

# Utilizing Repurposed Automotive Lithium Ion Cells for Stationary Energy Storage

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## ABSTRACT

Due to the nature of the battery chemistry, most automotive Li-ion battery packs will need to be replaced after approximately 10 years of service. After that time, they are no longer suitable for their original application, but most will have approximately 80% of their energy storage capacity remaining. Based on sales over the last few years (and future projections), battery packs will start coming out of vehicles in large quantities around 2020. These cells are suitable for repurposing applications.

To demonstrate the effectiveness of repurposing automotive Li-ion cells, a small stationary energy storage system was constructed that could easily have more cells added to power essential appliances in a small home. Data collection capabilities of the system enable it to be used for testing of multiple types of cells or modules. Such information is crucial for the development of a cell repurposing program.

The constructed energy storage system was used to demonstrate grouped cell characteristics, as well as Battery Management System functionality. The basis of this work can be expanded and used for different Li-Ion cells, while providing a stepping stone towards the construction of a larger system for a stationary energy storage application. Adequate monitoring and battery management can be obtained through the implementation of an off-the-shelf system, or with the original manufacturer's monitoring system if it is thoroughly understood.

## INTRODUCTION

Since 2010, the number of hybrid and electric vehicles sold in the US has been increasing, though not at the rate that some have anticipated. Automotive experts suggest that 5 – 10% of the global automotive market will consist of electric vehicles by 2020<sup>1</sup>. With the shift in focus by nearly all major players in the automotive world, it is certain that batteries will continue to provide key roles in the transportation industry in the upcoming years.

Lithium-ion batteries should maintain at least 80% of their energy storage capacity in order to be acceptable for automotive applications. After a service life of approximately 10 years, battery packs will need to be replaced. The used cells with plenty of remaining capacity for other

applications are now good candidates for repurposing applications. It has been shown that under chosen assumptions, the batteries from hybrid electric vehicles (HEVs) and electric vehicles (EVs) can serve the needs of commercial and industrial end users with payback periods ranging from 7 to 10 years <sup>2</sup>. “This calculation considers the effects of battery degradation in both automotive and grid service, repurposing costs, balance-of-systems costs, the value of aggregated energy storage to commercial and industrial end users, and competitive technology to access the economic viability of battery second-use strategies <sup>2</sup>.”

With a growing population now relying on the energy grid to fuel vehicles, the value of the used automotive cells that still have a significant energy storage capacity remaining becomes more evident. Some have proposed that companies will purchase the used cells for stationary applications. For example, Toyota Motor Corporation has announced a plan to repurpose used battery packs from their hybrid vehicles into energy storage systems for their dealerships <sup>3</sup>. However, there are many other residential and municipal systems that could also benefit from repurposed HEV and EV batteries for stationary energy storage.

In the consumer market, there are many products and systems other than the automobile that are hindered by the high cost of lithium ion cells. With the influx of a surplus of less expensive cells, devices such as residential home load leveling systems can be created. The cost of such a device can be offset by charging during off-peak hours and discharging to the home during on-peak hours. Data analysis of load usage in occupied homes shows a relatively consistent pattern, in which a residential or community energy storage system could provide beneficial peak-shaving savings <sup>4</sup>.

The Center for Automotive Research published a study that indicates that 469,000 hybrid & electric cars will be on the roads by 2015 <sup>1</sup>. A breakdown of years leading up to 2015 (not including vehicles sold prior to 2012) shows the following:

- 193,000 cars on the road in 2013
- 329,000 cars on the road in 2014
- 469,000 cars on the road in 2015

If it is assumed that each battery pack contains nearly 200 cells (as in the Chevrolet Volt and Ford Transit EVs), and if it is assumed that battery packs will be replaced after 10 years of service life, there will be a large quantity of batteries available starting in 2020 with upwards of 50-80% capacity remaining. Although the peak of the repurposed battery market is still several years away, research into repurposing of the HEV and EV cells that are available at present will prepare for the large supply of seasoned cells that will soon be available. Despite the challenges, IDC Energy Insights anticipates that "repurposed" batteries will be a multibillion-dollar market by 2020 <sup>5</sup>.

Once a cell is removed from a battery pack, three options exist for the cell; (1) repurpose it in another application, (2) recycle the cell, or (3) dispose of the cell in the municipal waste stream.

The focus of the research described in this paper is the repurposing of automotive lithium ion batteries for stationary energy storage applications. A scalable model of a stationary energy storage system was constructed to serve as a demonstration unit, and to provide an example of the benefits and effectiveness of utilizing repurposed Li-ion cells.

