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High Capacity and Low-Cost Lithium-ion Cell for Peak Energy Demand

(Advanced Clean Power Program)

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High Capacity and Low-Cost Lithium-ion Cell for Peak Energy Demand (Advanced Clean Power Program)

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Notice

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Abstract

Cadenza Innovation (Cadenza) was contracted by NYSERDA to develop a low-cost Lithium-ion cell that would be optimized for the peak shaving market in the State. In response, Cadenza is offering a cell design platform that will allow multiple individual lithium-ion jelly rolls to be packaged in a supercell that will enable cell manufacturers to further reduce the cost of lithium-based storage systems and increase the safety of the system. The combined innovations will allow cell manufactures to build the highest density, lowest cost system with their preferred lithium-ion electrode technologies. These electrode and electrolyte technologies have been used in commoditized 18650 cells and a rich roadmap with materials improvements exists that will drive capacity improvements for many years to come. This multi-roll construction can be referred to as a supercell, as it has some commonality with a module or brick found in cylindrical (18650) cell systems and other similarities with prismatic cells in terms of its high capacity. The benefits of Cadenza's novel packaging arrangement, how this is achieved, the low-cost properties, as well as the testing and verification conducted on the supercell is described in this project summary report.

Keywords

18650; aluminum; architecture; battery; Cadenza; cell; energy density; high density; high capacity; housing; jelly roll; lithium-ion; low-cost; material; module; multi-roll; multi-roll construction; novel packaging; peak energy demand; peak shaving; platform; safety; storage; supercell; thermal ceramic

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Acronyms and Abbreviations

BOM	Bill of Materials
CSG	Core Shell Gradient (Cathode)
LIPA	Long Island Power Authority
NMC	Nickel Manganese Cobalt
NREL	National Renewable Energy Laboratory
PDD	Pressure Disconnect Device
PTC	Pressure, Temperature, Current
REV	Reforming the Energy Vision
SOC	state of charge
NYSERDA	New York State Energy Research and Development Authority

Executive Summary

In this effort, Cadenza Innovation (Cadenza) was contracted by NYSERDA to develop a low-cost Lithium-ion cell that would be optimized for the peak shaving market in the State. In response, Cadenza is offering a cell design platform that will allow multiple individual lithium-ion jelly rolls to be packaged in a supercell that will enable cell manufacturers to further reduce the cost of lithium-based storage systems and increase the safety of the system. The combined innovations will allow cell manufactures to build the highest density, lowest cost system with their preferred lithium-ion electrode technologies. These electrode and electrolyte technologies have been used in commoditized 18650 cells and a rich roadmap with materials improvements exists that will drive capacity improvements for many years to come. This multi-roll construction can be referred to as a supercell, as it has some commonality with a module or brick found in cylindrical (18650) cell systems and other similarities with prismatic cells in terms of its high capacity. The benefits of Cadenza's novel packaging arrangement, how this is achieved, the low-cost properties, as well as the testing and verification conducted on the supercell is described in this project summary report.

For this project, the Li-ion technology platform being designed by Cadenza addresses the peak shaving, multi-hour discharge market segment. The State is targeting the peak-shaving application for a variety of reasons:

- With the expected downturn of fossil-fuel and nuclear plants, the State is targeting shaving the peak of their capacity curve rather than the baseload in order to accommodate future grid needs.
- Utilities are encountering shifting peak patterns from their customer base and requiring more flexibility to respond.
- The application allows developers to meet the goals of Reforming the Energy Vision (REV)¹ by providing a tool to create a more robust and resilient grid.

¹ In April 2014, the State announced its REV process. The initiative seeks to leverage distributed energy resources (DER) to transform the State's electricity grid into a grid of the future. The five-year process plans to accomplish the transformation by utilizing DER devices such as storage, rooftop solar, and additional distributed devices to enhance reliability and resiliency of the grid through controls, two-way communication and electricity flows.

The requirements of this specific application are for a system that is capable of a four- to six-hour discharge time and providing flexible and efficient response to grid operator commands. Finally, due to the number of benefits that can potentially be stacked in such an application, the target application area is considered one of the largest potential markets for storage systems not just in the State, but across North American and global markets as well.

Challenges to Application

The challenge for lithium storage to increase its capacity and duration while simultaneously lowering cost is clear. Increasing the capacity of the battery to meet the application requirements typically invites safety risks or increases the cost of the system. Typically, safety standards are only met by increasing cost and complexity in the end product. In Cadenza's solution, the opposite is achieved. By providing a safe supercell structure, cascading runaway is avoided and simplifications to the system can be made, leading to lowered cost and increased energy density.

Though multi-hour storage systems are offered in the market today with lithium-ion power cells as well as longer duration energy cells such as flow battery systems, there are still significant challenges facing the application. For lithium-ion batteries, with today's traditional cell structures, manufacturers only have the option of increasing cell capacity and inviting safety risks to the system or compensating for the safety concepts by oversizing the number of cells or using add-on safety systems, thus increasing cost. This may solve some of the safety concerns, but will increase the cost and size of the overall system. The market is just now beginning to see the need for longer duration energy cells emerging from a pre-commercialized development stage. However, these cells currently cost more than commoditized lithium-ion cells and introduce performance issues such as a lower AC efficiency and size/footprint considerations. The challenge is to find a means to utilize the fast response, high efficiency characteristics of popular lithium cell technology, but cost effectively push the application profile into the multi-hour application area.

Cadenza's supercell packaging technology aims to provide a pathway for lithium-based storage systems to safely break through the final cost barriers and achieve the discharge duration desired while maintaining the fast response and high efficiency performance characteristics that lithium-ion cells typically provide.

Cadenza Innovation Response

The supercell offered by the Cadenza cell platform achieves this goal through a series of innovations targeting the cost and safety challenges in a lithium system design, while maintaining the performance characteristics of the jelly rolls found in typical lithium-ion technologies. Cadenza has accomplished this goal by developing a platform architecture that:

- Utilizes the current cell chemistry of typical lithium-ion cells in an open, multi jelly roll configuration.
- Introduces an energy absorbing ceramic housing that isolates and insulates the individual jelly rolls, enabling the supercell to safely expand its energy density and achieve high discharge duration.
- Introduces flexible cell/platform geometrical design features, still utilizing low-cost electrode assemblies, which allows developers to more efficiently package the lithium cells and increase overall capacity in a lower footprint.

By combining the high cell capacity, safety, and efficient design innovations, Cadenza's technology enables increased capacity with a safer, lower cost system than manufacturers would be able to design with their typical lithium-ion cells, all while utilizing proven and commercially available system design approaches.

Aligning with New York State Needs and Philosophy

It is critical to note that Cadenza is offering an approach and design that can potentially benefit all manufacturers in the lithium-storage space. Through licensing, Cadenza Innovation is not offering a new lithium chemistry or adding new material into the traditional lithium sealed cell. Instead, the innovations are focused on insulation materials and packaging of a supercell or platform that will enable any manufacturer to maximize the utilization of the lithium cells to drive cost even lower than their initial designs. Hence, as innovations take place in chemistries, this platform reduces the cost of new materials by providing an envelope to further increase the density of the cell in multiple ways. In contrast to modules of cylindrical cells, the Cadenza platforms safely allow the addition of extra electrode wraps and/or height to the jelly roll. In addition, electrode assemblies may simply be packaged more efficiently by reducing the separation between individual jelly rolls, thus increasing the energy density potential of the system design while simultaneously maintaining the safeguards of the system. Such optimization of the jelly rolls is allowed, not only by the enhanced safety of the system, but also by the existing standard equipment (coating, slitting, winding) used in mature, high volume, Li-ion factories.

