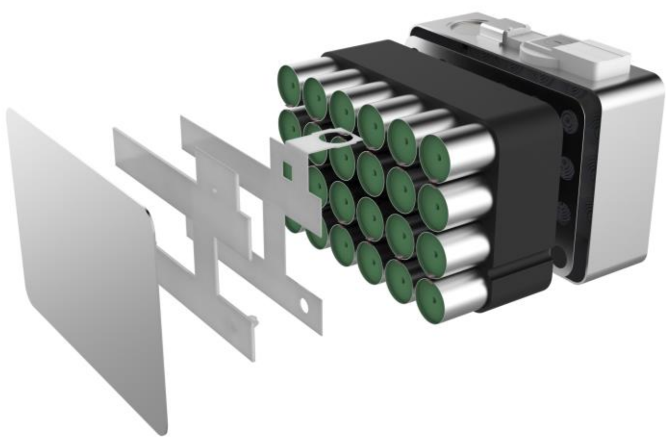
FINAL TECHNICAL REPORT

CADENZA INNOVATION, INC.
FINAL SCIENTIFIC/TECHNICAL REPORT
NOVEL LOW COST AND SAFE LITHIUM-ION ELECTRIC VEHICLE BATTERY
DE-AR0000392

A NOVEL PACKAGING ARCHITECTURE FOR LITHIUM-ION BATTERIES



Award:	DE-AR0000392
Lead Recipient:	Cadenza Innovation, Inc.
Project Title:	Novel Low Cost and Safe Lithium-Ion Electric Vehicle Battery
Program Director:	Dr. Grigorii Soloveichik
Principal Director:	Dr. Christina Lampe-Onnerud; Dr. Per Onnerud
Contract Administrator:	Mary Barnes
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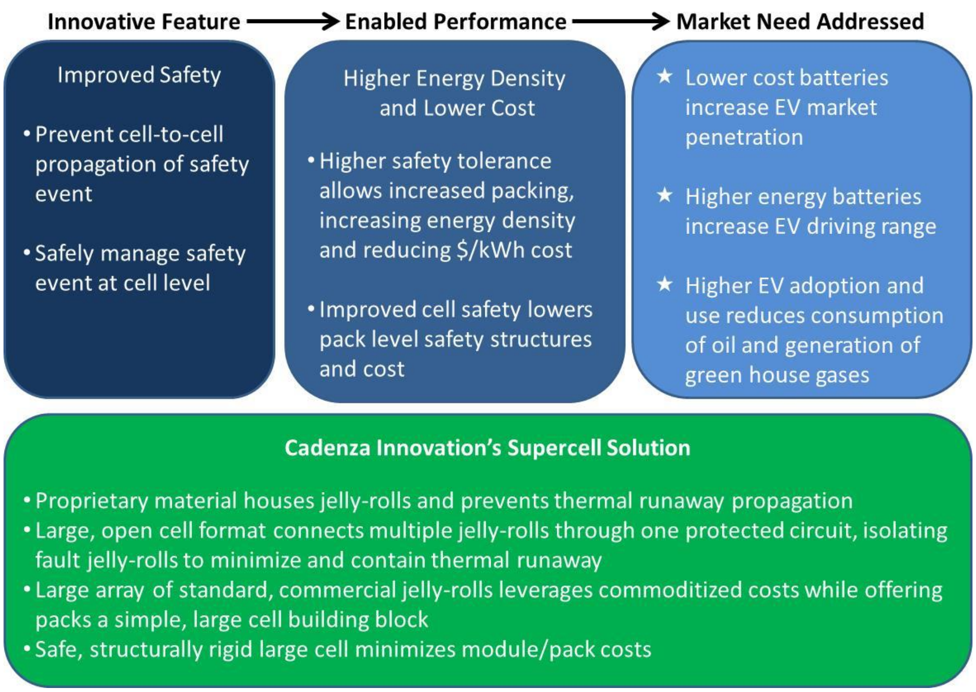
PUBLIC EXECUTIVE SUMMARY

Under its Robust Affordable Next Generation Energy Storage Systems (RANGE) program, the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) challenged the battery community to deliver a robust Lithium-ion (Li-ion) battery technology that could meet the cost and driving range requirements for wide spread adoption of electric vehicles (EVs). Cadenza Innovation, Inc. (Cadenza) delivered to that goal an innovative battery architecture that improves Li-ion battery safety and in turn, enables both increased energy density (that translates to longer drive distances) and lower cost.

The transportation sector is the single greatest source of dependence on U.S. oil imports. In 2017, 91% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.[1] Widespread adoption of EVs can substantially reduce U.S. oil imports while also increasing the energy efficiency of transportation and mitigating greenhouse gas (GHG) emissions.

To realize these benefits, EVs must compete with conventional vehicles on price and driving range, both of which are influenced by the cost and storage capacity of the EV battery. As stated in the founding RANGE program goals, RANGE aims to promote development of transformational electrochemical energy storage technologies that accelerate widespread electric vehicle adoption by dramatically improving their driving range, cost, and reliability. To achieve this long-term objective, RANGE targets maximizing specific energy and minimizing cost of energy storage systems at the vehicle level. Central to this system-level approach is the use of robust design principles for energy storage systems. Robust design is defined as electrochemical energy storage chemistries and/or architectures (i.e. physical designs) that avoid thermal runaway and are immune to catastrophic failure regardless of manufacturing quality or abuse conditions. In addition, this program seeks multifunctional energy storage designs that use these robust storage systems to simultaneously serve other functions on a vehicle (for example, in the frame, body, and/or crumple zone), thus further reducing an energy storage system's effective weight when normalized to the entire electric vehicle weight.

Figure 1: Cadenza Solution to Improved Li-Ion Batteries



Cadenza, a newly founded company led by world recognized battery experts, won an award under this program to develop an innovative new battery technology that could lower overall battery system cost while simultaneously delivering advances to battery safety and energy density. Li-ion batteries, as well publicized over the course of their history, pose risk for fire or explosion. This risk is mitigated through complex engineering around the core chemistry and includes numerous mechanical and electrical controls integrated at the cell, pack and application level. The Cadenza

[1] U.S. Energy Information Administration, *Monthly Energy Review*, Tables 2.5 and 3.8c, April 2017.

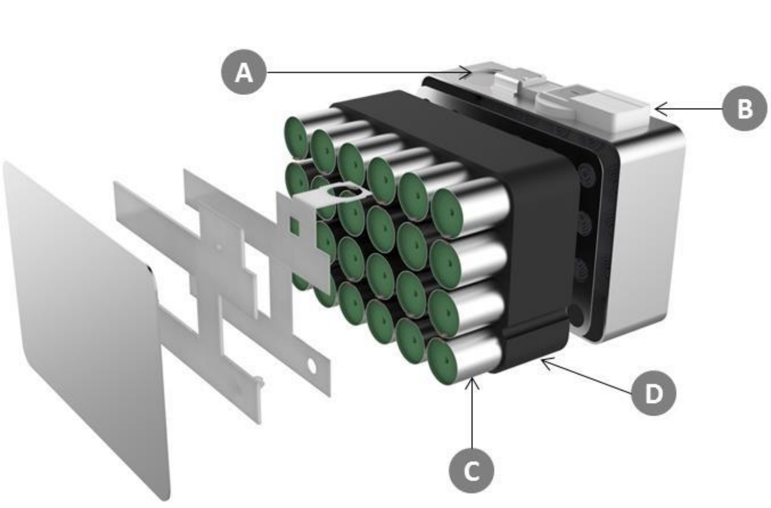
team recognized that an improvement in battery safety that specifically addressed the problem of a small system defect or fault initiating a large and dangerous release in energy, would enable significant advances in designing batteries with higher energy density and lower cost.