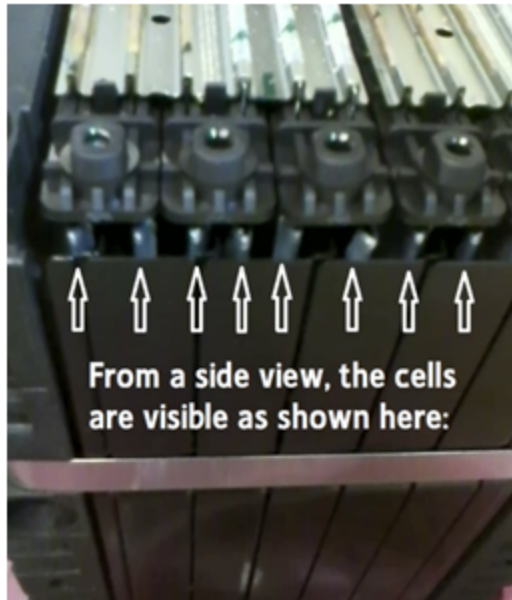
## SYSTEM ASSEMBLY

This system was constructed using components of A123 Power System's start-stop battery. The cathode active material within the cells of these batteries is lithium iron phosphate (A123's Nanophosphate® technology). In order to demonstrate the effectiveness of combining multiple modules together to increase the overall capacity, two modules were incorporated into the design.

The modules provided by the manufacturer had been cycled similarly during their service lifetime and were known to have similar state of life characteristics. However, these modules did not contain control hardware. The modules are shown in Figure 1.

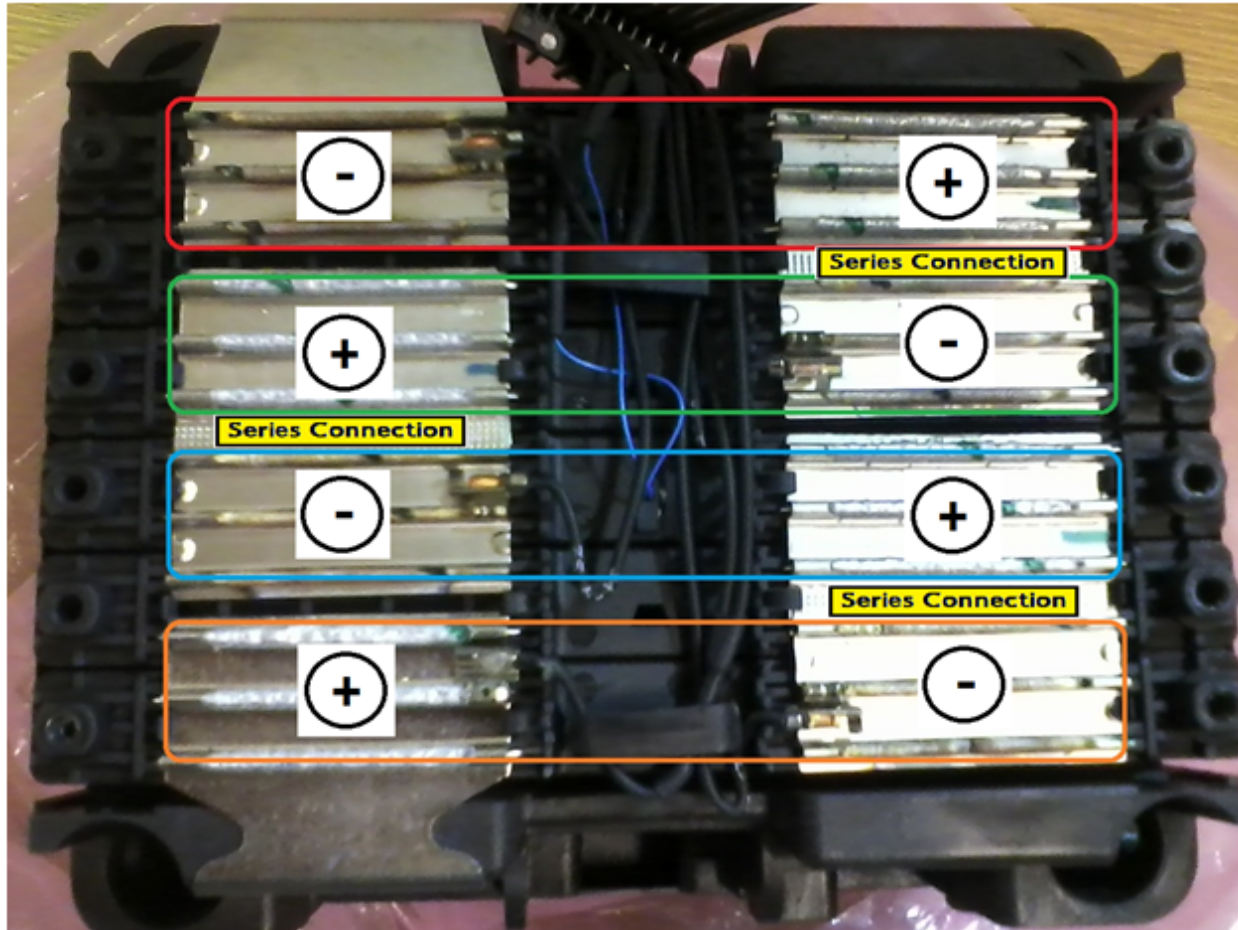


**Figure 1:** Complete A123 Power System's start-stop battery module (left), and view underneath the top cover (right).



**Figure 2:** Individual pouch cells stacked within a module.

The cells are stacked within the module, as shown in Figure 2. These modules have a 3p, 4s configuration (four groups of cells connected in series, with each group consisting of three cells in parallel). Each grouping of cells are connected by a bus bar with zipper fuse (labeled as “Series Connection” between each of the grouping of three cells outlined in Figure 3). Each individual cell has a voltage of 3.3 V and a capacity of 20 Ah. Three cells connected in parallel maintain the voltage of an individual cell at 3.3 V, however, because the capacity is additive in parallel, each group of 3 cells has a capacity of 60 Ah. Cell groups are connected in series (four groups of three cells) creating the net module voltage and capacity for this configuration of 13.2 V and 60 Ah, respectively.