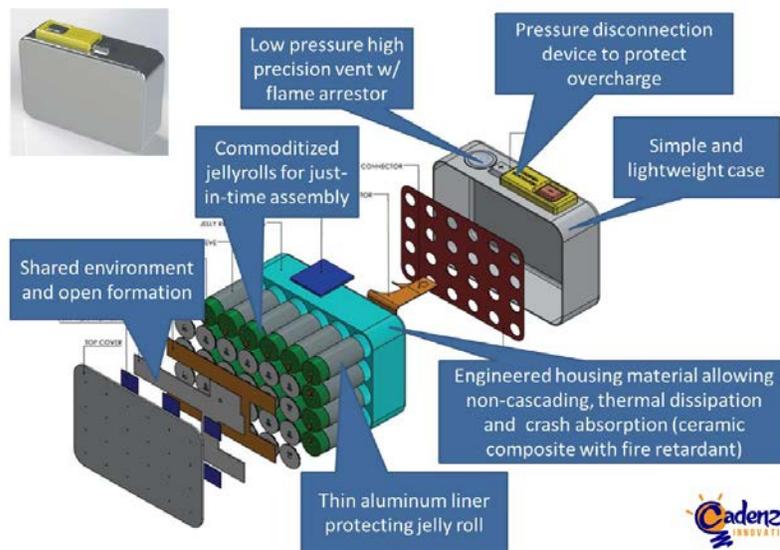
The solution developed by the Cadenza team has enabled designs that are non-cascading in nature, meeting conditions such as those listed by the new standards implemented in February 2016 by Underwriters Laboratory (UL1973), a requirement demanded by many fire departments in the State.

Cadenza believes this approach aligns well with NYSERDA's philosophical approach of investing in areas that can help the industry continue to push the cost curve of storage systems down and benefit industry players.

1 Cadenza Innovation Battery Architecture

Before reviewing the results of the project and the achievement of project objectives, it is important to summarize the design improvements of the Cadenza supercell to understand how the safety innovations of the design allow for higher density cells to be utilized and packaged closer together, increasing the energy output of the lithium-ion system. Typically, such innovations in safety would add to the cost of the system; however, Cadenza achieves these improvements via a design that results in a lowered cost. Figure 1 shows the basic design of the cell.

Figure 1. Schematic of the Cadenza Multi-Roll Architecture Platform (the supercell)



The key elements within this hermetically sealed supercell design are (1) the engineered, composite ceramic support structure that contains the electrode assemblies, in this case in Figure 1, 24 jelly rolls; (2) the open design of the individual jelly rolls combined with the overcharge disconnect and venting safety functions attached to the aluminum case; and (3) the aluminum liner for each of the individual jelly rolls important for both thermal management, as well as individual filling of electrolyte.

This arrangement allows a tighter jelly roll array than is typically found in modules of individual cells, such as 18650 cells. Standard modules deploying standardized cylindrical cells (18650) have a spacing between electrode assemblies that has 50% to 250% wider separation than modules using the Cadenza packaging concept. In addition, this packaging arrangement allows more energy to be placed into each

cavity while maintaining safety functions. This is achieved by adding wraps to the standardized 18650-type jelly roll (increasing width).

The project has optimized the wall thickness of the ceramic support structure, in the format chosen for the prismatic supercell form factor and jelly roll type available, so that energy density is optimized. Any electrode chemistry or capacity improvement can naturally be packaged in the concept using the design rules found by thermal models, resulting in significantly increased energy density. On average, a 20% improvement in energy density can be achieved by packaging jelly roll electrode assemblies tighter, and an additional 10–20% improvement in density can be achieved by increasing the number of wraps and height of the jelly rolls. This is allowed by the sustained safety created by the packaging technology.

The avoidance of nickel-plated steel cans used in 18650 cells improves thermal management in regular operation for the Cadenza concept due to easier control of thermal gradients. In addition, the ability to use one pressure disconnect for multiple electrode assemblies significantly enhances overcharge safety characteristics compared to modules using 18650 cells (individually sealed jelly rolls).

In summary, the enhanced safety cell platform increases the energy density and reduces cost by allowing the following areas of improvements compared to standard Li-ion modules:

- The Cadenza platform allows the individual multi-roll cells to increase in density and energy without introducing additional risk and the need for containing the higher density rolls due to the improved safety capabilities of the ceramic support and overall materials design.
- The safety design accommodates the Cadenza open jelly roll innovative structure, allowing cost reductions by the removal of traditional components used in standard sealed cell technology.
- Jelly rolls can be positioned closer together without increasing the risk of cascading thermal runaway within the supercell. For example, in the Cadenza design, jelly rolls can be placed 1.5 to 2 mm apart throughout the supercell compared to traditional systems that space the cylindrical cells 3 to 5 mm from each other, further contributing to cost reduction.
- The packaging density improvements from Cadenza's platform are not dependent on any individual lithium-ion chemistry. The improvements translate across cells from any lithium-ion manufacturer. A cell can be optimized for the application by creating arrays having a form factor that effectively translates to the pack level geometry. This along with protection from cascading runaway leads to higher pack level packaging efficiency.

The last point provides insight into the tasks and testing prioritized in the NYSERDA project objectives. The confirmation tests focused on proving the safety elements of the Cadenza platform and validating through standard test protocols used by the industry. Tests have shown that the ceramic support has no effect on cycling, life or power performance, which means that the performance of preexisting electrode assemblies (jelly rolls) used in the industry translates precisely to the Cadenza concept, and favorably at an increased energy density. The testing protocols also examined the performance of the lithium jelly rolls in the Cadenza design for life cycles to confirm the performance characteristics of the lithium cells would not materially change. The platform simply allows the individual cells to be packaged in a more efficient manner and provides additional margin for the supercell to increase cell density without introducing risks typically associated with operating high-density arrays of cells. Hence, emphasis in the testing focused on confirming the safety improvements and capabilities of the platform and then confirmed that the performance characteristics of the specific cells were not altered due to the packaging configuration.

Finally, the benefits gained from improving the safety characteristics of the supercell—enabling higher density configurations to be utilized—also result in a lower overall system cost. Traditionally, creating a system capable of containing the potential impacts of increasing energy density usually results in increased cost.

2 Project Objectives and Results

This project focused on Phase 1 of a 3-phased approach to developing the High Capacity Li-ion Cell design for the Peak Energy Demand project. The steps listed for the goals of Phase 1 were the following:

- Design and build a low-cost, high-performance product suitable for six hours peak shaving.
- Validate the supercell's performance and safety using testing protocols equivalent to peak shaving conditions that are typical for the State.
- Prove that a \$125/kWh cost goal is achievable.

These goals were set to be achieved through series of tasks that focused on development of the high-performance supercell, validating design and performance, and confirming the cost targets.

Specifically, the project is comprised of the following cell-related tasks:

- Design of the High-Performance Cell
- Sourcing of Components
- Testing and Validation of Components (cell)
- Assembling Cells
- Performance Validation of the Prototype
- Cost Verification

2.1 Task 1: Design of Cadenza Cell

The combination of tasks one through three confirm the design and validation approach of the Cadenza cell/platform. The theoretical concept of the cell is shown in Figure 1. These tasks address the development and testing of the key components of the supercell design. Summaries of these tasks were submitted to NYSERDA through monthly reports and in-person quarterly presentations. A quick review of the essential components of the design is shown in Figures 2 and 3. Figure 2 shows the ceramic housing as well as illustrates the open-cell jelly rolls that Cadenza utilizes in its design approach.

The components in Figure 2 and 3 show the features that are utilized in the innovative Cadenza supercell design. These features focus on creating a robust supercell that allows lithium cell energy characteristics to be increased without introducing additional safety risks to the cell. The key features are:

- Development of the ceramic support housing, shown in Figure 2. The thermal properties of the housing material are utilized to thermally isolate individual jelly rolls and absorb energy, thereby containing the potentially catastrophic failure of individual jelly roll elements. This feature allows the platform to space the rolls closer together and increase the density and performance characteristics of the cells while reducing cost.
- Cadenza's design incorporates wider, 26 mm diameter lithium jelly rolls to increase the energy capacity of the device. In addition, the open jelly roll design is utilized in this configuration to contribute to further cost reductions.
- Development of the pressure disconnect mechanism is shown in Figure 3. The pressure disconnect device is used to mechanically interrupt the electrical current flow to jelly rolls in case of severe overcharge, is shown in Figure 3. Moving the pressure disconnect safety components from the traditional placement on the individual cell to the outer case enables a lower cost approach while maintaining the basic safety approach to operating lithium-ion systems.
- The case design allows quick venting for the overall supercell. In the case of cell failure, the venting mechanism incorporated into the aluminum case of the entire cell package allows for a safe evacuation of hot and potentially flammable gases from the cell.