Cadenza's innovative solution that addresses this problem is a large cell design containing many smaller electrochemical storage units positioned inside a novel, housing material. The term "supercell" references this large cell formatted with multiple smaller units, eliminating components, reducing cost and adding increased safety. The smaller electrochemical units are based on proven, standardized technology that already exists in low cost, high volume mass production globally. Combining the novel housing with the open cell format prevents propagation of a safety event and enables a higher energy packing density compared to what is safely achieved in the market today. In short, Cadenza's supercell enables higher energy batteries while maintaining (or improving) safety at lower cost. This in turn results in longer EV drive distances, and, additionally, lowering cost due to less requirement for complex safety engineering on a per kWh energy basis. These motivations and ideas are conceptualized in Figure 1.

A key consideration in Cadenza's design that enables commercial success is the use of standard wound, cylindrical electrochemical units (called "jelly-rolls" in the lithium-ion industry) as the basic energy storage unit. Jelly-rolls for cylindrical cells represent the highest volume, lowest cost form factor. 18650 cells dominate this form factor but a number of closely sized variations are available, all taking advantage of standard and proven components and manufacturing processes. While many EV manufacturers have favored the use of larger cells in the design of battery packs, for reasons of ease and lower cost of assembly, larger cells exhibit many limitations: they pose higher risk in the event of thermal runaway, cost more, have a lower manufacturing yield, exhibit lower energy density, and require additional protective structure. By contrast, small-format cylindrically wound Li-ion batteries have a mature manufacturing process and all aspects of the cylindrically wound cell design have been optimized at very large scale, which has led to lower costs, higher manufacturing yield, and higher energy density. If a large number of jelly-rolls can be successfully integrated into packs, then an opportunity to improve EV batteries arises. Tesla is the most well-known applier of small cylindrical cells into EV battery packs, however safety requirements still limit how closely they can pack the cells together and their pack assembly process involving connection of thousands of small cells is costly and requires a complex cooling circuit.

By offering a safer, more efficient path to packaging, Cadenza delivers higher energy density, lower cost and higher reliability to vehicle packs. Cadenza's design is agnostic in terms of jelly-roll source, although Cadenza's innovation opens the door to new development paths in the chemistry and design of jelly-rolls. Further, Cadenza's design incorporates the jelly-rolls into a larger energy supercell that delivers an easy to integrate prismatic large cell to the EV battery pack, removing the need for costly assembly of small cells while keeping small cell advantages and not requiring complex additional module structures typically necessary for large cells.

Figure 2: Cadenza Innovation Supercell Design



Under its RANGE award, Cadenza designed and built a large-format "supercell" (Figure 2) that combines 24 jelly-rolls into a single container. This supercell behaves like a module of small format, cylindrically wound cells, but with several key enhancements designed to improve safety. The jelly-roll cells (energy units) within the supercell are open, which provides new opportunities with how safety abuse scenarios are managed, including thermal runaway, mechanical abuse, and over pressurization due to gas formation. Key supercell component attributes to safety are highlighted in Figure 2 and include: (A) a single rupture disc located on the supercell case and including a flame arrestor so that even when a cell creates a thermal event, there is minimal flame outside the supercell; (B) an overcharge disconnect device that activates with pressure formed during overcharge (or other abuse) to disconnect the entire array of jelly-rolls – this device creates a bypass electrical path using the cell casing so that in a large series pack, the system can safely operate while the abused cells remain isolated; (C) inside, the jelly-rolls are contained in an Aluminum tube that aids in both electrical connection and uniform thermal management; (D) a surrounding ceramic composite material acts to isolate, for safety, each jelly-roll, preventing direct thermal contact between jelly-rolls and chemically absorbing heat with discharge of gas – in a safety event, this ceramic housing allows heat to be effectively removed from the supercell and prevents cascading thermal events between neighboring jelly-rolls. Utilizing the advantages of the supercell design, jelly-rolls are designed to maximize energy density without compromising safety.

The ARPA-e program structure and funding allowed the assembly of a project team with the diverse expertise required to engineer a high-performance supercell that is competitively priced and safely meets the requirements of high demanding EV applications. Fiat Chrysler Automobiles (FCA) enabled a Fiat 500e EV platform to test the supercells. Morgan Advanced Materials' novel ceramic, originally developed to fireproof airplane "black boxes," is used as the basis for the novel protective housing surrounding the cells. NREL contributed thermal modeling expertise to confirm that the supercell system could prevent cascading thermal runaway. Massachusetts Institute of Technology (MIT) Professor Tomasz Wierzbicki provided knowledge on the mechanical properties of jelly-rolls. Karotech supported enclosure and metal component design. Alcoa supported design of cell safety components. Safety testing of cell and modules was supported by MGA Research. Performance testing was supported by DNV-GL, and AVL integrated Cadenza supercells into an EV pack for the Fiat 500e.

By the end of its ARPA-E award, the team met project goals and delivered a supercell that achieved the safety, performance and cost goals of the program, enabling a path to successful EV adoption. A scalable manufacturing process was established to support cost evaluation and supply products for application level testing. A detailed cost model including inputs from a costed BOM and the developed manufacturing process enabled battery pack estimated cost at less than $125/kWh, achieving the ARPA-e RANGE program target. Cost savings where especially highlighted at a battery module level, where the Cadenza design greatly simplifies and lowers the cost, first in assembly of smaller cells into modules that will be further assembled into large EV packs, and second in the actual design and assembly of the module for mechanical and thermal packaging at the pack level.

Four technical milestones were key in meeting the development objectives of the program. These are further detailed to elaborate on the accomplishments of the program and include:

- Developed a novel suitable ceramic housing material
- Validated ability of ceramic housing to prevent cascade (propagation) of thermal runaway
- Designed and validated 83 Ah and 100 Ah supercell designs
- Built supercell into Fiat 500e EV for application testing

Key Milestone: Development of Novel Ceramic Housing

Cadenza's design utilizes an internal cell housing to hold jelly-rolls that will be connected and enclosed to form a large sized supercell. One of the key novel concepts in Cadenza's cell design is that a housing with suitable properties will enhance safety and enable a higher packing density of jelly-rolls. Thus, the housing properties are critical and include: (1) chemical stability to Li-ion environments (electrolyte, voltage), (2) able to prevent propagation of thermal runaway from a single jelly-roll to other jelly-rolls, (3) able to support uniform temperature control (heat conduction) throughout the supercell, (4) mechanical structural stability for vehicle application and to

Figure 3: Composite Ceramic Housing Material

meet abuse tolerance requirements, and (5) manufacturability at low cost. Project team expertise was utilized to identify suitable candidates. Morgan Advanced Materials provided knowledge about key material properties and candidate materials commercially available with potential to meet technical, manufacturing and cost requirements. NREL provided thermal modeling of identified candidates for performance prediction and understanding. Candidate materials were identified, modified, developed and tested by the Cadenza team. The modeling and testing methodologies developed here also will serve to support ongoing development of the technology and provide the broader technical community new resources for consideration and use in advancing Li-ion battery technology. Using the teams' findings, three different basic housing materials were identified, further developed, and tested in detail to evaluate thermal, mechanical and safety properties. A final selection was made for a composite ceramic formulation embedded with a flame retardant additive. A picture of the housing constructed to hold 24 jelly-rolls is shown in Figure 3. This housing design was used for the 83 Ah and 100 Ah Cadenza supercells developed and tested in the program. The core technology is scalable to any number of jelly-rolls and can be optimized based on the needs of the end application.