**Figure 3:** 3P4S cell orientation.

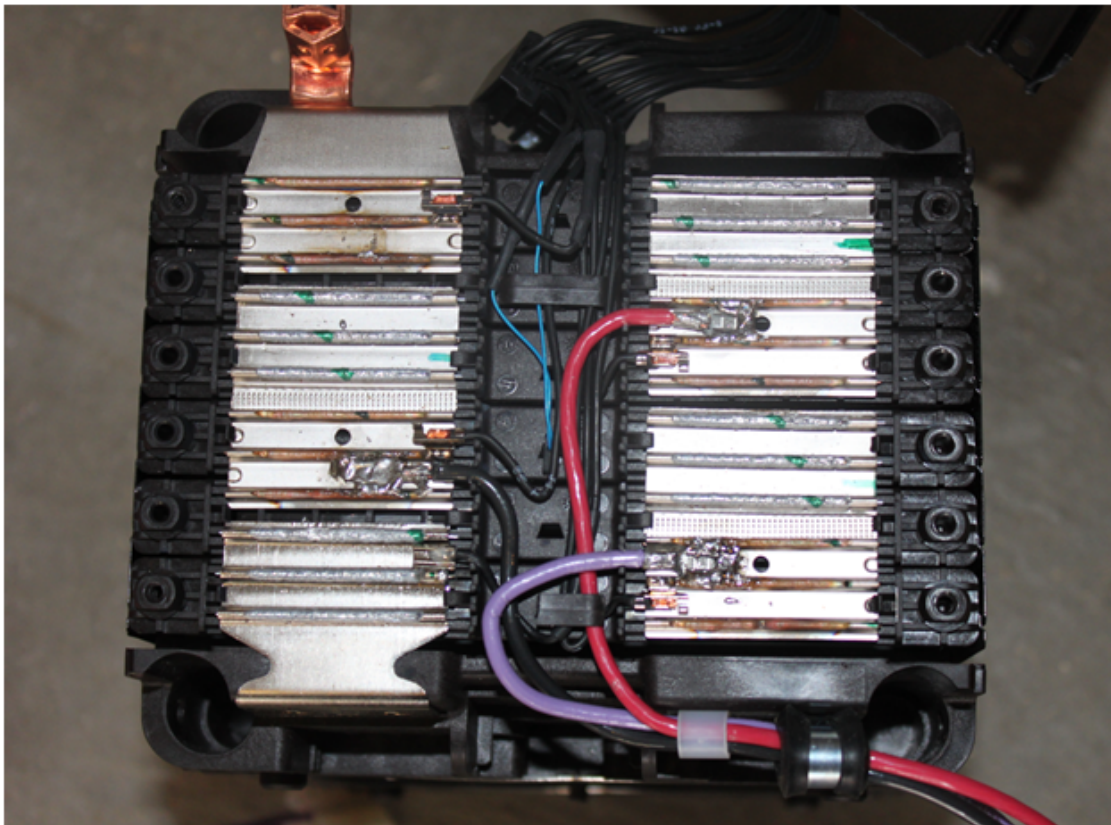
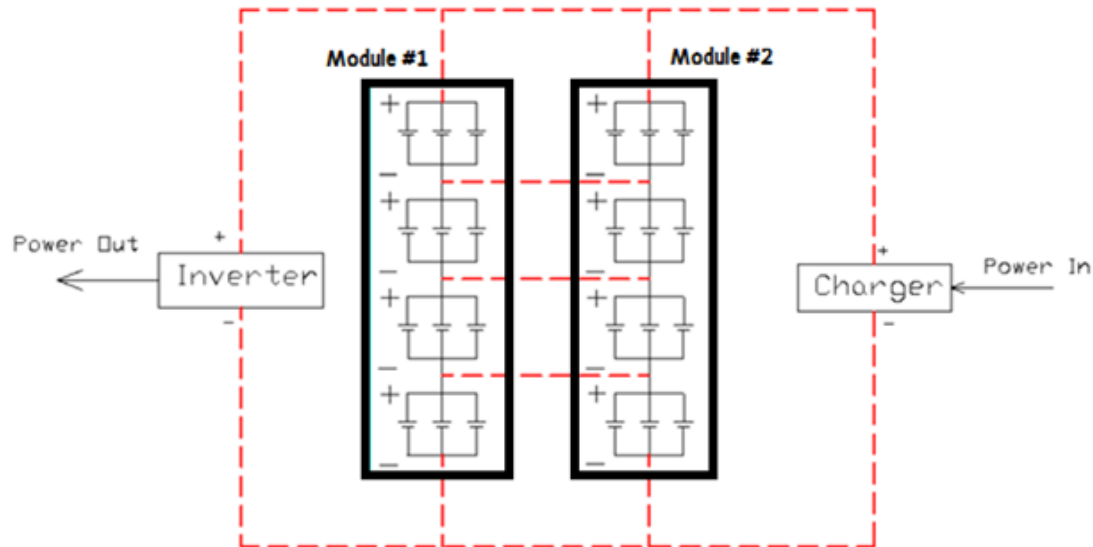
Two options were available for providing control for the modules: (1) to purchase an off-the shelf battery management system (BMS), or (2) to try to acquire the original manufacturer's control system. For this work, A123 provided a single BMS for the system.

