BATTERY SYSTEMS IN A SUBSTATION: MANITOBA HYDRO'S EXPERIENCE WITH ALTERNATIVE TECHNOLOGIES

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Introduction

Utilities use stationary battery systems in substations for such purposes as stand-by power supply or as a power source for communication systems. With stringent limitations on space and increasing requirements for safety and reliability, utilities need to consider new battery chemistries to enable reliable, secure, space-effective, and cost-effective substation energy storage. Despite their higher initial costs, Manitoba Hydro recently began investigating the possibility of employing alternative, high-energy battery technologies for use in specialized applications where otherwise high installation costs would most likely make conventional VLA technologies less competitive. Two examples include using these new technologies in isolated communities, where operations are hampered by high installation, transportation, and maintenance costs and when their small footprints obviate the need to install expensive additional structures such as "Ready-to-Move" (RTM) trailers in particularly cramped substations. Such potential benefits prompted Manitoba Hydro in late 2016 to fund a two-year project investigating the suitability of both Sodium Nickel Chloride and Lithium-Ion batteries, their chargers, and their battery management systems (BMSs) for specific substation standby applications. The purpose of this project was to generate reliable characteristics of the aging process of Lithium-Ion and Sodium Nickel batteries for substation applications by recording and analyzing battery performance in their native substation applications and to determine whether they can be considered viable alternatives to conventional battery technologies. Manitoba Hydro purchased and tested a Lithium-Ion battery system from Saft and a Sodium-Nickel battery system from FIAMM for evaluation purposes.

Although this project is expected to be completed on time, numerous practical issues have emerged to delay the completion of many experiments. This paper will present some of these issues and provide initial data generated while evaluating these new technologies' performance under "real-world" conditions.

Existing sizing procedures

While there is continuous work towards their development, IEEE has not yet published technical guidelines that outline sizing standards for either lithium-ion or sodium-nickel battery systems. In the absence of such technical standards, the batteries for this project were sized using lead-acid technologies and NERC guidelines as a reference point. Although further evaluation will likely determine that new battery technologies require different sizing methodologies than conventional chemistries, they provide a good starting point and enough information for experimentation i.e. Capacity requirements, Current magnitude needs.

The duty Cycle used in Manitoba Hydro's stations is shown on figure 1. Current Magnitudes and the total duration of each section is determined, based on following factors [5]:

- All steady State DC loads
- The worst-case protection events
- The DC loading for each switching device in the station
- Number of switching devices in the station

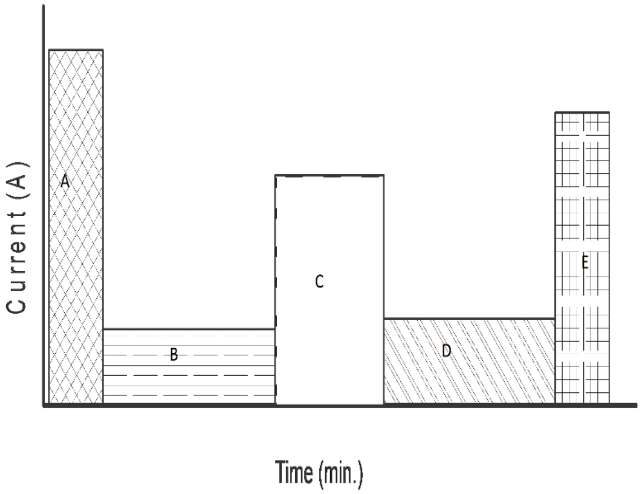


Figure 1. Typical duty cycle station load profile

Table 1. Duty Cycle example		
Section on Figure 1	66kV station	138kV station
A	266A -> 1 min	67A -> 1 min
B	8.1A->239 min	16A ->239 min
C	120A -> 5 min	30A -> 12 min
D	8.1A->234 min	16A ->227 min
E	128.1A->1 min	46A ->1 min

Lithium Ion Installations

The first installation was commissioned in the summer of 2016 at a Manitoba Hydro training center. The location was chosen as it would allow frequent cycling and usage of the batteries in their intended application. The Li-ion system (Figure 2) consisted of three parallel strings each having a 90 Ah capacity. There were five 24 V modules (Figure 3) in series in each string. This installation was suitable for a substation requiring 180 Ah and one string serving as redundancy. The initial float voltage was set to 125V since that is the most common voltage used in substations and it also corresponded to about 80% SOC (State of Charge). The float voltage later changed to 140 V to correspond with 100% SOC.