2.2 Task 2: Sourcing of Components

Cadenza is developing partnerships with multiple manufacturers to demonstrate the ability to build, replicate, and manufacture the design innovations promoted in the study. For the key areas within the cell platform itself, Cadenza teamed with Morgan Advanced Materials for the ceramic support housing, and with Alcoa (now Arconic) for the design of individual aluminum components.

Alcoa/Arconic also facilitated the manufacture of many of these components through its network of aluminum component manufacturers.

It is important to note that from the outset of launching the supercell design, Cadenza focused on the ability to manufacture supercell at high-mass production levels. Cadenza established supplier relationships and developed components in conjunction with the manufacturers that not only prove the performance capabilities of the components, but also demonstrate the capability of producing the components in high volume at favorable pricing. Competitive quotes were obtained from both U.S. and Asian suppliers, ensuring this sourcing capability is a key element of the ability to transfer innovation concepts to large-scale deployment.

2.3 Task 3: Testing and Validation of Components

Task 3 focused on confirming the performance of the supercell components. Specifically, the validation focuses on showing the safety approach adopted by Cadenza would contain any catastrophic failure of a jelly roll and prevent destructive, cascading thermal runaway from occurring within the supercell platform design. For the specific task, Cadenza validated subassembly testing comprised of the following protocols:

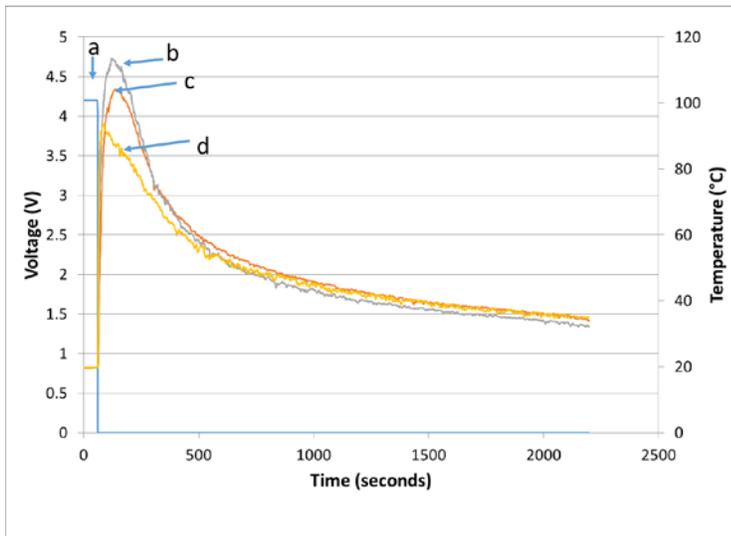
1. Electrochemical test of electrode assemblies (jelly rolls)
2. Electrolyte filling test
3. Helium leak and pressure test of the assembly and overcharge disconnect components, and electrical validation of high current capability with fusing mechanisms
4. Screening test to validate housing material's mechanical and thermal functionality
5. These specific tests were conducted on the Cadenza Vertical 83 Ah supercell and comprised of the following specific tests:
 - Nail Penetration testing
 - Overcharging of System—Validating the Pressure Disconnect Device
 - External short—Freedom Car Criteria
 - Internal Short Circuit Test
 - Shock and Vibration testing
 - Crush Test

The results of the testing are discussed in the following sections.

2.3.1 Nail Penetration Test

Figure 4 shows the results from the nail penetration test of the 83 Ah Vertical supercell, where the cell was penetrated by a 3-mm wide steel nail at a rate of 8 cm/s. The plots show cell voltage (a); temperature near nail penetration location (b); temperature near the top of the penetrated cell (c); and temperature near the vent (d). The results showed only white smoke venting of the gases from the supercell and no cascading failures.

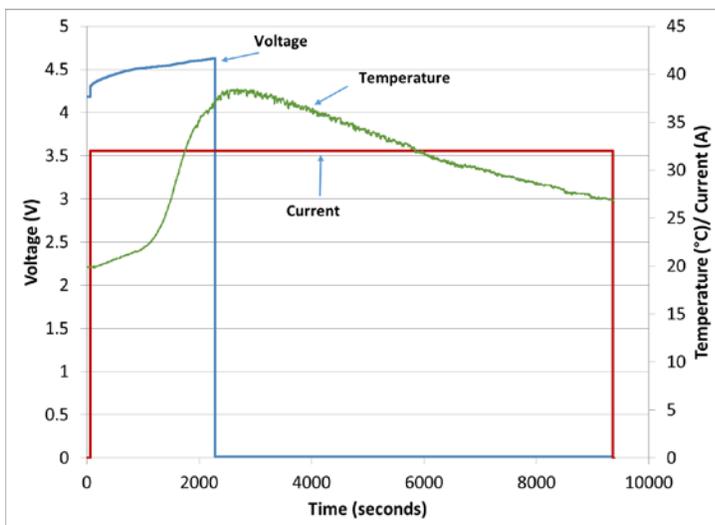
Figure 4. Results of nail penetration on vertical 83 Ah supercell



2.3.2 Overcharge Test—Testing of Pressure Disconnect Device

Figure 5 shows the results of the overcharging test designed to test the pressure disconnect device for the Cadenza supercell case. In this case, the supercell is charged to 100% state of charge (SOC). For this supercell, that equates to 16 amps (C/5), 4.2 V and then charging the devices at 32 amps to 200% SOC. The PDD was expected to activate above 4.6 V. Data from the test is shown in the graph with the PDD successfully activating at 4.63 V and cell temperature maintained below 40 °C.

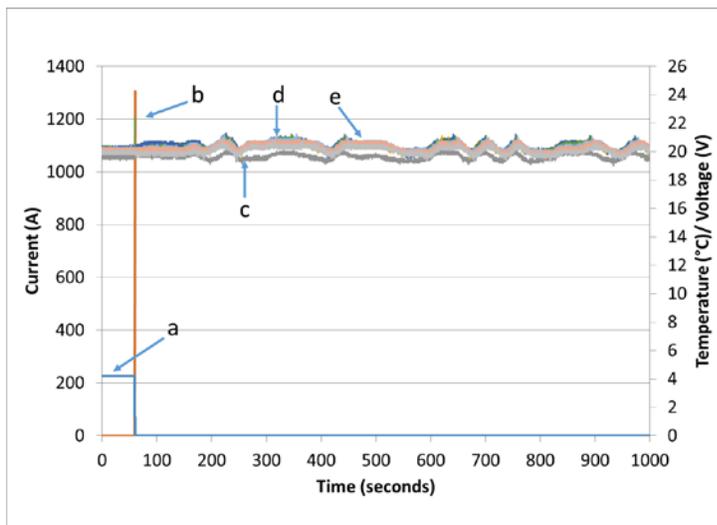
Figure 5. Results for overcharging – PDD activation test



2.3.3 External Short

In this test, cell temperature rise and cell damage are investigated during an external short circuit test. In the test, a short (<1 mOhm) is induced on a 100% charged cell where the temperature of the cell is monitored as an indicator of potential damage to the cell. The short circuit current reached 1300 A upon applying the short mechanism. After applying the short mechanism for 0.2 seconds, both measured current and voltage dropped to zero. This resulted from the activation of the fuse residing at the negative terminal. The chart in Figure 6 shows a plot of temperatures during the test period and indicates the measured cell temperature increased less than 2°C during the test. The plot shows: cell voltage (a); current, and temperature at middle of the cell (b); near negative (c); positive (d); and terminals(e). The temperature fluctuation seen during experiment is normal to the environment of the test, showing no increase from resistive heating due to the high current or fusing mechanism. Except for the activation of the fuse, no other changes in the cell were shown after the test.