Battery management systems utilize voltage measurements from individual cells or groups of cells in parallel. This is evident in Figure 3 as an array of wires soldered at various locations across the battery bus bars. In order to increase the capacity of this energy storage system, it was desired to connect multiple modules in parallel. This was a challenge because only 1 control system was available.

As stated earlier, each module consists of 4 groups of cells, and each group contains 3 cells in parallel. The BMS reads the temperature and voltage across each group. By adding another module in parallel, the number of cells in the assembly increased to 4 groups of cells, each group containing 6 cells. To ensure that the BMS is measuring the voltage across adjacent cell groups in the two modules, additional wiring was added to each module. This allowed Cell Group #1 in



Module #1 to be connected to Cell Group #1 in Module #2, Cell Group #2 in Module #1 to be connected to Cell Group #2 in Module #2, and so on. With the jumpers in place, the BMS can still function as designed and adequately control the increased number of cells. Figure 4 shows the balancing wires configuration.



**Figure 4:** Wiring schematic of 2 modules in parallel with jumper wires attached (upper). Jumper wires soldered to one module (lower).

The desired output for the system was chosen to be 120 VAC. In order to obtain useful electricity for commercial electronic devices, a power inverter was selected to generate 120 VAC from the DC battery source. Due to the wide variety of devices that may be drawing power from this unit, a Samlex 1000 W pure sine wave inverter was selected. This inverter can handle 10.5 – 15.3 VDC input, which is sufficient for the 13.2 V battery system. This system will provide a maximum of approximately 8 A at 120VAC, which will be sufficient for most devices.

As the modules are depleted, a source is needed to recharge them; therefore, a high-performance CellPro PowerLab 8 battery charger was selected for the assembly. This charger can provide up to 40 A of charge current, has many available Li-ion charge settings programmed, and also enables the user to program custom charge settings. Once connected, the software that accompanies the charger enables the user to record charge and discharge curves at the location of each balancing wire connection.

To provide a maximum charge current of 40 A for the module assembly, a Tripp Lite PR60 power supply was selected to compliment the charger. The input for this power supply is 120 VAC, and the maximum output is rated to be 13.8 VDC at 60 A.

An alternative means of charging was also incorporated into this design. Two Siemens SM46 solar panels were used to provide a source of power for the charger, as long as the output voltage was maintained within the specification limits of the charger. For the demonstration unit, the two solar panels could be connected at a distance of up to 50 feet away and were capable of outputting 46 W, or 14.6 V at 3.15 A. These panels were connected in parallel to maintain a charge voltage of 14.6 V. Due to the wide range of voltages accepted by the charger, these panels were able to be directly connected as a power source to the charger. The charger was then able to recharge the battery, based on user specified settings.

Since controlling of the system was already accomplished with the BMS, data acquisition was accomplished using a Cell-Log-8 Voltage Monitor to record data during charge and discharge cycles. With the help of Logview software, test data was collected, exported, and/or plotted for analysis. This complete system serves as a scalable demonstration of a residential energy storage system (ESS).

## **SYSTEM TESTING**

Multiple tests were conducted on the ESS to verify its functionality. A summary of the tests conducted were as follows:

- 1) Cell Balancing without a BMS: After the harnesses were initially constructed for the modules, the two modules were connected in parallel with the BMS disconnected. Due to slight voltage differences between the modules when initially connected, the cell groups balanced between the two modules in order to achieve a steady state condition. The balancing of the cells was recorded for analysis.

- 2) Solar Charging for 30 minutes: To increase the functionality of the ESS, it was desired to incorporate a solar power supply. For any ESS, the option of supplying power that is “off the grid” is of great interest. For testing purposes, it was important to analyze the effects of a renewable energy supply (such as solar panels) on the cells. In addition, an energy storage system is much more marketable if it can act as a stand-alone system, or reduce the amount of energy that a consumer purchases from the grid (when renewable resources are incorporated). This demonstration tested the effectiveness of charging the ESS with the two Siemens solar panels that were specified. The test was conducted on 04/21/2013 at 3:00 p.m. near Rapid City, MI. The weather was slightly overcast as shown in Figure 5. The panels were positioned at approximately 70 degrees from the ground, facing the sun.



**Figure 5:** Overcast weather conditions during the time of study (left and center) and position of the solar panels at approximately 70° from the ground (right).