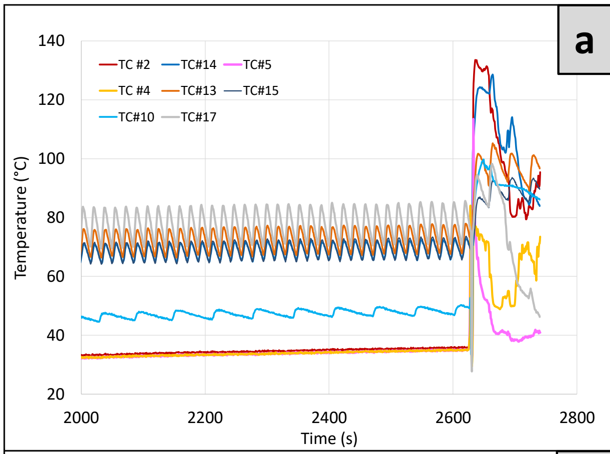
This composite ceramic housing includes silica, a combination of metal and glass fibers, an organic binder, and the fire retardant alumina trihydrate (ATH). ATH endothermically reacts at around 220 °C to release gas. This temperature corresponds to just above the temperature range at which a Li-ion battery will start thermal runaway reactions. Thus, in case of a cell runaway event, the ATH will immediately begin to react, consuming heat and releasing gas. In contrast to similarly utilized phase change materials that are much less efficient at removing heat while offering a reversible solution, the ATH reacts non-reversibly in a chemical reaction that is much more efficient at removing heat, focusing on maximizing the opportunity to increase safety. This technology has the ability to significantly control thermal runaway, a critical characteristic of the ceramic housing and a core concept of Cadenza's technology.

Key Milestone: Validate Non-Propagation Safety

The risk of thermal runaway in a Li-ion cell is well recognized based on the fundamental nature of high energy density storage and over 25 years industry experience. Acknowledging the inherent risk, recent Li-ion battery development has emphasized the ability to contain and minimize the effects of a thermal runaway event. Specifically, non-propagation of a thermal runaway event has received extensive interest over the past few years. Cadenza's innovative housing provides a solution to this challenge while enabling improved energy density. Critical to this program was validating the non-propagation performance of the technology. Cadenza accomplished this through an iterative design process and evaluating safety using multiple industry-standard techniques. These included electrical, physical and temperature abuse tests. Additionally, the team used a cell internal short-circuit (ISC) device test recently developed by scientists at NREL.[2] This test is considered especially important in representing known field failures related to internal cell defects that are not detectable with today's manufacturing technology. The approach to validating safety considered both fundamental features within Cadenza's novel housing and a more complete cell level design with interdependencies amongst numerous cell components. First, safety was demonstrated in a baseline block using standard commercial 5 Ah, 26700 cylindrical cells. This enabled proper design of the housing material. A linear six cell block was populated with fully charged cells spaced 2 mm from each other and then a single cell was forced into thermal runaway. The housing material prevented propagation to all the other cells. In fact, multiple housing materials were identified that successfully achieved this level of propagation protection. Building on this accomplishment, non-propagation was demonstrated in a first generation cell design that included a block housing 24 jelly-rolls in a parallel electrical connection within an open cell format. Propagation safety was verified using both NREL developed ISC device testing and nail penetration testing. Figure 4 shows the results for both types of testing. Under both conditions, a single jelly-roll inside the supercell is driven into thermal runaway, leading to complete combustion of the jelly-roll materials. The supercell design prevents propagation to the neighboring cells and temperature rise on the outside of the supercell is limited to less than 200 °C in areas closest to the abused jelly-roll (based on multiple tests). Results are consistent with predictions made via NREL thermal modeling calculations. These results are a key demonstration of the Cadenza technology advantage. Currently, full product-level

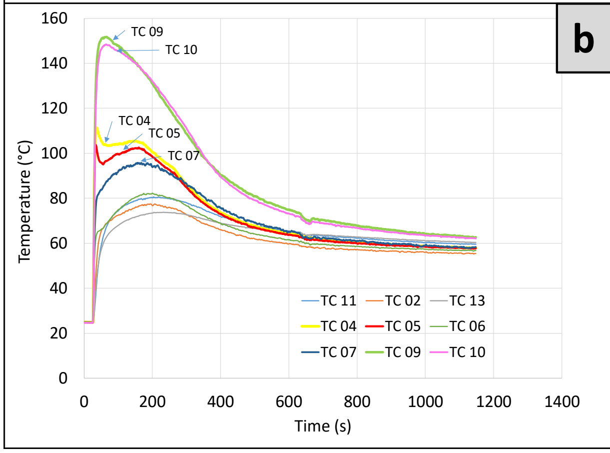
[2] Finegan, D.P. et al., "Characterising thermal runaway within lithium-ion cells by inducing and monitoring internal short circuits", Energy & Environmental Science, Issue 6, 2017.

Figure 4: Abuse Testing on Cadenza Supercell



Internal Short-Circuit (ISC) Device Abuse Test

1 of 24 jelly rolls driven into thermal runaway using ISC device. Temperature monitored on outside of supercell case. Thermocouples closest to abuse jelly roll (TC2, TC14) show highest temperature rise. Other thermocouples show significantly lower temperature rise. Post-mortem confirms only 1 jelly roll experienced thermal runaway with no propagation to neighboring jelly rolls.



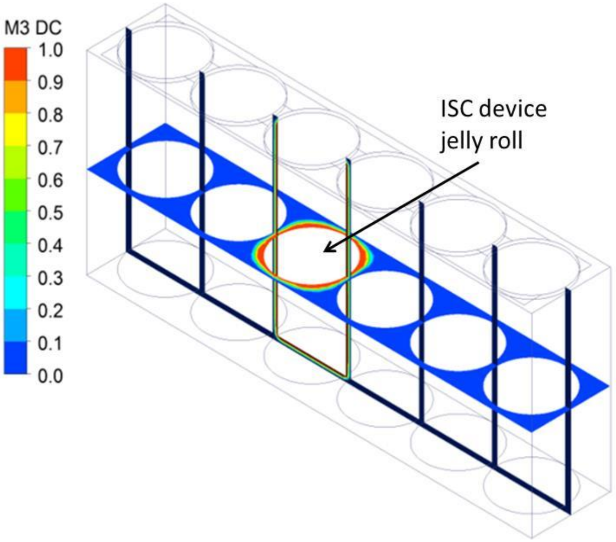
Nail Penetration Abuse Test

1 of 24 jelly rolls pierced with nail, including supercell casing, driving jelly roll into thermal runaway. Temperature monitored on outside of supercell case. Thermocouples closest to abuse jelly roll (TC09, TC10) show highest temperature rise. Other thermocouples show significantly lower temperature rise. Post-mortem confirms only 1 jelly roll experienced thermal runaway with no propagation to neighboring jelly rolls.

safety is being validated for the Cadenza supercell design. This involves complete design of a supercell product capable of meeting market requirements and achieving high volume, high quality and low cost manufacturability.