Figure 6. Temperature, voltage and current profiles for external short circuit test of 83 Ah supercell at 100% SOC

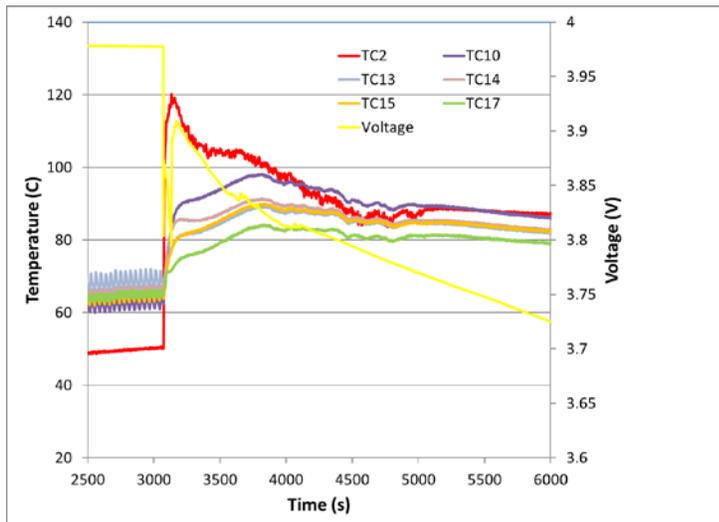


2.3.4 Internal Short Test

The internal short circuit test is designed to assess the ability of the cell design to prevent a cascading thermal runaway event from a faulty cell. An internal short circuit device developed by NREL was incorporated into a Li-ion jelly roll in a specialty 23-jelly roll 80 Ah cell configuration. This cell's jelly rolls are similarly configured to the 24 jelly rolls used in the supercell. The test results in Figure 7 show the temperature of the cells was initially maintained at less than 120°C after the internal shorting was initiated. The supercell only vented, with no cascading thermal runaway. This, along with the nail

penetration result, shows the Cadenza packaging concept protects the supercell from cascading runaway, even when an internal short activates inside one of the jelly rolls. This type of internal short within the electrode assembly is the most common manufacturing defect of the Li-ion industry, sometimes resulting in fire or even an explosion. Such shorts are typically caused by metal particles from the manufacturing environment that have positioned inside the electrode assembly. The Cadenza concept avoids the progression of thermal runaway from one such short-ignited jelly roll to neighboring jelly rolls (referred to as cascading runaway). This allows the decreased spacing between the energy containing elements, which increases energy density of the supercell. The temperature plot in Figure 7 shows that although areas of the cell is heated to above 100 °C, no cascading runaway is initiated that further could increase the heating of the cell in a secondary reaction.

Figure 7. Results from internal short circuit testing



2.3.5 Shock & Vibration Testing

The vibration testing focuses on verifying the robustness of the supercell design by subjecting the cell to a series of vertical, lateral, and longitudinal vibration. The tests assess key components of the supercell design such as the case vent, pressure disconnect device, ceramic housing, individual jelly rolls, and the ceramic housing as well as the internal welds and busbars of the supercell. The objective of these tests was to study cell components following shock and vibration protocols used by the automotive industry to simulate years of operation. Post mortem analysis showed the design objective of a robust and compact design was achieved, as there was no significant damage after testing.

The results are verified through (1) general visual observation and post mortem analysis; (2) Helium leak detection; (3) weighing of the cell; and (4) removing the case vent and checking whether the vent was still able to function. The table in Figure 8 demonstrates the supercell passed testing with only minor impacts to the plastic negative busbar and jelly roll caps. The summary of the results is listed in Table 1.

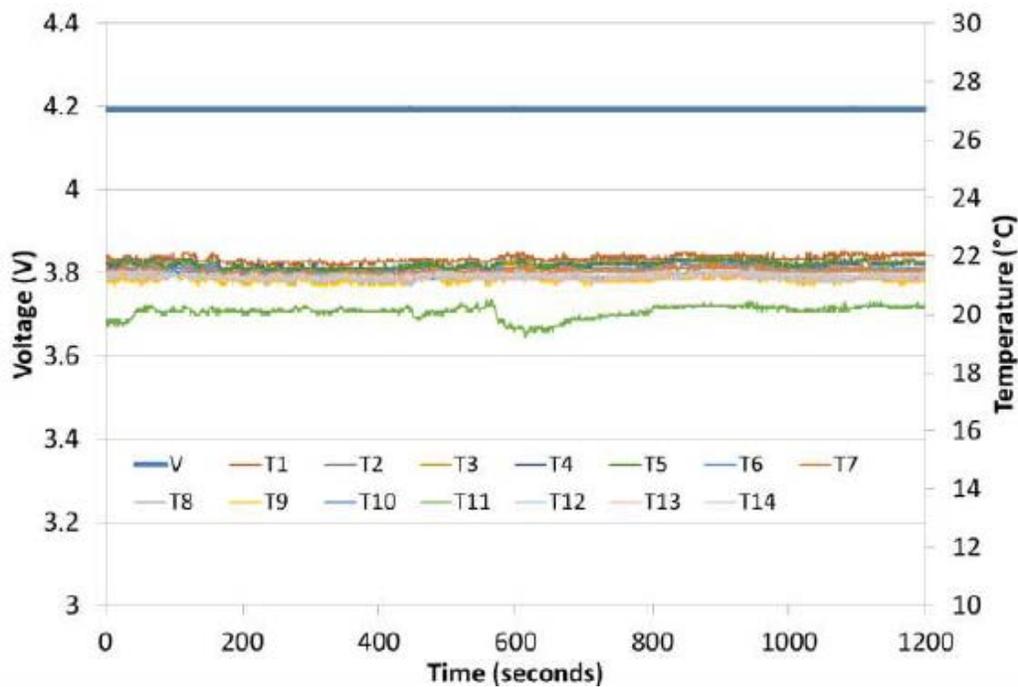
Table 1. Results from Assessment of Shock and Vibration Testing

Items	Any Change	Description
Cu (Copper) busbar/terminal connect welding	No	Pass. All welds intact.
Cu busbar insulator	Yes	Plastic used was 3D printed (known to swell) and not final solvent resistant grade. Require re-test, moved to Phase 2.
Cu tabs and busbar welding	No	Pass. No movements.
Cu Terminal connector and Cu fit-through terminal welding	No	Pass. No movements.
Jelly roll plastic cover	Yes	Plastic used was 3D printed (known to swell) and not final solvent resistant grade. Requires retest and moved to Phase 2.
Flame arrestor adhesion on the case	No	Pass. Stable arrestor position.
Ceramic housing support	No	Pass. No wear areas seen, indicating stable parts with no vibration movements.
Jelly roll and Al (Aluminum) can	No	Pass. In particular no ripping of tab areas.
Jelly roll Al can/Al busbar welding	No	Pass. Laser weld is stable, stable electrical contact.
Al busbar and case bottom welding	No	Pass. Resistance is 1.5 mohm.

2.3.6 Crush Test

Similarly, to the shock and vibration test, the supercell was subjected to a crush test typically used in the automotive industry. This simulates a transportation slow crash situation or the unintentional load of a heavy blunt object. For the crush test, the cell is subjected to 1,000 times its weight at 99.9% SOC. The crush resulted in a vertical compression of about 20% with no shorting issues. After testing, verification is conducted by observing the mechanical properties and monitoring temperature and voltage of the cell. Figure 8 shows the results of the testing.

Figure 8. Temperature and voltage monitoring during crush testing at 1,000x cell weight



The crush test resulted in no observable impacts except for cell deformation. The data in Figure 9 shows the voltage and temperature of the cells remained consistent and indicated no shorting issues.