## RESULTS

### *Cell Balancing Without the BMS*

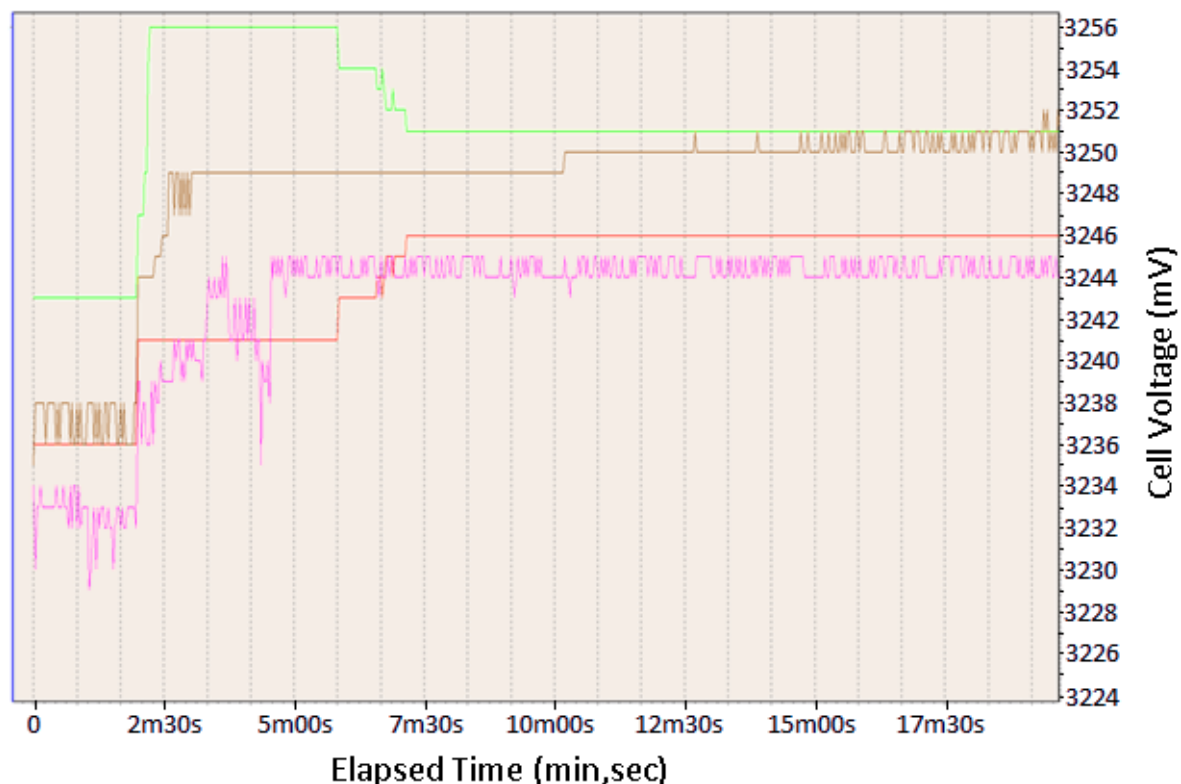
The two modules for this system had slightly different voltages before balancing. The module being monitored (module 1) had an initial voltage of 12.95 V, and the module being connected in parallel (module 2) had an initial voltage of 13.05 V. First, the 12 V module terminal wires were connected in parallel as illustrated in Figure 4 (upper), followed by the balancing wires. At this point, modules were joined in parallel and the CellLog provided measurements of each group of cells as the BMS performed balancing operations.

Module #2 had a higher voltage, therefore it was acting as the charging source for module #1. As shown in Figure 6, each of the cell groups in module #1 (the module being monitored) increased in voltage immediately after the two modules were connected. This occurred at



approximately 2 minutes after the Cell-Log began collecting data. After approximately 8 minutes, individual cell voltages plateaued, indicating that their voltage was approaching steady state.