Safety technical assumptions were validated through thermal modeling analysis performed by NREL. Figure 5 shows the results when modeling a six jelly-roll supercell. One jelly-roll is caused to have an internal short consistent with the NREL ISC device test. The NREL model considers physical and chemical properties about the housing material, including physical isolation of the jelly-rolls and use of the embedded heat-consuming ATH. The model shows that the heat released upon internal short in one cell does not propagate to its nearest neighbors when packaged into the Cadenza supercell design. The result can be explained by a combination of insulation between neighboring jelly-rolls due to the ceramic fiber housing, uniform heat conduction within the jelly-rolls and housing material, and heat consumption by the endothermic reaction of the embedded ATH in the housing material.

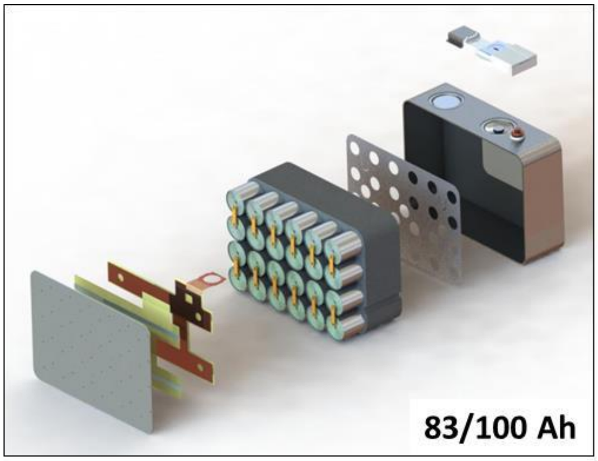
Figure 5: NREL Thermal Model Profile of Cadenza Technology during ISC Device Test



Key Milestone: Design and Validate Supercell Performance

Because Li-ion batteries require many components interacting chemically, mechanically and electrically, and because the industry requires low cost, high volume manufacturing, new technology must demonstrate success at a product level. The Cadenza team's background in high volume Li-ion manufacturing and multiple global battery product releases provided critical perspective and knowledge on this point. This drove the project team to demonstrate performance at levels consistent with a fully capable product. A detailed CAD rendering of the supercell design developed under this project, representing both 83 Ah and 100 Ah versions, depending on jelly-rolls used, is shown in Figure 6.

Figure 6: Cadenza Supercell Design



The novel open cell format of Cadenza's supercell enables critical safety features that minimize any thermal event. This includes the ability to minimize pressure generated inside a thermal runaway cell, controlling the release of hot gasses in a predictable and reproducible way, and electrically isolating a parallel cell array during an abuse event. Compared to small cylindrical cells, the supercell uses a larger vent that can activate sooner during an abuse event, i.e. at a lower pressure. More practically, the supercell design must effectively enclose and electrically connect the jelly-roll housed block, as well as serve as an efficient large cell building block for assembly into large energy battery modules and packs for EV and other applications.

To realize these benefits, the Cadenza team designed a fully functional supercell, leveraging established low cost components already existing in cylindrical cell manufacturing, and designing new components consistent with established low cost materials and manufacturing processes. New components and processes were validated and verified for ability to scale to high volume manufacturing processes. Design accomplishments included the supercell's internal structure to house and connect the jelly-rolls, a case enclosure, internal fusible tabs, terminals and safety components that include a low pressure vent with flame arrestor, an over pressure disconnect, and an isolation fuse. Electrolyte work was also accomplished to identify a formulation that met the specific needs of the supercell design. Individually, each of these design accomplishments represent significant research and development efforts, highlighting the complexity of developing new battery technology and how funding, such as from ARPA-e, can help establish programs that move the technology forward.

Two supercell designs were produced and tested during this project: an 83 Ah supercell using 24 3.5 Ah, 2746-sized jelly-rolls containing an NMC523 cathode with a graphite anode, and a 100 Ah supercell using 24 4.2 Ah, 2746-sized jelly-rolls containing an NMC811 cathode with a graphite anode. Besides using different jelly-rolls with different chemistry, casing and components were constant for both designs. Other chemistry, capacity and format variations of the supercell have been considered and in some cases made, demonstrating versatility in the core concept, but results for other designs are not discussed in this report.

Table 1: MGA Safety Testing on Cadenza 83 Ah Supercell

Safety Test	EUCAR Abuse Rating
Crush	Level 3
Overcharge	Level 2
Short Circuit	Level 2
Nail Penetration	Level 3

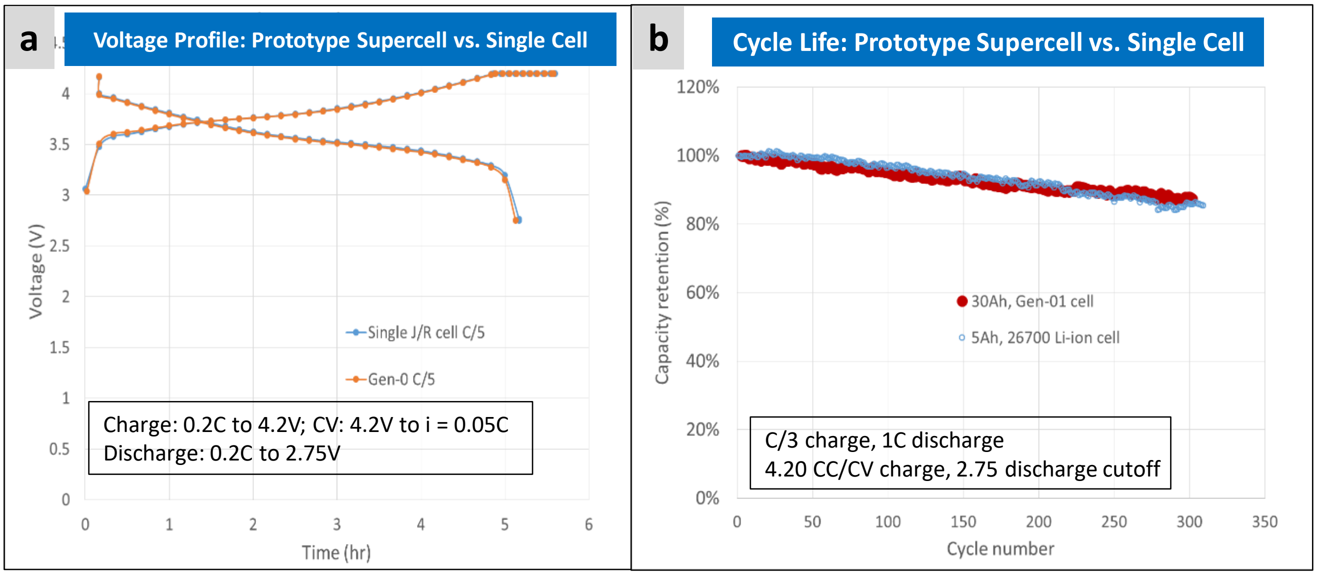
Cadenza's supercell demonstrated performance consistent with the sourced jelly-roll cells and achieved high safety ratings. Table 1 shows program partner MGA Research's safety test results for the 83 Ah supercell. Evaluating performance against industry recognized EUCAR criteria that includes abuse testing for crush, overcharge, short-circuit, and nail penetration, shows safety levels at 2 or 3 and within requirements for safe use in EV application (most auto OEMs will accept up to EUCAR level 4).