2.4 Task 5: Performance Validation of the Prototype

The Cadenza team built 110 Ah and 83 Ah prototype supercells containing 24 jelly rolls. The 83 Ah supercell utilized NMC (Nickel Manganese Cobalt) technology and the 110 Ah cell utilized CSG (higher nickel content) technology for the cathode structure. The approach to validating the prototype was to follow a series of test protocols on the supercell and its jelly rolls. These protocols match the peak shaving application performance characteristics being targeted by NYSERDA, in particular capacity and efficiency tests, while thermal tests at various temperatures were postponed to phase 2. These protocols are listed below:

- power testing—capacity
- cycle testing
- Roundtrip Energy Efficiency Test
- Roundtrip Duty Cycle Efficiency Test
- abuse testing (confirmation cell validation testing)—see previous data

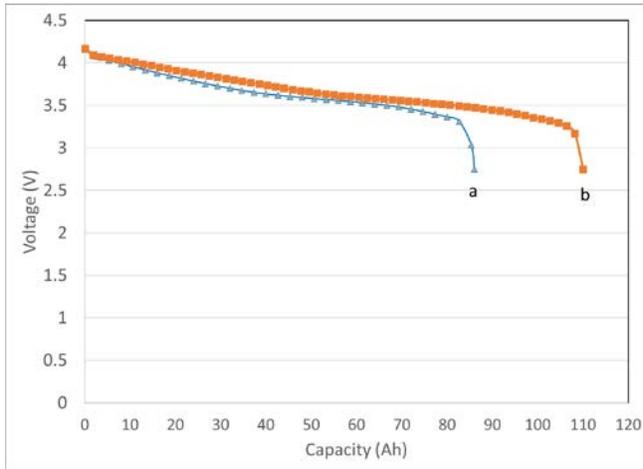
Though listed, the storage vs. temperature and the thermal tests were moved to phase 2 of the development cycle.

As previously stated, the supercell design does not materially change the performance of any particular Li-ion jelly roll technology being utilized. The supercells will maintain the same characteristics in efficiency, capacity, and discharge duration, as observed in single cell configurations. The tests are designed to confirm that the performance of the cells is not degraded, altered, or that the life of the cells is not degraded due to the configuration of the supercell. The testing results are discussed in the following sections.

2.4.1 Capacity—Power Testing

Testing of the cell capacity is shown in Figure 9 for two cells; 83 Ah cell and 110 Ah. In addition to the capacity, the chart in the table shows the average power (watts) for cells at various discharge rates, deploying the two respective electrode technologies. The 83 Ah configuration has NMC cathode and 110 Ah configuration has CSG type (high nickel) cathode.

Figure 9. Cell Capacity of the 83 Ah and 110 Ah Cells

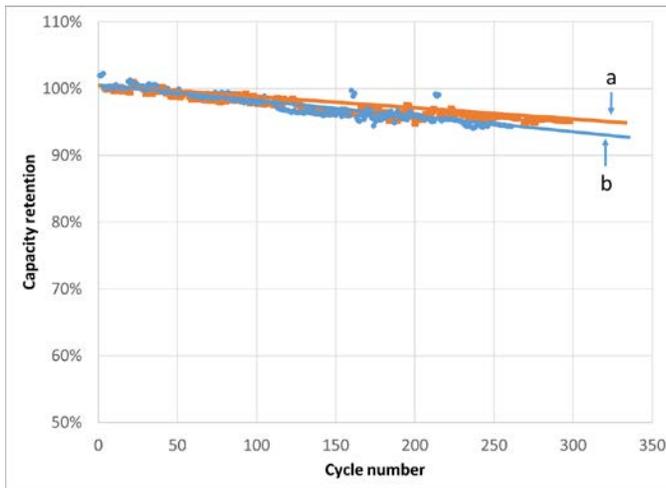


Usage profile	83Ah cell	110 Ah cell	
Average power (W)	1 hour	284	391
	2 hour	143	201
	4 hour	76	113
	5 hour	62	80
	6 hour	51	68
	10 hour	32	40

2.4.2 Discharge Cycling Test

The charts in Figure 10 show the cycle capability of the 110 Ah technology being charged at a C/3 rate and discharged at C/2 rate for a range of 90% SOC (a) and 100% SOC (b). The data in the chart projects out to over 1,000 cycles sufficient to support a 10-year module warranty. The projections are based on the capacity retention remaining above 80%.

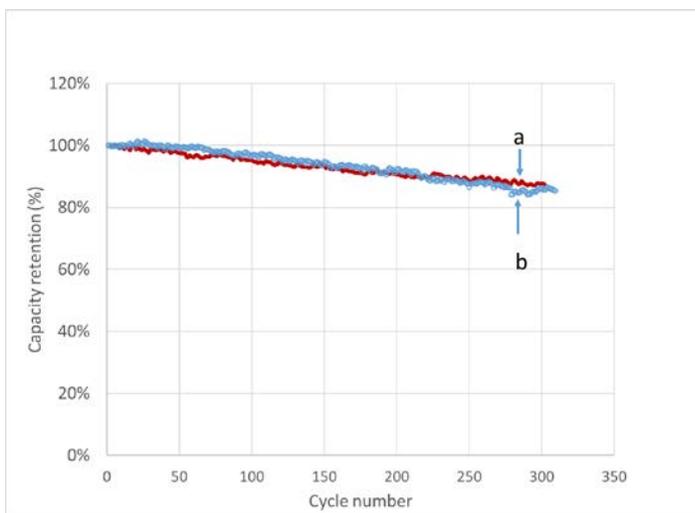
Figure 10: Chart Showing Discharge Cyclability of the 110 Ah CSG technology version



2.4.3 Cell Performance Comparison with and without ceramic support housing

The chart in Figure 11 shows a comparison of the cycle testing of a typical lithium 26700 mm jelly roll in the ceramic support housing developed by Morgan Advanced Materials for Cadenza's technology (Figure 12, curve a). In this case, the housing is a six-roll configuration. The cycle testing, at $C/2$ discharge and $C/3$ charge is compared against a single roll 26700 standard lithium-ion cell with identical electrode formulation and no ceramic material present (curve b). The data shows a strong correlation between the cycle numbers validating that the ceramic housing employed by Cadenza does not have a negative impact on the supercell's cycle life.

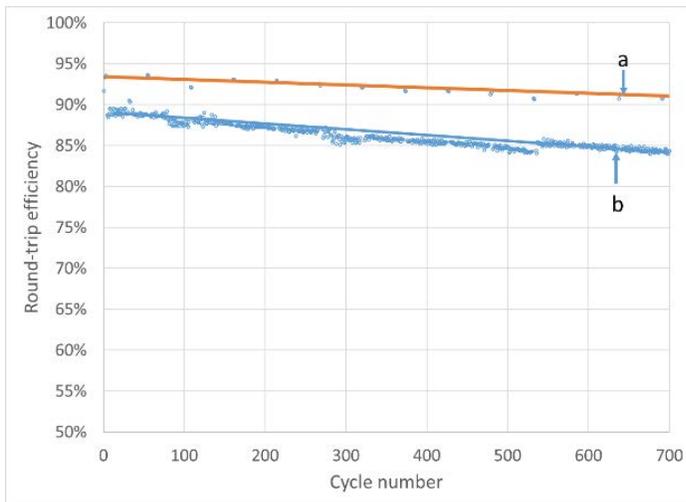
Figure 11. Comparison of the cycle life between the Cadenza supercell vs. stand-alone, lithium-ion cell



2.4.4 Round Trip Efficiency Testing

Roundtrip efficiency was tested for the CSG technology using worst-case duty cycles for two charge and discharge combinations; see Figure 12. The data illustrates the electrode energy optimization for longer discharge and charge times, as efficiency is higher for the lower rates. For a five-hour application, assuming full peak demand is used in each duty cycle, 100% battery utilization of the available energy (full discharge), efficiencies between 91–93% range were recorded, while the shorter in time charge and discharge rate combination tested is about 5% less efficient for this particular electrode formulation. Efficiency slowly degrades with time, due to increased resistance with time, a typical Li-ion degradation scenario, with the rate of degradation being slower for the longer duty cycles.