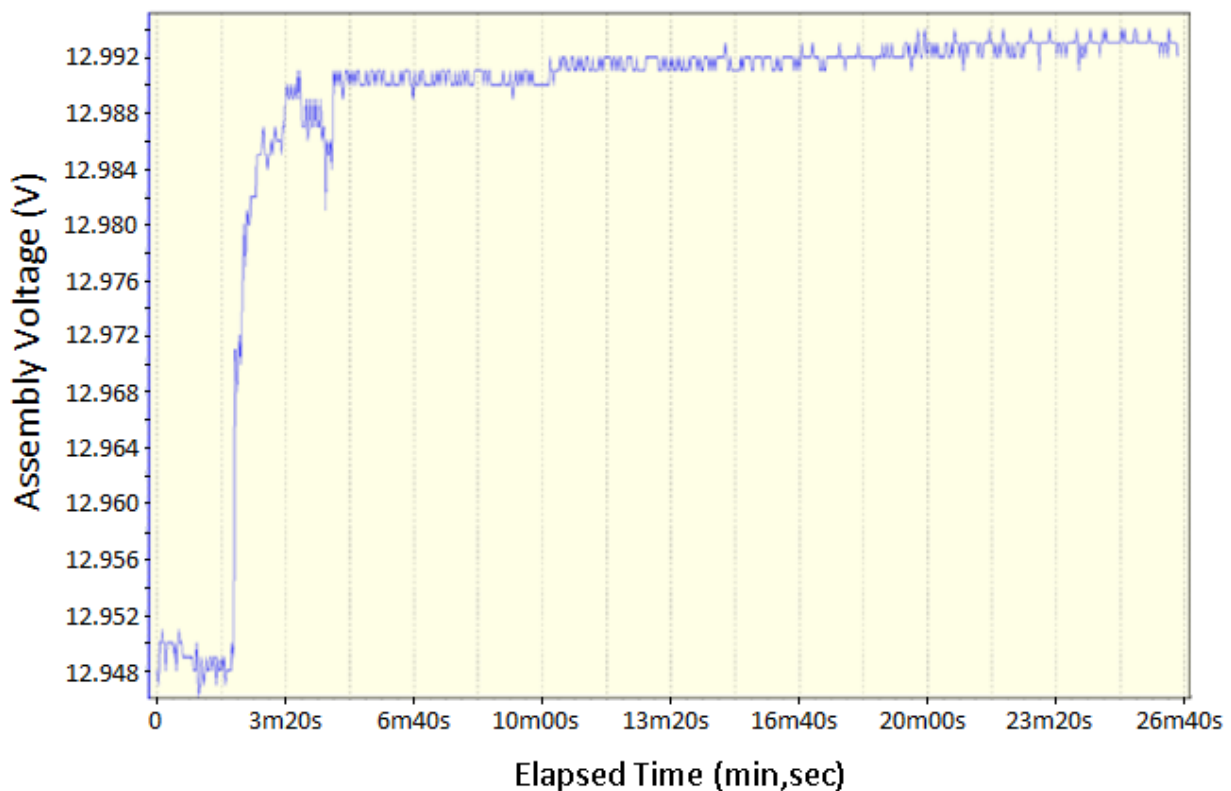
Even at what is being considered steady state conditions, the voltage for each cell group is still slightly different. This is to be expected, as no two cells or cell groups are exactly identical. The difference between cell group voltages is shown in Figure 7. At steady state, the maximum difference between the group of cells is approximately 7-8 mV.



**Figure 6:** Balancing of cell groups after modules were connected in parallel. Cell Group #1 = Red, Cell Group #2 = Green, Cell Group #3 = Brown, Cell Group #4 = Pink

As shown in Figure 7, the overall voltage of module #1 was monitored at the same time that the data in Figure 6 was collected for each cell group. The largest increase in module voltage occurred within the first 3 minutes of the modules being connected. The lack in voltage gain prior to the first 2 minutes was partially due to voltage data being collected as the modules were being connected. Earlier, it was concluded from Figure 6 that cells approached steady state after approximately 8 minutes. Between 8 and 20 minutes, the overall pack voltage increased by

approximately 3 mV. The steady state voltage that was achieved after approximately 20 minutes was 12.993 V. This balancing was safely performed due to the low difference between cell groups in the different modules. If there was a large difference, this method would not be recommended.

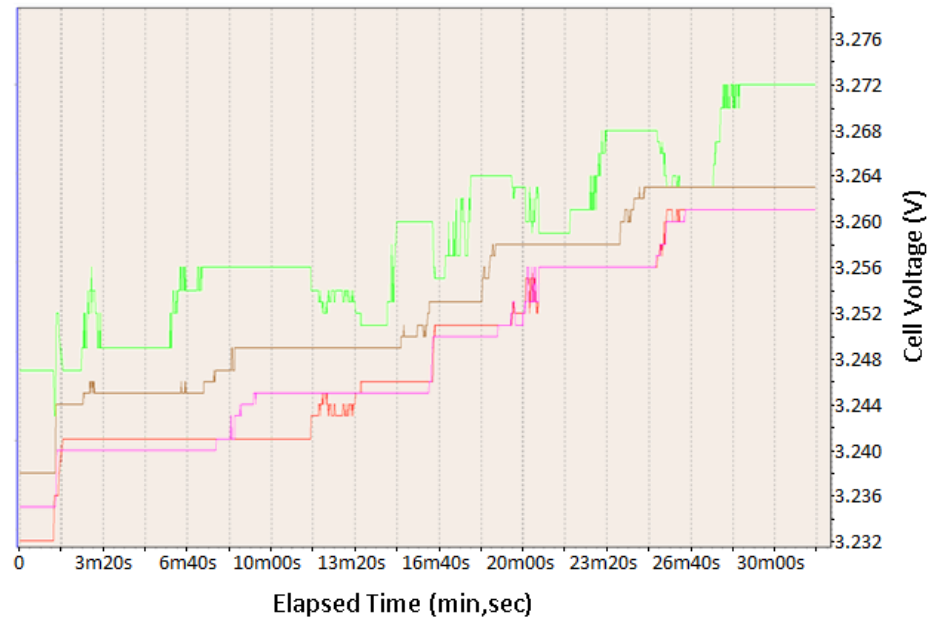


**Figure 7:** Voltage versus time for Module #1 (with an initial voltage of 12.95 V) after Module #2 (with an initial voltage of 13.05 V) was connected in parallel.