Figure 2. Li- ion installation

Figure 3. 140 V string

In December of 2017 two additional Li-ion systems were commissioned for experimentation and testing purposes. Four strings of three 24 V modules were each mounted on a rack and placed inside an oven (Figure 4, 5). The strings battery management systems were placed outside the oven to protect the electronics, and to allow for easy connection of the diagnostic tools (Figure 5, 6).It is important to note that cell management is done by electronics inside each individual module and therefore are subjected to increased temperature of the oven. It is expected that exposing the batteries to oven temperatures would accelerate the battery aging process [1]. The oven was set at 60°C which is the maximum temperature recommended by the manufacturer. Each string was stored on a different SOC. Module 1 at 20%, Module 2 at 50%, Module 3 at 80%, Module 4 at 100% and connected to the charger.

Figure 4. String inside oven

Figure 5. Oven-charger-BMS setup

Figure 6. BMS

Lithium Ion Testing

The Battery Management Module (BMM) of the batteries allowed a PC connection and use of diagnostic software to record various battery parameters (e.g. Minimum/Maximum Cell voltage).

As an initial test the values for the instantaneous resistance were calculated after performing a Current-Off Test [2], using the current discharge profile shown on Figure 7 . Although the method is not the most accurate it was chosen for its simplicity and can provide a comparison tool.

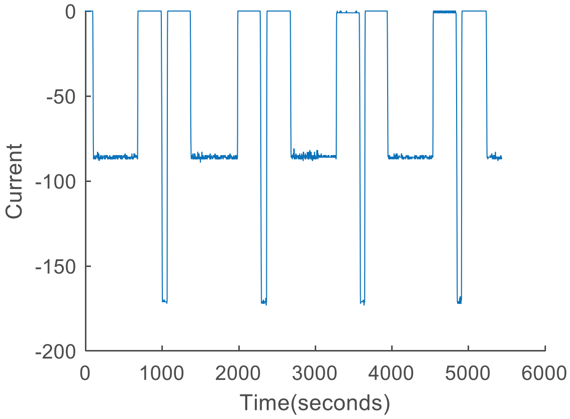


Figure 7. Discharge profile 140V system

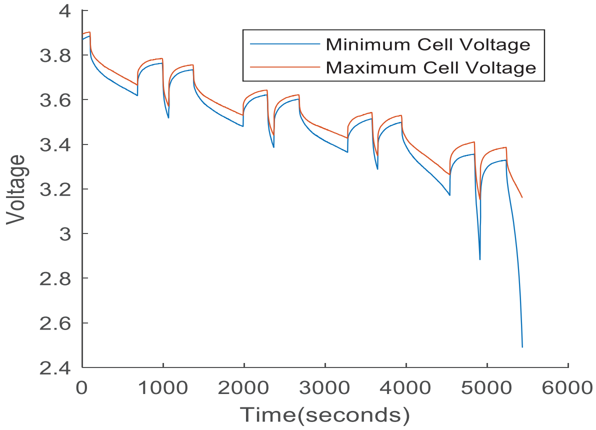


Figure 8. Cell Voltage 15month old batteries

The batteries installed in the Training Centre were periodically completely, 100% depth of discharge (DOD), discharged at 1C (1-2 times a month), and were often used to power a circuit breaker, motor operated disconnects, relays and re-closers. Table 2 shows a comparison between the instantaneous internal resistances after roughly 15 months of usage.

Table2.InstantaneousResistance calculated 15 months apart.

Depth of Discharge (DOD)	New Batteries R(mOhm)	15month batteries R (mOhm)
27%	0.68	0.9
31%	0.62	0.76
49%	0.53	0.75
53%	0.64	0.86
69%	0.36	0.75
73%	0.54	0.85
89%	0.76	1.929
93%	0.86	N/A

Even when factoring in calculation errors from the methodology, and test procedure variations there is a noticeable increase in internal resistance after 15 months. and particularly on higher DOD. The 15-month batteries were unable to complete the intense discharge profile of Figure 7. Internal resistance monitoring will continue to determine the correlation between time used and internal resistance. Eventually we hope to have enough data to develop a model based on Randles circuit [4] to predict and assess batteries performance. It is important to note that batteries installed in the field will be discharged far less often if at all hence the increase of the internal resistance is expected to be a lot lower.