Figure 7 shows side-by-side camparison of performance for a single jelly-roll cell and a prototype 6x1 jelly-roll, 30 Ah supercell. The intent here is to show that building smaller sized jelly-rolls up into a large format supercell does not alter the electrochemical performance delivered by the jelly-roll's chemistry and wound electrode structure. Thus, scaling of performance to multiple large-sized variations can be made predictable and enable more efficient battery designs based on the needs of the end application. A consistent voltage profile (Fig. 7a) is observed using a full depth-of-discharge (DOD) 0.2C charge/discharge test. Also, cycle life performance (Fig. 7b) matches between the 30 Ah supercell design and the single jelly-roll cell when using a standard C/3 charge and 1C discharge rate, full DOD, cycle profile. For the full 83 Ah supercell design, cycle life performance is shown in Figure 8 and matches expectations based on single jelly-roll cell performance. Data in Figure 8 result from testing that simulates conditions consistent with use in an EV application. Approximately 90% DOD cycling at C/3 rate shows 93% capacity retention after more than 500 cycles. Approximately every 50 cycles, full 100% DOD is measured, showing similar capacity retention to the 90% DOD condition. Consistent performance for two tested supercells demonstrates reproducibility.

These validations of the Cadenza supercell technology enable use of high energy density lithium-ion battery technologies and show a roadmap for a platform capable of supporting many generations of continuing advances to materials. For example, commercialization of high nickel cathodes, such as NMC 811, is desired due to their high capacity and low cobalt content, an expensive metal with global sourcing challenges. High amounts of gas release in lithium-ion battery environments when using 811 and other high nickel cathodes has created challenges that are currently limiting commercialization. Cadenza's technology offers a safe and low cost solution to implement high nickel cathodes while addressing the issue of gassing. Likewise, the technology presents opportunities to support more rapid development of other new cathode technologies such as high voltage materials.

Of additional note, the supercell component accomplishments developed in this work offer potential industry value beyond the core focus of this project. A reproducibly working vent mechanism that prevents flames from exiting a runaway cell, and an over pressure disconnect and fuse that can electrically isolate a parallel string of cells are needed solutions to battery packs built from arrays of cells.

Figure 7: Cadenza Supercell Performance Validation



Best practice guidelines for large battery packs target a thermal gradient less than 5 °C under most common use conditions. Generally, a pack's component modules and cells should demonstrate even less variation. Thus, thermal uniformity was a critical consideration in the design of the Cadenza supercell. To achieve temperature uniformity, design considerations were given to the housing and connection of jelly-rolls, as well as analysis of key housing properties. The jelly-rolls are held inside aluminum tubes. These tubes take advantage of the jelly-rolls inherent thermal uniformity and help conduct heat evenly away from the jelly-rolls. Contrast this to standard wound cylindrical cells using a steel case – aluminum has 5x higher thermal conductivity compared to steel. Again, NREL thermal modeling supported project efforts, here analyzing the thermal profile of the Cadenza supercell. A 24 jelly-roll (4x6) Cadenza supercell was thermally simulated under heat generated during a standard power US06 drive cycle. Results (Figure 9) show consistent thermal profiles both within jelly-rolls and throughout the entire Cadenza supercell. Using time stamps at 50 and 100 minutes, overall gradients are less than 1 °C within a jelly-roll and less than 2.5 °C across the cell.

Figure 9: Cadenza 83 Ah Supercell Cycle Life Test

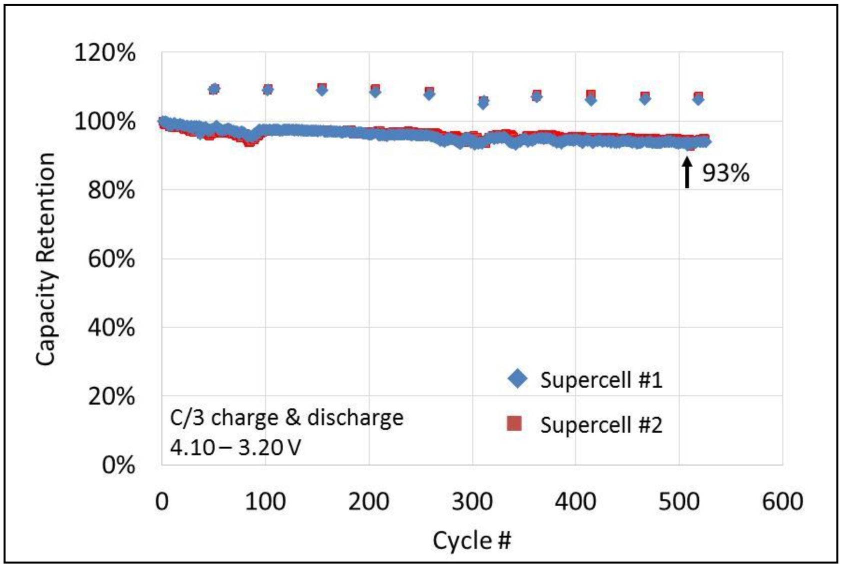
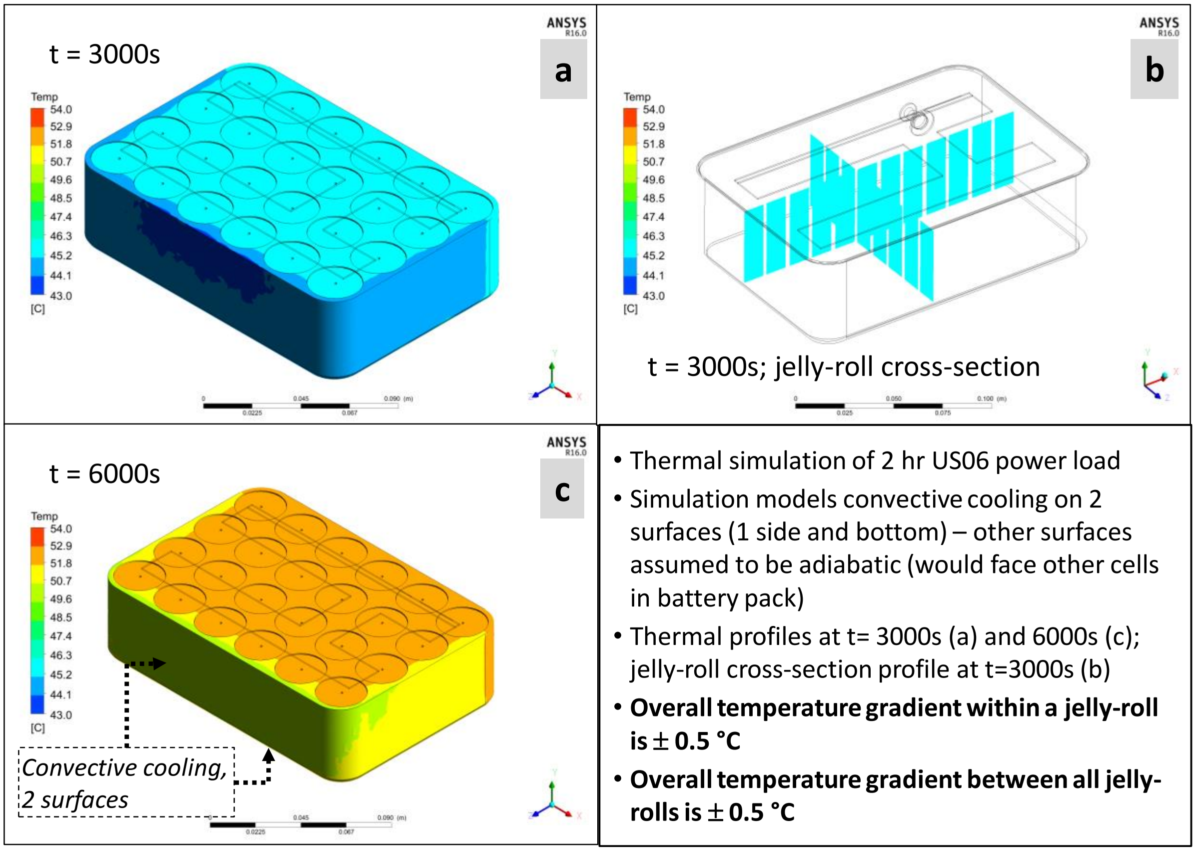


Figure 8: NREL Thermal Profile of Cadenza Supercell Under US06 Drive Cycle Load



Key Milestone: EV Application Level Validation – Fiat 500e

Figure 10: Fiat 500e Pack Built Using Cadenza Supercell Modules

For final project validation of Cadenza's supercell design, a battery pack was designed for testing in a Fiat 500e EV application. FCA made available the Fiat 500e vehicle test platform and AVL constructed the pack using 2x 6-series and 7x 12-series supercell modules (83 Ah, 22 V; 83 Ah, 44V), for a total 9-module pack configuration of 96 series supercells (83 Ah, 350 V). Figure 10 shows a 6-series module, the completed pack and a rendering of the Fiat 500e.