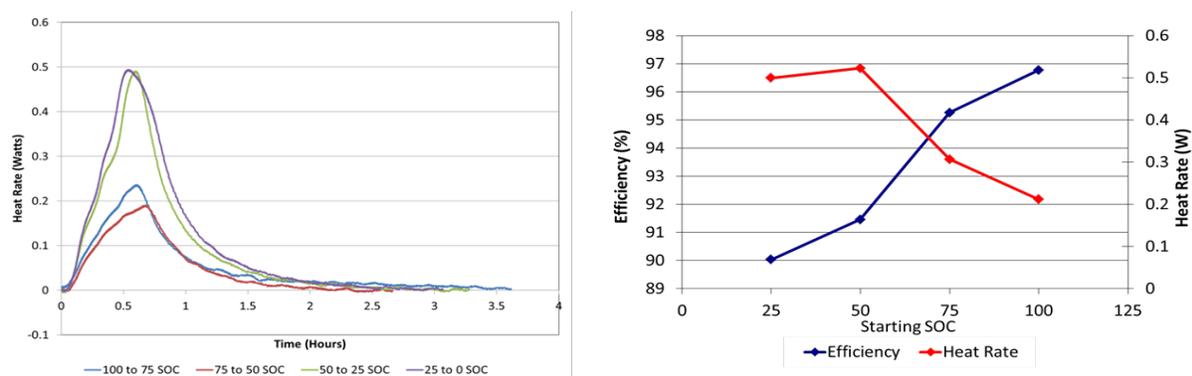
Figure 12. Worst case roundtrip efficiency for CSG technology, assuming 100% depletion duty cycles: (a) five-hour charge (C/5) and five-hour discharge (C/5), and (b) three-hour charge (C/3) and two-hour discharge (C/2)



Efficiency of fresh jelly rolls was also studied by the US Department of Energy’s National Renewable Energy Laboratory (NREL) by utilizing calorimetric data during discharging and charging single cells having the same chemistry as the jelly rolls used in the supercell. The data showed the upper SOC range has lower heat generation than the lower SOC range, which would directly correlate to charge/discharge efficiency measured electrochemically. This shows a duty cycle that only experiences a partial discharge, for example between 100% and 75% would be about 96–97% charge/discharge efficient, while a partially discharged cell that is cycled between 25–50% SOC would only experience 91% efficiency. Typical duty cycles in peak demand reduction start from a fully charged system, with systems only being partially discharged in most use cycles, as the systems are sized to handle the most severe use conditions to avoid

exceeding contracted power levels. Based on these use scenarios, it is anticipated that the Cadenza platform, if deployed with this particular electrode formulation choice, would be 93–96% efficient in real-life applications, which is planned to be tested in Phase 3 of this development project.

Figure 13. Efficiency of 110 Ah (CSG) technology; (left) heat rate as a function of discharge time, (right) heat rate and charge efficiency as a function of SOC



2.5 Task 6: Cost Validation and Application Economics

2.5.1 Cost Reduction Mechanisms

In Task 6, Cadenza showed how the \$125/kWh battery cost goal is achievable with the Cadenza supercell architecture. The cost goals are met due to the multiple efficiencies gained from the cell/platform design. The efficiencies are gained by leveraging the advantages the ceramic support housing provides to increase cell packing efficiency and the innovative open cell design and safety approach.

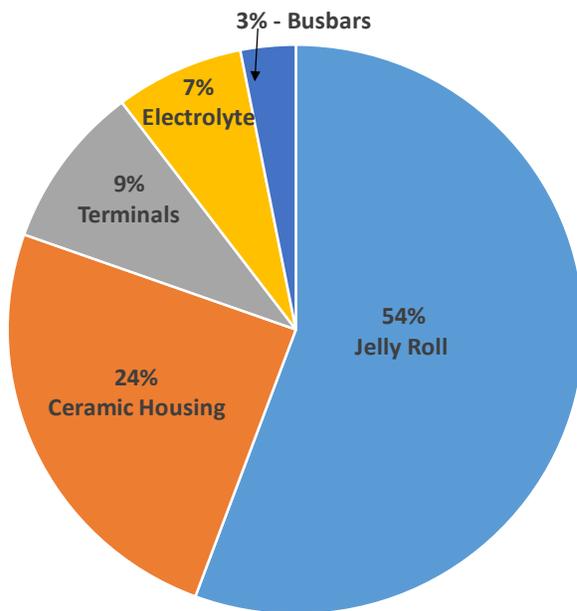
The first step in achieving cost reduction is to utilize the lowest cost lithium-ion electrode assembly available to the industry, which is cylindrically wound jelly rolls. The most common version of this cylindrical cell is the 18650 cell, which was initially deployed in notebooks. Costs have been worked out of the 18650-cell manufacturing system for more than 25 years. This cell is very mature in the market and is considered bankable across the entire value chain, as it is manufactured in the billions of units per year. Additionally, the 18650 cell is continuing to achieve annual cost reductions through innovation in electrode materials (both anode and cathode), continued improvements in equipment design and process capability and through the ongoing application of quality techniques in manufacturing such as Six Sigma methods. The jelly roll utilized in this project is based on a shorter version of a mass produced 26700 lithium-ion cell, which in turn is basically a wider and taller version of the 18650 cell. The cells are manufactured using equivalent and equally mature production techniques.

The second cost reduction technique is the innovative open multi-roll design utilized by Cadenza which enables design simplification through component elimination and manufacturing process efficiencies. The supercell platform shifts the protection and pressure disconnect elements typically found on each individual cell to the aluminum case. This step further reduces cost by removing several components that typically make up an individual 18650 or 26700 lithium-cell. The components that are removed are the seal lid, CID (Current Interrupt Device), PTC, and plastic spacers. Elimination of these components reduces the 18650 or equivalent cell form factor bill of materials (BOM) cost by 20%. In addition to the BOM cost reduction, the final assembly, grading, and test processes are simplified due to the narrower distribution of the supercell capacity, which is a direct result of using 24 or more individual jelly rolls within the structure. In addition, net factory capital expenses are lowered mainly due to reduction of channel monitoring electronics by a factor of 24, although each channel has somewhat increased hardware cost as higher currents to each individual supercell are used. Due to each supercell containing an average distribution of jelly roll capacities, it is possible to use the full population of jelly rolls produced as the varying individual capacities are aggregated within the supercell structure. This provides a further cost improvement opportunity, compared to cell technologies that requires sorting of capacity for each module. The cost efficiency gains increase as the supercell configuration size increases. The more jelly rolls fit inside the supercell structure, the lower the cost per kWh. The open design concept of the lithium cell is made possible by the ceramic support housing and its ability to act as a safety containment vessel and preventing a cell failure from cascading as well as the use of the entire housing (pressure disconnect and vent) as a safety feature typically associated with an individual cell.

The charts shown in Figures 14 and 15 illustrate the costs in terms of dollars per kWh that result from the simplified Cadenza cell design using largely standard components available within the industry, and the cost trajectory associated with scaling energy density and volumes.

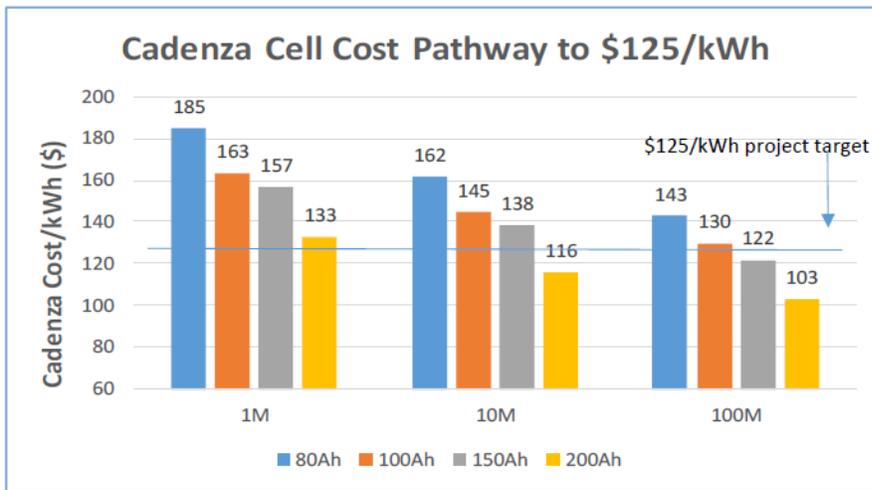
This first chart, Figure 14, indicates the pareto analysis of the BOM costs. As can be seen, 76% of the BOM cost are standard components readily available within the industry, from multiple vendors, at high quality and low cost. The only non-standard component is the ceramic composite material used for the support housing surrounding the jelly roll electrode assemblies. While a custom ceramic composition and format is used in this specific application, the base materials are commoditized. In particular, the base ceramic fiber manufacturing process is quite standard within that industry, is available from global locations and relatively low-cost increases are incurred in the customization of the ceramic housing for Cadenza's supercell technology. The ceramic support housing used in this project was developed in collaboration with Morgan Advanced Materials.