A similar procedure was used for the batteries stored at 60°C. The current off method was again used for the determination of the internal resistance. A different discharge profile (Figure 9) was used, however, and it was tailored to the reduced voltage of a 3-module system (83V).

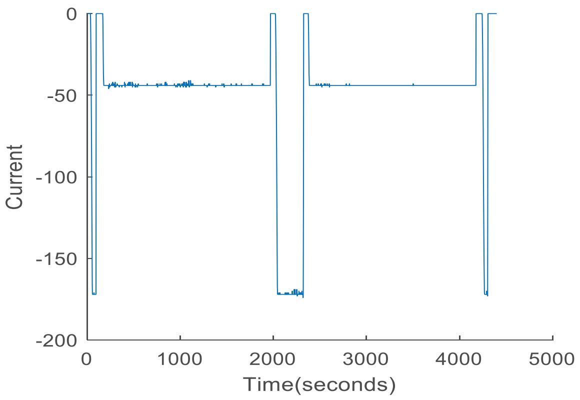


Figure 9. Discharge profile for 83V system

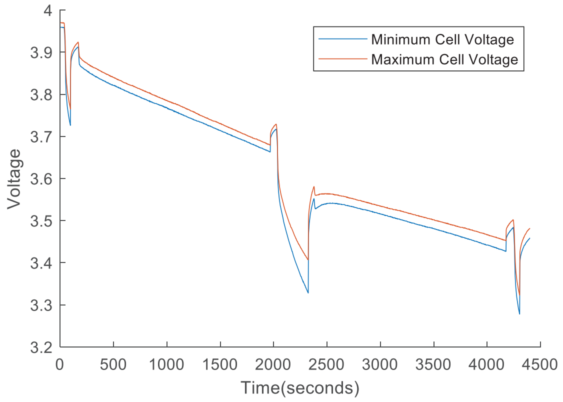


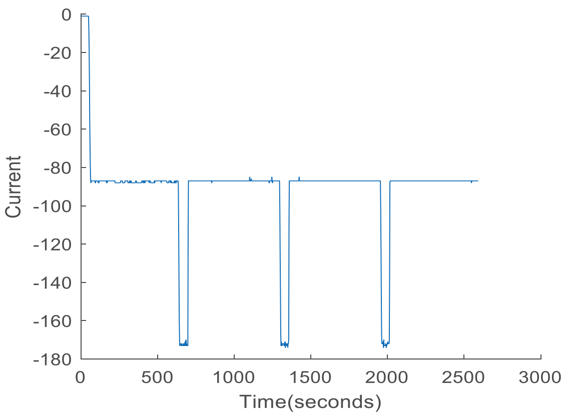
Figure 10. Cell Voltage 83V system new Batteries

Table 3 shows the measured internal resistances of the batteries after being stored at 60°C for two months. The initial results have shown that batteries stored on lower % SOC have a lower internal resistance. Further measurement will be taken to determine if the trend continues although results seem to agree to those obtained by [3].

Table 3. Batteries stored at 60°Celsius

DOD	OVEN 20% SOC R(mOhm)	OVEN 50% SOC R(mOhm)	OVEN 80% SOC R(mOhm)	OVEN 100% SOC R(mOhm)
2%	0.46	0.49	0.68	0.6
30%	0.48	0.69	N/A	0.71
40%	0.63	0.67	0.72	0.65
54%	0.44	0.47	0.67	0.69
59%	0.47	0.51	0.66	0.64

Although performing pulse tests and measuring internal resistances is expected to be of future use in statistical modeling what is also of interest in how batteries perform on a duty cycle following the pattern discussed in the sizing section. Due to time constrains an accelerated and more intense duty cycle was used (Figure 11), over the one normally used in the field.



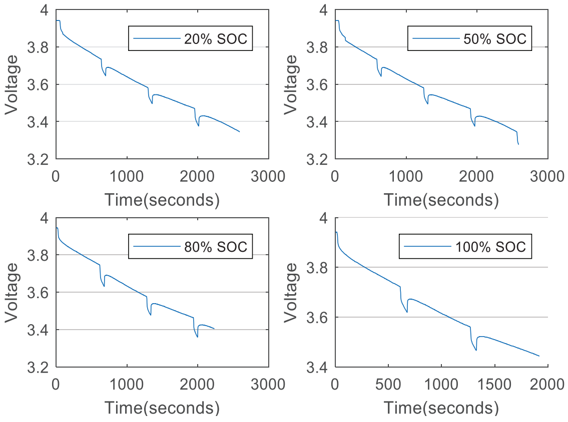


Figure 11. Intense Discharge Current profile.