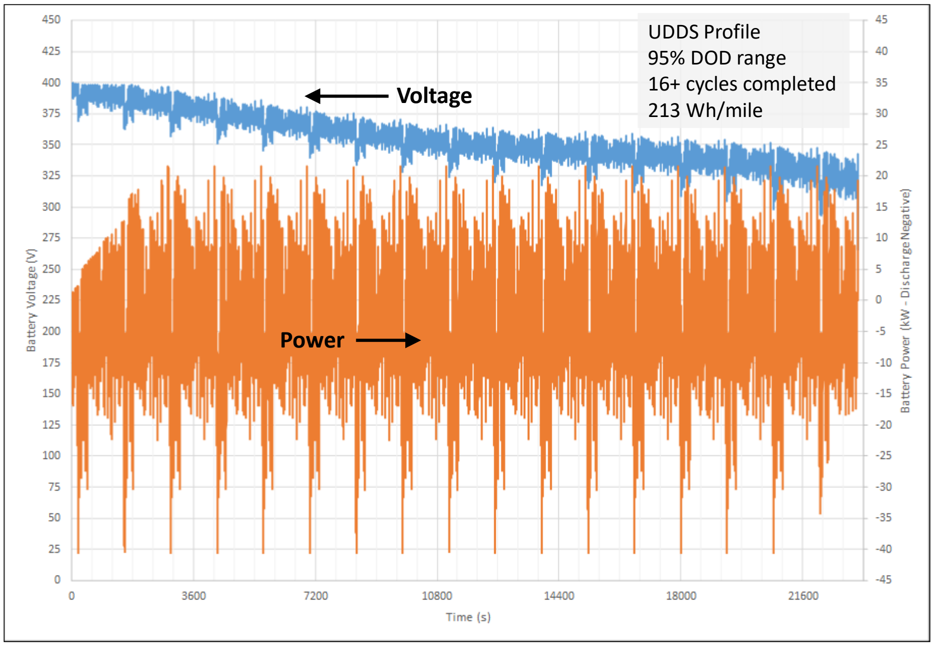
The unique supercell design enables advantages in terms of pack design. From a pack perspective, the supercell can be viewed as a large prismatic cell. Large cells are generally viewed as aiding in easier design and assembly of EV packs compared to smaller cells. Compared to polymer cell formats and some types of prismatic cells, the Cadenza supercell is structurally rigid so as not to need pack-level support for added stack pressure or in-pack mechanical stability. Again, this makes pack design and building easier and provides opportunity for lower cost. At the same time, the supercell is leveraging lowest cost small cell jelly-rolls and thus combines the advantages of small and large cells, while addressing the deficiencies of each, to provide an optimized pack solution. For example, soft-case cells, such as Li-polymer type cells, require significant external cell support structures in order to work within a pack. Such added pack mechanical components add cost and weight (reducing energy density). Meanwhile, small cylindrical cells do not have this same issue; however packs using small cells require a high degree of complexity to effectively connect and safely manage the cells. Anecdotally, assembly of the Fiat 500e pack using Cadenza supercells confirmed many of these advantages. A comparison of Cadenza's supercell advantages as compared with both large and small cell alternatives is presented in Table 2.

Table 2: Pack Perspective: Advantages of Cadenza's Supercell Design

vs. 18650 (Cylindrical) Cells	vs. Prismatic / Polymer Cells
• Enabled by improved safety design, tighter packaging of cells (jelly-rolls) provides increased pack energy density • Supercell behaves as a large cell, enabling easier and improved thermal management, and simplifying pack assembly • Minimized cell welding – pack sees single +/- connection to large cells (welds to jelly-rolls all internal); opportunity to use non-weld connections from module to cell	• Easier to manage safety (minimized energy release in safety events through use of more easily contained, small-sized jelly-rolls; better ability to prevent cell-to-cell thermal runaway propagation) • Lower cost based on standard, high volume, cylindrical jelly-roll units • Lessens component requirements for thermal management and fixturing, thereby lowering cost, weight and complexity • Potentially easier cell configurability to pack requirements (easier to customize supercell format compared to traditional large cell)

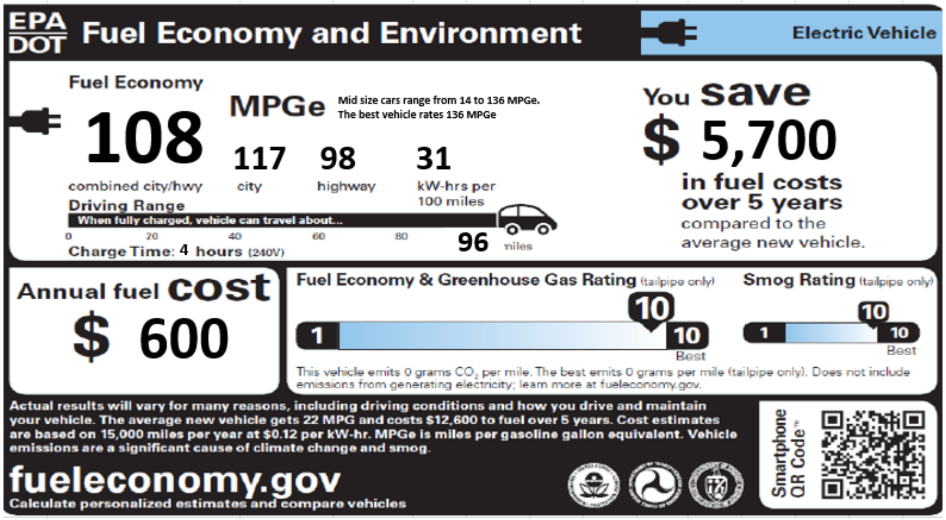
The advantages described above and listed in Table 2 are particularly relevant when considering battery sub-assemblies, or modules, used when building a complete, high energy, battery pack system from smaller energy cells. The modules accomplish the critical tasks of (1) forming electrical contact to the electrochemical energy storing cells, (2) defining the battery capacity in ampere-hours (Ah) through parallel cell connections, and (3) creating a standard packaging unit, including mechanical, electrical power, and electrical communication connections, that can be used in building the final EV battery. Additionally, the module design will consider and support effective thermal management of the pack. For the reasons described, the Cadenza supercell design better enables all of these module requirements. The electrical connections to jelly-rolls in the Cadenza design are established using standard cell manufacturing techniques while delivering, outwardly, a relatively simple electrical connection for packaging. This focuses the cell connecting function on cell manufacturing, where the expertise is well developed and the cost is lower, and lessens this burden on the pack side. This benefit is especially strong when compared to small-sized cylindrical cells. The Cadenza supercell removes the need to parallel connect cells, as the supercell can be designed to the specific capacity need of the application. Besides simplicity, this has value in better management of safety scenarios, since the entire array of cells can be bypassed in packs using the Cadenza supercell design. Finally, the Cadenza supercell module design requires less mechanical hardware, especially when compared to large prismatic and polymer type cells, and less thermal management hardware, especially compared to cylindrical and polymer cells. Preliminary cost analysis by Cadenza estimates that costs associated to parts and assembly of modules can be reduced by nearly 50% when using the Cadenza supercell design as compared to other cell formats.