Figure 14. Bill of Material Cost Pareto Analysis



The second cost chart, Figure 16, conveys the dual impact of both energy density and volume. The proprietary ceramic housing has the capability to provide safety as both the capacity (Ah) of the individual jelly rolls increase and as the physical size of the cell increases. As cell capacity is increased, cost benefits per kWh accrue as the balance of cell costs are aggregated over the higher cell energy. Volume increases also drive down costs due to better utilization of factory capacity, streamlined component supply chain efficiency, and the ability to negotiate with multiple qualified global vendors.

Figure 15. Manufacturing costing estimates for the Cadenza cell/platform



2.5.2 Application Economics

For the targeted application, Cadenza requested DNV GL to conduct an economic assessment of the customer-side, peak-shaving application area to guide Cadenza’s Phase-2 system design step.

The DNV-GL team modeled applications in New York City and Long Island, assessing the benefits from peak shaving applications as well as differences obtained from utilizing longer duration systems.

The modeling effort examined the benefits of multi-hour storage systems under typical commercial tariffs by comparing the savings that can be captured by a two-, four-, and six-hour storage device under specific ConEd and Long Island Power Authority (LIPA) commercial tariffs.

Lithium storage systems are great technologies for demand reduction applications, but the application economics can be enhanced by longer duration storage systems as that will also allow the application to address facilities with extended peak periods. In summary, the reasons why longer duration systems may be necessary for the application of load reduction are:

- For facilities with multi-hour peaks, short duration storage system will not be able to cover the entire facility peak, which will reduce the effectiveness of the application.
- Inability to cover the entire facility peak will simply reduce the returns of the peak shaving applications and not optimize revenues.
- Many utility demand reduction programs have performance requirements that include multiple-hours of duration. Short duration storage devices may be prevented from participating in programs.

In the applications assessed, these factors are muted because the system is being combined with a solar system. In this case, the combined solar + storage system is capable of addressing the entire facility peak.

2.5.2.1 Application Assessment

The profile of the application being assessed in the Use Case is shown in the charts in Figure 16. The specific application case is peak-shaving, storage located behind the meter, where the facility has a 58 kW, multi-hour storage device combined with a 160 kW solar array. The deployed system is coupled with a solar device to capture the entire facility peak and the Federal Investment Tax Credits of the storage device by being coupled with the solar system. The parameters of the two tariffs are shown in Table 2.

Figure 16. Site Operation and Storage Charge/Discharge Profiles in Demand Reduction Case

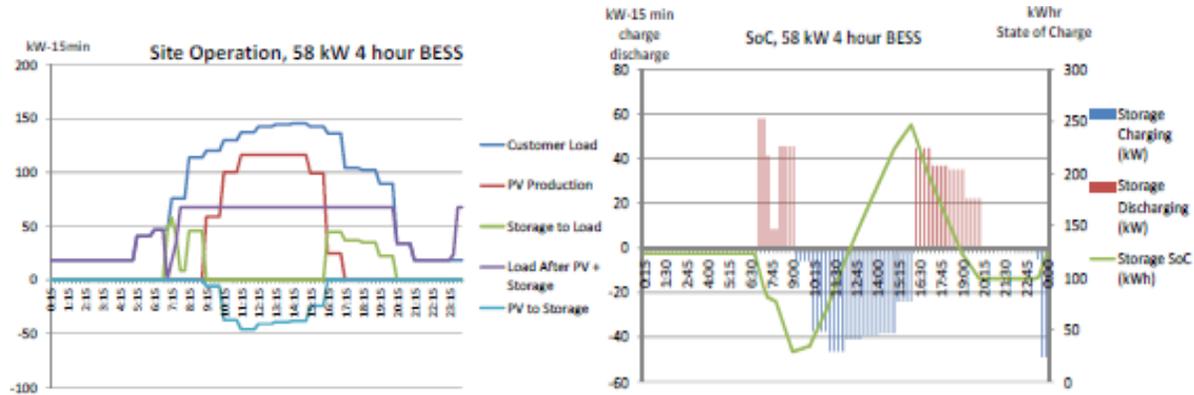


Table 2. Demand and Energy Charges for ConEd and LIPA Tariffs

Tariff	Energy Charge (\$/kWh)	Demand Charge (\$/kW)
ConEd SC9-I Commercial	4.46 – 9.58 cents per kWh	\$36.9 - \$42.7 / kW
LIPA 282 Commercial	2.7 – 4.37 cents per kWh	\$44.78 / kW during summer peak, \$3.84 / kW during mid-peak and no charge on off-peak hours.

The listing of the tariffs provides insight into the business case evaluations. Though the storage systems are capturing savings from three areas: energy, net metering, and demand; it is the demand savings in the application that drives the business case. Reasons for this are simply the high demand charge in each tariff. For ConEd, the tariff in the evaluation has a summer peak demand charge of \$42.70/kW and a \$36.9/kW peak demand charge for the winter. For the LIPA use case, the tariff in the evaluation has a

summer peak demand charge of \$44.78/kW; however, the winter peak drops to \$3.84/kW. Hence, the ConEd business case will likely have better returns due the ability to capture high demand savings for the entire year.

The charts in Figure 16 show how storage works in combination with the solar system, charging in off-peak hours or via the solar system and discharging around the solar output to optimize its demand reduction potential. Table 3 shows a summary of the benefits streams for each of the storage durations for the New York City case. For these cases, the four- and six-hour storage system produces greater benefits than the two-hour storage application.

Table 3. Summary of Benefit Comparisons of Two-, Four-, and Six-hour Storage Devices in NYC Applications

Power Size (kW)	Storage Capacity (kW)	Storage Duration (hrs)	Energy Charge Savings (\$)	Demand Charge Savings (\$)	Net-Metering Revenue (\$)	Total Savings (\$)	Savings from BESS (\$)
160			\$16,210	\$14,644	\$555	\$31,409	
160	58	2	\$13,441	\$31,345	\$104	\$44,890	\$13,480
160	58	4	\$15,629	\$34,802	\$48	\$50,480	\$19,070
160	58	6	\$16,124	\$36,551	\$95	\$52,770	\$21,361

The chart in Table 4 illustrates how greater benefits can be captured via the longer duration systems. For this particular application in New York City, the goal is to reduce demand. Each of the Cadenza configurations show the potential for strong economic returns.

Table 4. Simple Payback Chart for the ConEd Tariff Application

Con Edison Tariff – SC9-I Summer Demand Charge = \$42.7/kW, Winter Demand Charge = \$35.9/kW							
Power Size (kW)	Storage Capacity (kW)	Storage Duration (hrs)	Energy Charge Savings (\$)	Demand Charge Savings (\$)	Net-Metering Revenue (\$)	Total Savings (\$)	Savings from BESS (\$)
160			\$16,210	\$14,644	\$555	\$31,409	
160	58	2	\$13,441	\$31,345	\$104	\$44,890	\$13,480
160	58	4	\$15,629	\$34,802	\$48	\$50,480	\$19,070
160	58	6	\$16,124	\$36,551	\$95	\$52,770	\$21,361

The chart in Table 4 summarizes a simple payback approach of each of the storage systems for the NYC application. For the low-cost case of the system, the simple payback method shows a compelling project opportunity. However, it needs to be noted that this method can provide a high-level indication of the number of years it will take for benefits to exceed the cost of the installation, the method is lacking as a full indicator of project potential. One drawback is simply that the ratio doesn't take into consideration the project length of operation. Hence, when a project length covers multiple years, the simple payback method will not account for the profit potential of a project once the zero crossing is met.

One method to examine the full potential of a project is shown in Figure 21. In this assessment of the Cadenza NYC and LIPA applications, a benefit to cost ratio methodology is utilized. In this approach, the benefits and cost streams of the entire project term are discounted and utilized in the ratio. Table 5 shows a series of benefits to cost assessments of the system based on varying factors. These factors are: high-cost/low-cost estimates of the system, types of financing between debt and equity, and whether the project is based on a 10-year life cycle (storage system not refurbished) or a 20-year life cycle (where the battery is replaced to match the solar system life cycle).