Figure 12. Minimum Cell voltage for batteries stored at 60°C

As it is expected from the internal resistance discrepancies, the systems performed a lot differently and there are clear differences in the discharge ability of each string (Figure 12). The systems stored at lower SOC (20% and 50%) were able to discharge 67 Ah and 69 Ah before critical voltage. On the other hand the systems stored at 80% and 100 % were only able to discharge 56Ah and 48 Ah. Further tests are required to find the cause of these differences as they are greater than expected. The temperature of the modules was monitored with both the BMS diagnostic software and FLIR infrared camera and there were no large deviations in temperature between modules<2°C.

To further test the difference, the strings stored at 50% and 80% SOC were discharged with 1C from 100% SOC (Figure 13). The discharged capacity was measured as 75Ah and 63 Ah before the critical voltage was reached which is a significant decrease from the rated capacity.

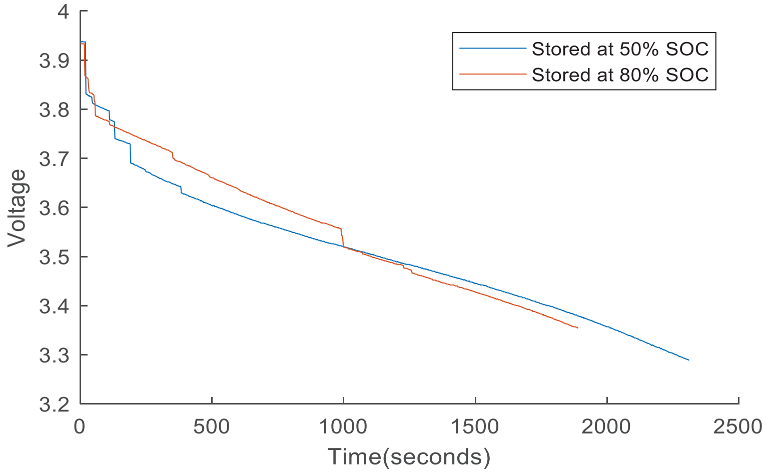


Figure 13. – 1C discharge from batteries stored at 60°C

Sodium-Nickel

The second Chemistry was a Sodium Nickel Chloride battery from FIAMM (Figure 14). The system consists of two modules rated at 110 V with an 80 Ah capacity. Their float voltage was set at 130 V with rest voltage being at 117 V. This was lower than the desired but at the time of purchase there was no option available for the desired substation voltage.

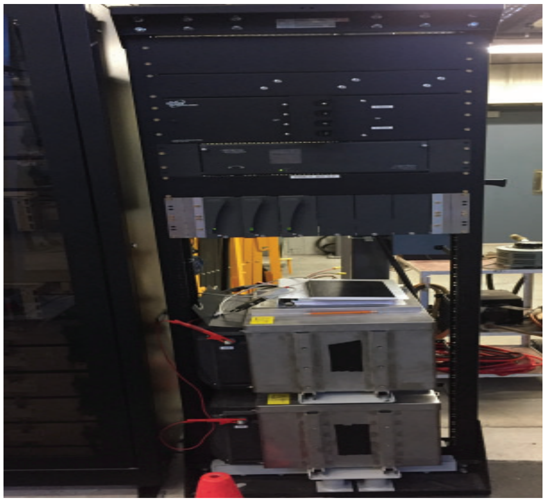


Figure 14. Sodium-Nickel installation

Figure 15. Switch between sodium nickel and li-ion.

Our testing currents were limited to 125 A because of the system internal circuit breaker. The biggest concern with Sodium-Nickel was whether a high current would cause the internal temperature to reach critical values and thus shut down the battery. With our test that was achieved using a current of 110 A for <30 min. Two different load profiles were tested.