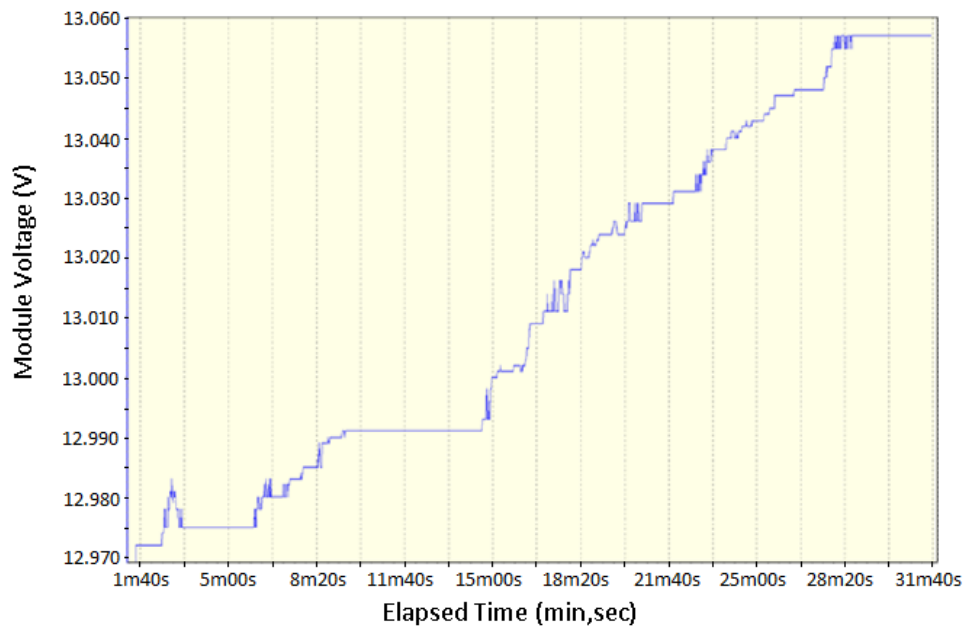
### *Solar Charging*

A plot of the recorded data from solar charging of the ESS is shown in Figure 8. Two factors contributed to the variation in the plotted data. First, due to cloudy conditions, the source of sunlight provided a variable power source. The power that is being applied to the battery system appears very sporadic on Figure 8 as a result of this variation. Secondly, continuous fluctuations of the cell voltages are due in part to the BMS conducting cell balancing operations.

The BMS continuously switched how the voltage is distributed to each cell group as the solar energy was supplied. Instances where a cell group voltage spikes and then plateaus are due to the BMS halting the supplied energy, prior to its redistribution. The overall pack voltage for the solar test is shown in Figure 9. Plateaus in the data are likely due to cloud cover when the solar panels are not providing enough power to charge the pack.



**Figure 8:** Individual Cell Voltages During 30 minute charging cycle. Cell Group #1 = Red, Cell Group #2 = Green, Cell Group #3 = Brown, Cell Group #4 = Pink



**Figure 9:** Battery pack assembly voltage versus time during charging with solar panels.

## DISCUSSION

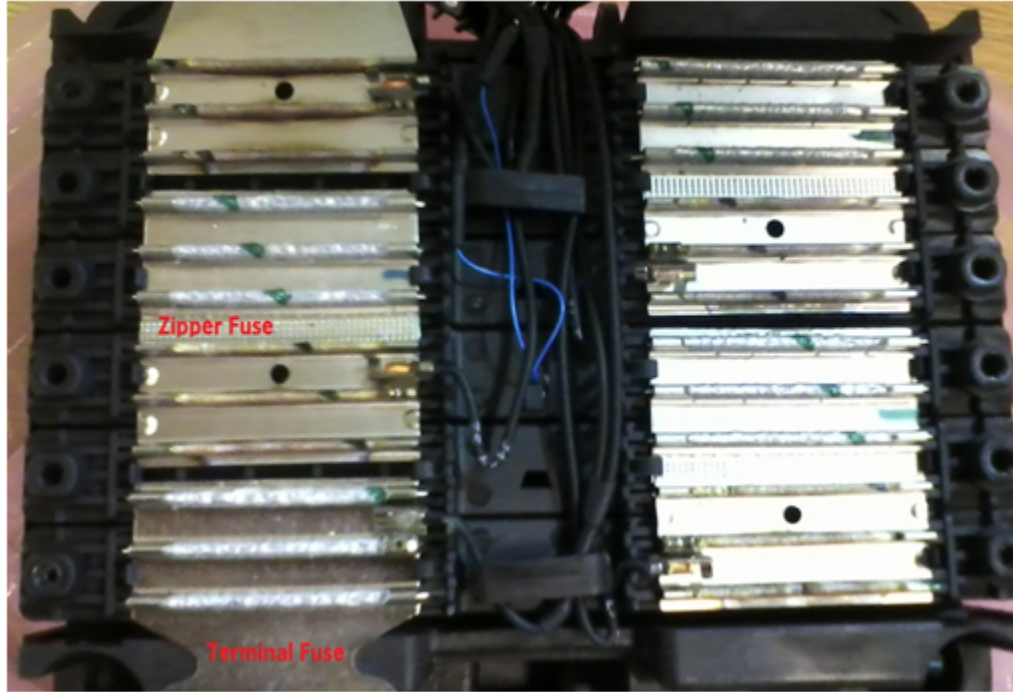
Controlling multiple modules with one BMS required careful thought and planning and several items merit further discussion. Connection of the jumper wires for merging cell groups was the key component to utilizing multiple modules with the single control system. With a schematic laid out as shown in Figure 4, the connections were made to each module as indicated. For future iterations, the same connections must be replicated for any module connected in parallel to this system. However, there are limits to what the control system can handle. This limit is primarily for balancing the cells.

