finally, the use of a large-scale battery backup system to serve as a centralized UPS seems feasible for facilities with large numbers of UMS systems. If issues regarding power cable security and routing over longer distances can be mitigated, then there may be cost savings in that situation. Reducing the service locations from dozens to a few would speed up maintenance and replacement operations.

Table 11 - General Characteristics of Battery Technologies Surveyed

<i>Characteristic</i>	<i>Lithium</i>	<i>NiMH</i>	<i>Tesla</i>
Direct DC	Possible	Yes	Yes
Expected Lifetime	12 y	5-10 y	10 y
Multiple UMS/UPS	No	No	Yes
Small UMS vs Large UMS (i.e. seals vs detectors)	Both	Small	Both
Additional Shipping requirements	Yes	No	Yes

5.1 FUTURE WORK – TESTING OF UMS/UPS SYSTEMS

In order to compare relatively disparate technologies, a testing protocol must be developed for each UPS proposed. Testing protocols will be developed for each individual UPS to mimic the conditions that may occur during the UPS operation such as building voltage fluctuations, repeated short power loss/charging cycles, temperature fluctuations, and so on. Since each UMS works at different locations and experience different interruptions, the testing

for each UPS system should vary accordingly. Of note, even for batteries from the same vendor, each type may behave very differently under interruptions. It is necessary to develop specific UPS abuse testing protocols, which can be programmed in a lab-simulated environment that mimics the anticipated applications for each type of UPS system to predict the battery/UPS life, reliability and safety under abuse.

A fast testing protocol will be developed to drain the battery during a relatively short time at rates equivalent to full load operation. The measured lifetime will be used to predict the battery life under real operation conditions. The data correlations will be analyzed and used to construct a database for future use. The benefits of building a complete UPS abuse testing protocol includes, but is not limited to:

1. A clear understanding of the tolerability and reliability of different batteries/UPS under abuse.
2. Prescreening of the batteries/UPS that will not meet the requirements of UMS.
3. Accelerating the evaluation of battery technologies for UMS applications.
4. Providing guidance to design future UPS systems.

The stress testing of UPS systems only tests the performance of the battery systems. However, the UMS components will need to be tested in line with the UPS to ensure continuity of knowledge and preservation of data. Therefore, the battery technology will be installed in testing locations and subjected to various facility operation scenarios including, but not limited to, voltage fluctuations, complete loss of mains power for extended periods, temperature gradients, and repeated short power loss/charging cycles. The data from the associated UMS systems will be reviewed to ensure no loss of signal has occurred. The data from these tests will be collected in a report.

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