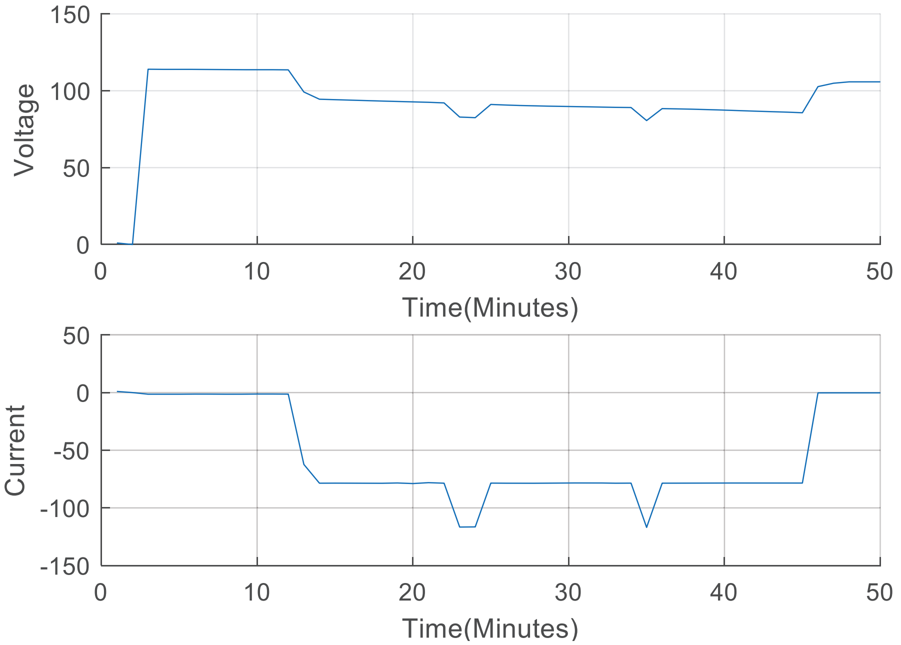


Figure 16. Voltage (Top) and Current Discharge Profile (Bottom)

In this case the voltage dropped from 114 V to 79.6 at the end of the Test after discharging a capacity of 45 Ah.

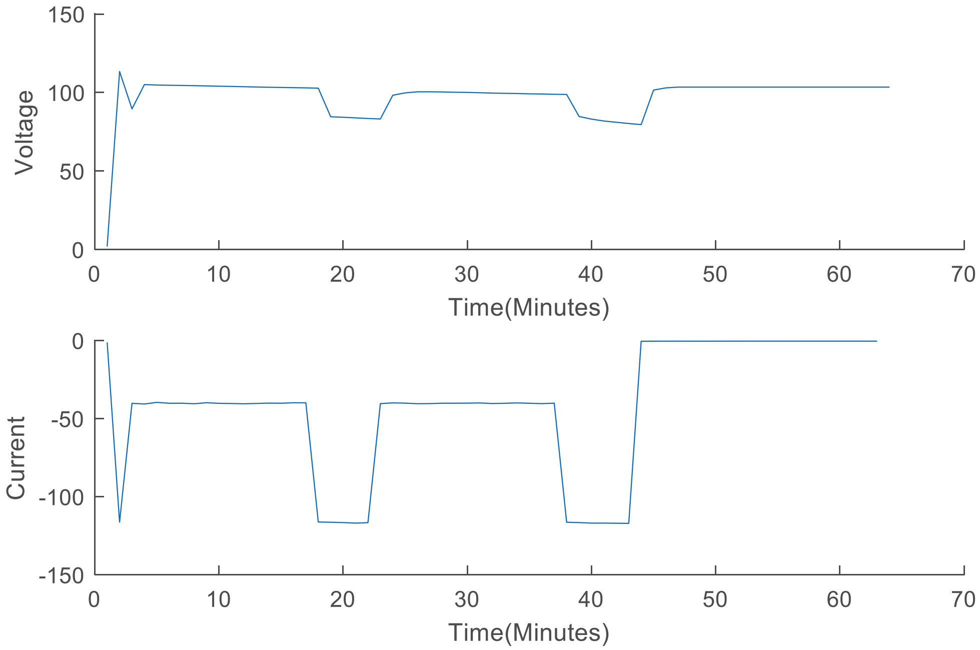


Figure 17. Voltage (Top) and Current Discharge Profile (Bottom)

In this case the voltage dropped from 114V to 85.7 at the end of the Test discharging 43.5Ah.