Manual soldering of the bus bars was done with caution. Prior to soldering, the technical specifications of the cells were reviewed to find the maximum allowable temperature for the cells. Excessive heat can damage the internal components of the cell. In order to assure that the maximum cell temperature was not exceeded, a thermocouple was connected to a multi-meter and placed near the zone being soldered. Soldering was halted as soon as the local temperature reached 120 – 130°F and resumed once the temperature cooled. As the cells are charged, the system has a limited capacity to redistribute charge. A temporary heat sink located between the soldering area and cells also helps.

Once the wires were secured, wire clamps were connected to the mounting plate on the terminal, as shown in the lower right hand corner of the bottom image in Figure 4. This prevents the soldered bonds from breaking loose should anyone ever tug on the harness wires.

The blue wires shown in Figure 4 were used to monitor module temperature. With only one module connected to the BMS, this could be accomplished as designed by the supplier of the system. However, when multiple modules are connected in parallel this connection becomes lost. Therefore, it is recommended that future iterations of this project incorporate a temperature measuring/monitoring feature to disable a module if excess temperature becomes a factor. Due to the fact that both modules are nearly identical in nature (as they had the same lifetime experiences), if module #2 experiences elevated temperature, so should module #1. The BMS will perform its programmed response. With the current design, it is recommended that the system is monitored if being charged or discharged for long periods of time. In the future, existing thermocouple wires could be utilized if they were multiplexed. By incorporating an analog multiplexer, it becomes possible to forward each of the individual temperature inputs to the BMS.

A123 did well at incorporating three key safety features into the module design; the BMS, zipper fuses, and terminal fuses. If an incident were to occur where module terminals were improperly connected, the tapered neck, labeled as “Terminal Fuse” in Figure 10, would break (acting as a fuse). Zipper fuses connect the cell groups in series on bus bars, as shown in Figure 10. If current becomes too high (exceeds 300 Amps), these fuses will break. Additionally, if functioning properly, the BMS will prevent any voltage or current overload.



**Figure 10:** Zipper and terminal fuses.

The demonstration unit that was constructed for this project has potential to be scaled as a marketable product for multiple applications. However, the industry surrounding reclaimed or repurposed cells faces several challenges. In order to construct a repurposed battery system, cells must have similar capacities and product characteristics (such as maximum and minimum voltage and current limits) in order to merge control systems. As the repurposing industry is ramping up, perhaps the first hurdle to overcome will be obtaining a supply of cells that have similar characteristics such as product make/model and remaining capacity. This will be a challenge until cells begin coming out of vehicles in mass quantities.

Prior work in the sector of control systems for repurposed batteries has demonstrated that by using DC-DC power electronics, individual batteries can be isolated, allowing the use of batteries with different states of charge and output voltages<sup>8</sup>. However, the construction of large systems with cells from multiple manufacturers requires further development. Because Li-ion cells are susceptible to thermal runaway and failure during overcharge or cell reversal, battery packs will require electronics at the module or cell level that prevent this from happening<sup>9</sup>. When integrated into a stationary storage system, these electronics will need to be integrated at the pack level.

The work in this project proved that it is possible to construct small scale modules or battery packs (at least one of which has an operating control system) that could merged into a larger system. This would help to overcome the need to match tens or hundreds of cells in order to make a large pack.



Another challenge is the market's perception of a remanufactured good as being "used" or lower quality. To address this, remanufacturing facilities will need to supply a warranty, which many consumers will demand. This will likely be similar to the used car market.

Much of the demand for products containing Li-ion technology seems to be restricted by the high cost of the Li-ion cells. This is primarily due to high manufacturing costs of the cells, which is to be expected of a newer technology. If cells were less expensive, there may be more of an influx of new products that are currently limited by production costs. The influx of a less expensive, yet just as effective product such as repurposed cells and modules may play a key role in the development of future products.

## CONCLUSIONS

The energy storage system that was constructed served as a learning tool as well as a stepping stone towards the construction of a larger system for a residential application. Adequate monitoring and battery management can be obtained through the implementation of an off-the-shelf system, or with the original manufacturer's monitoring system if it is thoroughly understood.

Despite the technical issues that need to be addressed, the legal issues are the most challenging. Many battery manufacturers are hesitant to repurpose used batteries. This is due to the liability born by the company performing the repurposing. In addition, shipping regulations make transport of retired battery systems difficult as well.

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