Table 5. Benefits to Cost Assessments for NYC Application (top) and Long Island Applications (bottom)

Benefits to Cost Summary for Con Edison Application								
	Low-Cost System No module replacement		High-Cost System No module replacement		Low-Cost System Module replacement in 11th year		High-Cost System Module Replacement in 11th year	
BESS System	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity
58 kW 2 Hour	2.07	2.16	1.30	1.36	2.96	3.08	1.68	1.75
58 kW 4 Hour	2.03	2.12	1.30	1.35	2.82	2.94	1.56	1.63
58 kW 6 Hour	1.76	1.84	1.13	1.19	2.41	2.51	1.82	1.61
Benefits to Cost Summary for LIPA Application								
	Low-Cost System No module replacement		High-Cost System No module replacement		Low-Cost System Module replacement in 11th year		High-Cost System Module Replacement in 11th year	
BESS System	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity	100% Debt	50% Debt, 50% Equity
58 kW 2 Hour	0.87	0.90	0.55	0.57	1.24	1.29	0.71	0.73
58 kW 4 Hour	0.98	1.02	0.62	0.65	1.36	1.41	0.75	0.78
58 kW 6 Hour	0.90	0.94	0.58	0.61	1.23	1.29	0.78	0.82

For a benefit-to-cost assessment, a ratio greater than one indicates that a project is going to be profitable. Hence, when the full stream of benefits is taken into consideration, all applications for the NYC application in both high- and low-cost estimates for the Cadenza system are showing B-C ratios greater than one. Like the simple payback, the two-hour system is showing a slightly better ratio than the four- or six-hour system. For the LIPA case where the demand reduction potential is less than the NYC/ConEd tariff, the B-C ration is less favorable with only the 20-year projects and the four-hour, 10-year project showing ratios greater than one.

2.5.2.2 Conclusions for the Application Assessment

The conclusion drawn from the evaluations is that the Cadenza system, due to its lower cost structure, is showing compelling economic viability numbers across all project profiles for the NYC tariff and favorable economic numbers for the LIPA case of the four-hour battery. The numbers for the two- and four-hour systems are comparable in the NYC case and the four-hour appears to be the optimum sizing in the LIPA case.

As stated, the project economics are mainly driven by the demand reduction potential of the facility and the high demand charges of the local tariffs. Hence, in the case of the NYC application, all the application profiles are cost effective and it is difficult for the devices of different duration to differentiate themselves. However, in the case of the LIPA case study where the demand charge is less favorable, the four-hour duration and flexibility of that duration allows the system to optimize the application space.

2.5.2.3 Extending the Application to Other Territories

The applications that were assessed in the NYC and LIPA case studies show that in any territory where there is a high-demand charge, the Cadenza system has the ability to be economically viable both as a stand-alone system designed to reduce facility demand and as a complement to solar applications at the field.

The numbers also show that as the tariffs become less favorable, i.e., lower demand charge as seen in the differences between transitioning from the NYC ConEd tariff to the LIPA tariff, the four-hour system begins to be optimized. This is because of the additional energy in the extra capacity of the battery coupled with the relatively lower cost. The four-hour systems will have other benefits as well. The additional storage energy will allow the device to expand its application capabilities. In addition, as developers begin to look at stacking applications or having the device perform multiple revenue generating tasks, the longer duration system will allow for increased flexibility and the ability to perform multiple roles. Finally, in cases where the storage system is acting as a stand-alone demand reduction application, the longer duration systems will most likely optimize versus the shorter duration as the longer duration system will be able to capture the entire peak of the facility rather than just a portion of it. As stated, because in this specific application the storage device was coupled with a solar system, that entire peak was captured due to the combination of the systems.

2.5.2.4 Facilities Types for Next Phase Demonstration

For the next phase of the Cadenza project, a 50 kW, four-hour or up to six-hour system at a third less power is being targeted as the optimum full system, ideally using a 200-kWh storage system. When examining the best location for the system, two considerations should be made with the facility profile, and the local tariff.

First, for the facility profile, facilities should be selected that have high peak periods (typically 12 p.m. to 6 p.m.) that coincide with the peak utility tariff. In addition, in the case of stand-alone storage, the application will be maximized with facilities that have a peak of four hours or less. If the peak were longer than the storage duration, the demand savings would be lost in the last hour of the facility peak. If the storage system is coupled with a solar system, as was the case in the case studies described, there is less risk of missing portions of the peak due to the combined capabilities of the solar system and the storage system.

Second, for the utility, any area where the local utility has a high demand charge is preferable. As was noted from the case study example, the demand reduction is where most of the savings of the application was created. Both LIPA and ConEd have high summer peak tariffs (around \$45/kW). However, the ConEd tariff has a high demand charge throughout the year, whereas the LIPA tariff has the high demand charge only in the summer. This is the reason why the economics were more favorable in the ConEd case, but also gives insight into the best type of tariffs to target.

Finally, the case studies showed that facilities that have solar already installed would be able to enhance that system with a storage system. However, because of the energy production of the solar system, there is less pressure on the storage device to have a long duration. An application targeting multiple applications or a stacked benefit approach are alternative implementations, with clear economic impact, but have not been evaluated in this first phase.

3 Proposed Next Steps

With the successful completion of Phase 1, Cadenza recommends continuing to advance the Supercell Storage System by transitioning into Phase 2 of the development cycle. As stated in the introduction, the tasks in this project made up Phase 1 of a proposed three-phase effort. For clarity, the individual phases are listed below:

1. Phase 1: Cell Prototype Development. Design and build a low-cost product cell suitable for six hours peak shaving conditions. For Cadenza, this Phase leverages and optimizes the existing technology platform sponsored by the DOE/ARPA-E Cadenza initiative.
2. Phase 2: Battery Pack and Module Development. Prototype cells developed in Phase 1 will be integrated into a battery pack system with performance attributes tailored to the State's commercial power users.
3. Phase 3: Productization of the Final Grid Energy Storage System Product. The battery pack system will be deployed into a selected commercial demonstration site for peak shaving, enabling onset of deployment and real use data.

Knowing the need for and the value of a cost-effective, multi-hour storage systems, Cadenza is beginning the next phase of development of translating the benefits of the supercell into a commercial building and utility-scale storage system based on the Cadenza platform. The initial design concept of that system, represented by one battery storage rack, is shown below in Figure 17 and compared to state-of-art systems available in the market today.

The 2017 target system is based on jelly rolls already available in mass production, while the 2018 target capacity is based on jelly rolls proven in pilot production and anticipated to be available for volume purchase in that time frame. Within the same footprint as competitive technologies from existing high-cost suppliers, the Cadenza System would provide about 50% more energy for less cost, and more than likely, improved safety features as well. Assuming Phase 2 could reach 200 kWh per battery rack, a set of four racks would generate 0.8 MWh, with an average inverter power optimized to 150 kW for six hours of operation and 200 kW for four hours of operation, which would fit the power window for many types of commercial buildings within the State.

Figure 17. Comparisons of Cadenza Phase 2 Battery Pack with Alternative Systems



	LG		SDI		Cadenza	
Model	R800	R1000	Mid V	High V	C-2017	C-2018
Energy [kWh]	137	166.4	56	56	195.4	221.7
Wh/L	139.4	153.9	46.9	93.7	162.8	184.8
Nominal Voltage [V]	725.2	880.6	710	947	725.2	725.2
Operating Voltage [V]	588 – 823.2	714 – 999.6	576 – 787	750 – 1050	600 – 830	600-830
Configuration	196s3p	238s3p	192s3p	256s1p	200s2p	200s2p

Having proven the design innovations proposed by Cadenza lead to increased safety in Phase 1, lower cost and longer duration, the next step of the process is to advance the supercell into Phase 2 of the development plan and allow for the build-out of the battery system in order to assess the system in field testing conditions.

Cadenza is incorporating the analysis from the DNV-GL economic analysis study to determine the optimized size and form factor for the system This optimization will be inclusive and selecting and matching to the proper inverter (ABB’s inverters are being utilized) and will drive the performance requirements of the developed battery rack system.

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