In both cases the BMM terminated the test. The internal temperatures of 340°C were very close to the disconnect point of 350°C. We are still investigating ways to artificially age the modules and for the time being we are familiarizing with the technology and record data. No significant changes in performance were observed over 15 months, but arguably those batteries were tested less that the lithium-ion but at the same time was the battery of choice of the training crew.

At the training facility the staff tried a close operation on a breaker and the breaker failed to close because the battery was not in the circuit. The technician did not realize that the battery had tripped because there was no indication on the charger or battery. This caused the close coil to not operate and burnt the windings of the coil.

Two more sodium nickel systems are expected to arrive in March of 2018 for testing purposes.

Observations

The needs of a utility when choosing battery banks can be summarized as follows:

- Amp hour sizing
- Physical size (footprint)
- Right voltage
- Life duration guarantees
- Compatibility with different chargers
- Simplicity
- Cost
- Maintenance intervals and procedures

Both technologies are fairly new to the substation bank market and were also new to us thus setbacks, especially under test conditions, were expected. We would like to share some of the difficulties experienced both from testing/planning side as well as a field side. None of the difficulties are insurmountable and are presented to serve as a checklist for other utilities before installing similar technologies.

Lithium-ion

- Difficulties in connecting to diagnostic and recording results
- Unable to connect to individual strings must go through Master Battery Management Module (MBMM)
- In the four string system there is significant back charging between strings, with charging currents in excess of 70A for an individual string.. We are not aware if this is a desired behavior and if it is, why is charging limited to 40 A to protect the system.
- Limited to using a specific charger, fear of future compatibility issues
- No Sizing standards
- Random tripping of strings at the training center location. No testing was being done at the time and when staff would check on the charger an alarm was up indicating a string had tripped. We have yet to determine the cause.

Sodium-Nickel

- Recording intervals high in diagnostic software.
- Difficulties in disconnecting and connecting the two strings
- Less literature available for aging, harder to model behavior and evaluate battery life
- Capacity is affected by discharge current and can make sizing difficult. Maximum capacity is available at C/4
- No Sizing standards

- The battery voltage is only 110 Vdc whereas the station voltage preference is between 125-135 Vdc

Field Experiences
Lithium-ion

- Issues and difficulties with the way alarms are set
- Seems complicated
- Expensive, current system use components that can add significant cost and are unnecessary (e.g. a 200 A circuit breaker)
- Have to bypass the BMS to charge a cell if voltage drops low enough

Sodium-Nickel

- Issues with alarms, although FIAMM did have a solution to bring out an external alarm to wire into a charger digital input. This was tested but the alarm does not appear to work. Currently working with supplier on a solution.
- Charge current limited to 14A. This makes it difficult to achieve the required recharge time of 8-12 hours after a complete discharge.
- There is no need to store batteries under a float charge. Shelf life of stored replacement batteries is not a concern.
- Little to no concern for ambient temperature at the site. Batteries are not affected by high or low operating temperature.

In closing

The market will need batteries with higher power density and both li-ion and sodium-nickel-chloride will be contenders. Both technologies satisfactorily meet substation needs. Further tests are needed to evaluate their long term performance and sizing standards will need to be determined and later published. Our plan is to build a test schedule for the sodium nickel system, to continue li-ion testing and to work on the maintenance standards needed for both technologies. If deemed practical, Manitoba Hydro intended to generate purchase specifications and maintenance criteria for caring for these batteries during their operational lifetimes. Initial failure modes, components, and subcomponents for these apparatus along with Mode/Cause/Task (MCT) analyses and P-F curves are to be developed in order to establish the most effective maintenance tasks and intervals with respect to both system reliability and lifecycle costs. These reliability and lifecycle costs would then be compared to those of vented lead-acid (VLA), valve-regulated lead acid (VRLA), and Nickel-Cadmium ("Ni-Cad") battery technologies. Additionally, specific input parameters and weightings will be required in order to develop Asset Condition Assessment/degradation and Asset Health Indices, which the utility industry is increasingly developing for each of their apparatus in order to establish systematic repair/replace criteria that can be demonstrated to regulatory bodies. As a final point because these battery technologies are intended to be used in an electric utility setting, a set of purchase specifications, tender evaluation matrices, commissioning and maintenance documents will also be required.

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