Figure 11: Fiat 500e EV Using Cadenza Supercell Pack - Drive Cycle Test



AVL performed dynamometer drive testing on the Cadenza-powered Fiat 500e. Testing a UDDS (Urban Dynamometer Driving Schedule) profile and using a 95% DOD range, the vehicle successfully completed over 16 full cycles for a total distance of 200 km (124 miles) and an energy per mile rating of 213 Wh/mile (4.7 miles/kWh). The resulting voltage and power profile for this testing is shown in Figure 11. The test begins with a fully charged battery at nearly 400 V and simulates a driving profile with varying power loads and including regenerative breaking (charging). Testing includes acceleration pulse loads (discharge) of approximately -40 kW or 1.4C, and regenerative loads of approximately 20 kW or 0.7C. The test concludes once the battery reaches its lower voltage cut-off setting. This dynamometer data was inputted into standard models for calculating vehicle EPA-rated drive cycle efficiency (aka Monroney sticker data). Figure 12 shows this result, with modeled EPA ratings of 108 MPGe (combined city/highway) and 96 mile range. These values are nearly equivalent to the production released vehicle, which is quite impressive considering this demonstration is a non-optimized retro-fit design. Extrapolating from the 83 Ah supercell used in this Fiat 500e pack, to the 100 Ah supercell also developed and tested in this program, one can anticipate superior EPA-rated MPGe and RANGE from the 20% higher energy delivered in the same packaging footprint. This highlights both the long driving range capability in Cadenza's supercell technology, and the scalability of Cadenza's platform to developing battery chemistries. This Fiat 500e with Cadenza battery will continue to undergo performance evaluation and support additional development of Cadenza's technology beyond this ARPA-e program.

Figure 12: Fiat 500e with Cadenza Battery – Modeled EPA Rated Drive Efficiency



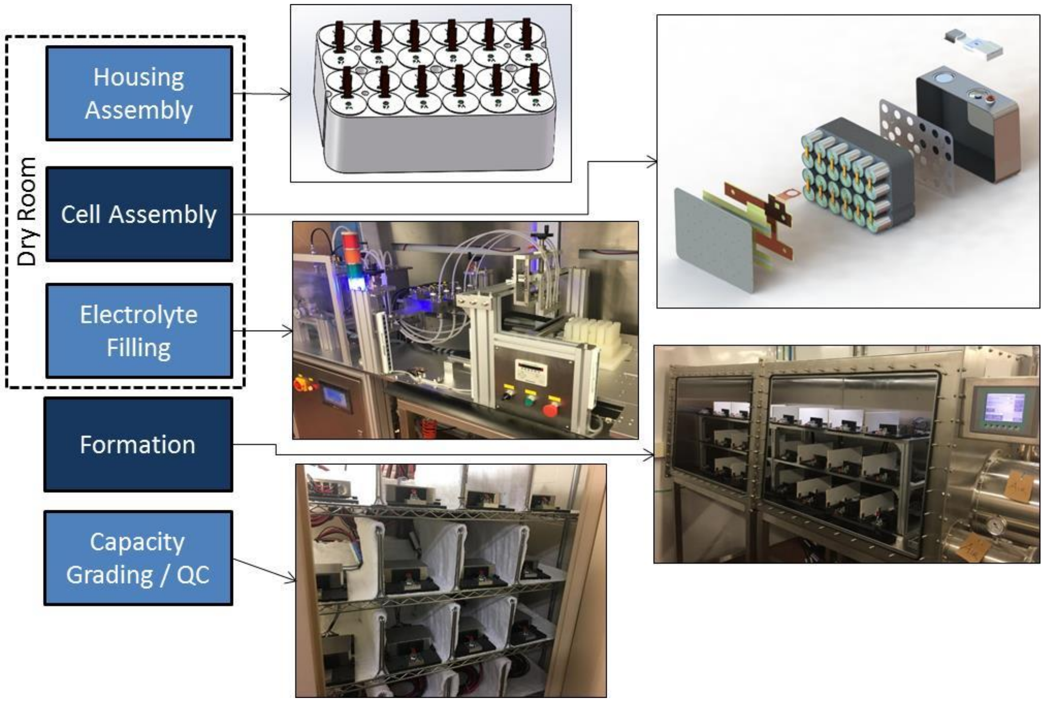
Technology-to-Market (T2M)

In addition to achieving program technical milestones, the Cadenza team addressed important commercialization requirements under the guidance of ARPA-e's T2M support. Key accomplishments include:

- Designed and built in-house low volume manufacturing line capable of producing 10 supercells per day
- Detailed total pack cost analysis using Cadenza's supercell design and manufacturing process
- Supported by results of this ARPE-e project, Cadenza has won follow-on funding of $1.5M from New York State and $10M from capital investors

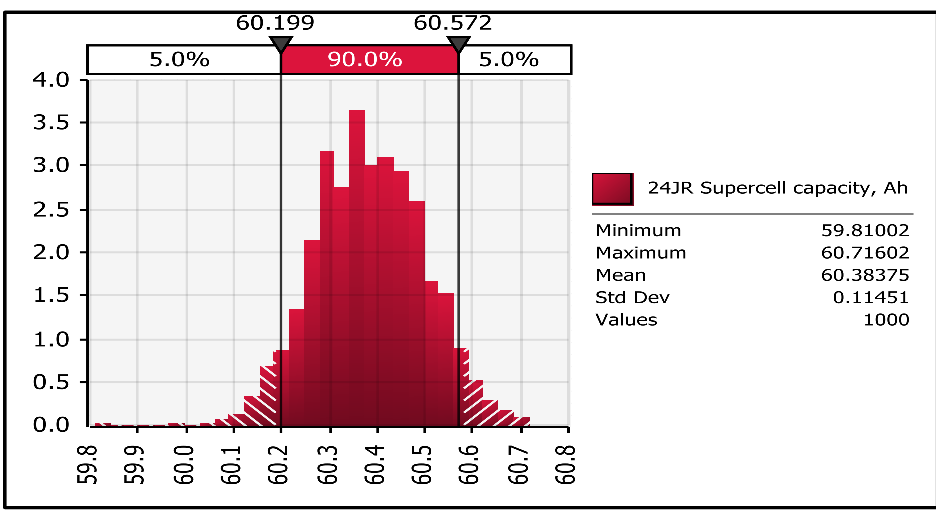
Figure 13 shows a process flow for manufacturing the Cadenza supercell. The Cadenza process begins with commercially sourced jelly-rolls. The jelly-rolls are assembled into Cadenza's proprietary housing and then electrically connected and enclosed into Cadenza's supercell format. This "cell assembly" process is unique to the Cadenza design and was developed as part of this project. All processes were developed with design for manufacturability in mind. This targeted standard manufacturing practices for high volume and six-sigma quality control. After cell assembly follows electrolyte filling, cell sealing, cell formation, and final grading and quality control. These steps are fully analogous to existing Li-ion cell manufacturing practices, requiring modification to meet the specific requirements of the supercell design. Key process steps validated include the use of automated laser welding to seal the supercell and automated electrolyte filling equipment for Cadenza's large format design. Of note in the overall cell manufacturing of the Cadenza supercell is that early process steps follow techniques established for small cylindrical cells where manufacturing throughput rates of ~200 ppm are standard, and then later process steps are more analogous to large cell manufacturing with standard rates of ~10 ppm – both capable of the same factory GWh (energy) throughput. Based on this process, Cadenza has achieved a production volume of 10 supercells per day in their Bethel, CT facility. Besides supplying cells for ongoing development and testing, this manufacturing line allowed validation of the supercell manufacturing process and supported cost analysis efforts.

Figure 13: Cadenza In-House 10x Supercell per Day Production Line



One area of manufacturing where the Cadenza supercell enables a cost savings is in the selection of jelly-rolls to populate the supercell. Normally, cell manufacturing will bin cells into groups of similar capacity range. The purpose of this binning is to keep cells of similar capacity together when building a battery pack. The normal capacity distribution between cells made on today's high volume production equipment is typically broader than what is desired for use in a battery pack. Thus binning prevents creating a capacity imbalance between cells in series in a pack, where such capacity imbalance can lower battery performance and accelerate capacity fade. Binning cells requires both time and equipment. In the case of Cadenza's supercell, combining multiple jelly-roll capacities into a single large cell capacity (in-parallel) means that with random selection of jelly-rolls, the larger supercells will naturally get produced to a tighter capacity distribution. This can eliminate the need for binning. Depending on the capacity distribution of the as-made jelly-rolls, the number of jelly-rolls used to create the supercell, and the desired level of capacity matching for series cells in a battery pack, the need for binning can be determined. A real-world example was verified through statistical modeling. The result of an analysis that modeled capacity for 60 Ah supercells made from 24, 18650 jelly-rolls, and using actual 18650 cell production capacity data is in shown in Figure 14 (analysis courtesy of Matt Hull at Duracell, Inc.). The

Figure 14: Supercell Capacity Distribution Analysis

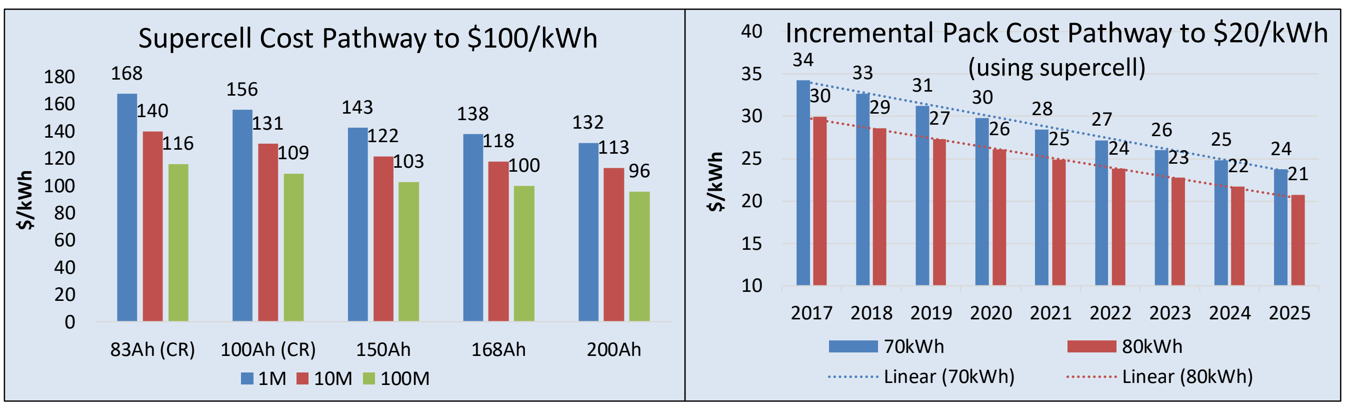


- Monte Carlo methods used to model capacity distribution of supercells built using a random selection of 18650 cell jelly-rolls
- 18650 capacity data taken from actual production batch of 70,000 cells

resulting distribution suggests that no binning of cells is required. This is because the capacity distribution in Cadenza supercells is within a range that is normally acceptable for building large battery packs with multiple series cells.

Using a detailed design costed-BOM combined with standard Li-ion battery manufacturing costs (consistent with Cadenza's in-house manufacturing line), Cadenza showed a path to the ARPA-e RANGE program's Li-ion battery cost target of $125/kWh. Firstly, since Cadenza's cell design leverages current high volume, wound cylindrical cells, costs were modeled using an 18650 cell jelly-roll. By building on this standard format, the largest volume format in Li-ion industry, both today and historically, ongoing world-wide cost down initiatives can quickly translate into Cadenza's design. For the complete Cadenza design, newer components from the global supply chain will scale with volume, consistent to industry practice. Cost also scales with cell capacity as the Cadenza super cell design allows for advances in cell chemistry and jelly-roll design to directly translate into the existing supercell architecture, thus achieving a lower $/kWh cost. The result of Cadenza's cost analysis is shown in Figure 15. Cell cost can reach less than $100/kWh and incremental pack cost can be less than $25/kWh, for a total battery pack cost meeting the ARPA-e RANGE goal. The supercell cost scales with both production volume and technology advances (higher capacity supercells). Higher capacity supercells can be achieved by both packaging improvements and advances in chemistry. Packaging improvements fit more jelly-rolls into the same space and this is enabled by Cadenza's technology and the ability to more safely package the jelly-rolls. Advances in chemistry are ongoing globally in the industry and can be readily adopted into jelly-rolls and thus into Cadenza's supercell design. Pack costs are modeled based on known industry pack designs and requirements. Cadenza's supercell technology enables pack cost savings, especially at the module level, due to ease of assembly and no need for external constraint on the supercells in order to maintain electrode stack pressures inside the cell. Further, estimates are made for savings in thermal management costs based on the improved thermal properties of the Cadenza cell design. Beyond the cost savings enabled by the supercell design, incremental pack costs trend forward in time based on the assumption of industry established cost-down trends.

Figure 15: Cost Analysis of Cadenza Supercell and EV Pack with Varying Production Volume and Cell Capacity



To-date, Cadenza has secured funding from investors to build a 25-person company and is currently in discussions with potential licensees. Battery system demonstrations include the above discussed Fiat 500e EV and a stationary energy storage system. Achievements under this project have led to Cadenza winning two awards, totaling $1.5M, from the New York State Energy Research and Development Authority (NYSERDA) to develop the technology into a product optimized for the peak shaving market in New York State. With the lower cost, driven by higher energy density jelly-rolls and simplified safety control features, this supercell could be disruptive for both EV and stationary storage utility markets.

As of January, 2018, Cadenza Innovation's project has generated nine invention disclosures to ARPA-E, with 8 U.S. and 10 foreign patent applications. The team has presented its technology and achievements at a number of open scientific conferences and publications, including the annual ARPA-e summit.

The novel battery architecture developed in this project offers an innovative approach to meeting the cost and performance requirements needed for the widespread adoption of EVs. Inexpensive and safe batteries will also find application in stationary energy storage, especially for behind-the-meter storage, which can help increase penetration of intermittent renewable energy sources. By supporting both EV adoption and renewable energy sources, the Cadenza team directly impacts the U.S. goals of reducing dependence on oil and lowering GHG emissions while developing and innovating US industry.

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