Critical Analysis of Battery Technology for Utility Level Storage

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Abstract:

This paper analyzes batteries for utility level storage and the efforts of Tesla to bring this technology to consumers. Tesla's vision for utility level storage as well as their home utility level storage technology are discussed. Three individual cells similar to the 21700 Li-ion cells that will be used by Tesla were tested for charge/discharge capacity over time at a charge/discharge rate of 1C and for their reaction to discharge rates from 1-5C. The capacity data was analyzed to see if these batteries, which are similar to the ones that will be used by Tesla, are cost effective by calculating their levelized energy cost. The tests performed at different discharge rates determine if these batteries will be able to handle the variable load they might encounter in a utility level storage application. It was found that these batteries and the battery proposed by Tesla are not yet cost effective in utility level storage applications. However, high volume production and research of Li-ion batteries are expected to reduce the overall cost in the near future. The future vision of this paper discusses the use of all solid state batteries and the performance characteristics of the ideal battery for utility level storage.

Introduction:

In the world today the demand for power at certain times outweighs the power plants ability to supply. These times known as peak times cause a rise in the price of electricity and put on a strain on the grid to keep up with demand. In order to meet the demand of all of the people who need power, power companies need to do one of two things. The first option is for power plants to establish smaller auxiliary plants that can be turned on and off at peak times. These are aptly called peak plants. A common fuel source for peak plants is natural gas. The second option is known as load shifting by means of utility level storage. Opposite of the peak times where there is a shortage of power and it is expensive to use electricity, there are also off- peak times where electricity is readily available and cheap. Depending on the structure of the utility level storage system, either the power plants themselves or individuals will take advantage of this low cost and high availability to store power for later use.

There are several options for utility level storage that can be implemented to meet the peak electricity demand. Historically the most popular form of utility level storage has been “pumped- hydro” where power is used to pump water to an elevated reservoir during the off-peak period and flow down the pumped water to generate power by turbines during the peak demand period. Other examples of storing energy conventionally include (i) a flywheel (mechanical energy storage), (ii) heated molten salt, (iii) compressed air and many more. An example of storing energy unconventionally by gravity utilizes dragging a heavy train up a hill then letting it roll back down to generate electricity from the turning wheels of the train that turn turbines[1]. The main idea of utility level storage is to take the power conventionally generated in a power plant and then store it as efficiently as possible in some other form until you need it back again.

Recently, there is increasing focus on exploiting battery technology for utility level storage. The advantage that batteries have over many other conventional utility level storage methods is their compactness, portability, and lack of toxic chemical emission. Different battery chemistries are able to store a high density of energy in a given volume which is good for individuals who would want to implement utility level storage within their homes. Similarly, batteries for utility level storage are able to be placed anywhere as they have virtually zero emissions. Pumped hydro on the other hand would not be practical in a garage. The main factors limiting batteries from widespread use in homes for utility level storage are safety, longevity and cost. Batteries for utility level storage cost significantly more than many other utility level storage solutions and even peak power costs.

The cost of power generation and utility level storage is the single most important factor in determining whether a given technology will be viable for general use. Individuals and power companies alike aspire for competitive electricity rates. While an average American may pay around $0.12 per kWh for electricity[2], it only costs around $0.03-0.04 per kWh for the power companies to produce[3]. Therefore, the cost target of any alternate technology for utility level storage has to meet or exceed $0.03-0.04 per kWh to be successful for power companies. For individuals trying to reduce their costs, the same is true, but the benchmark cost they must consider is the amount they pay for power during peak times. When a power company or individual is considering peak power production and/or load shifting by means of utility level storage they should first consider the benchmark cost, and then secondly consider what is feasible within those cost parameters.

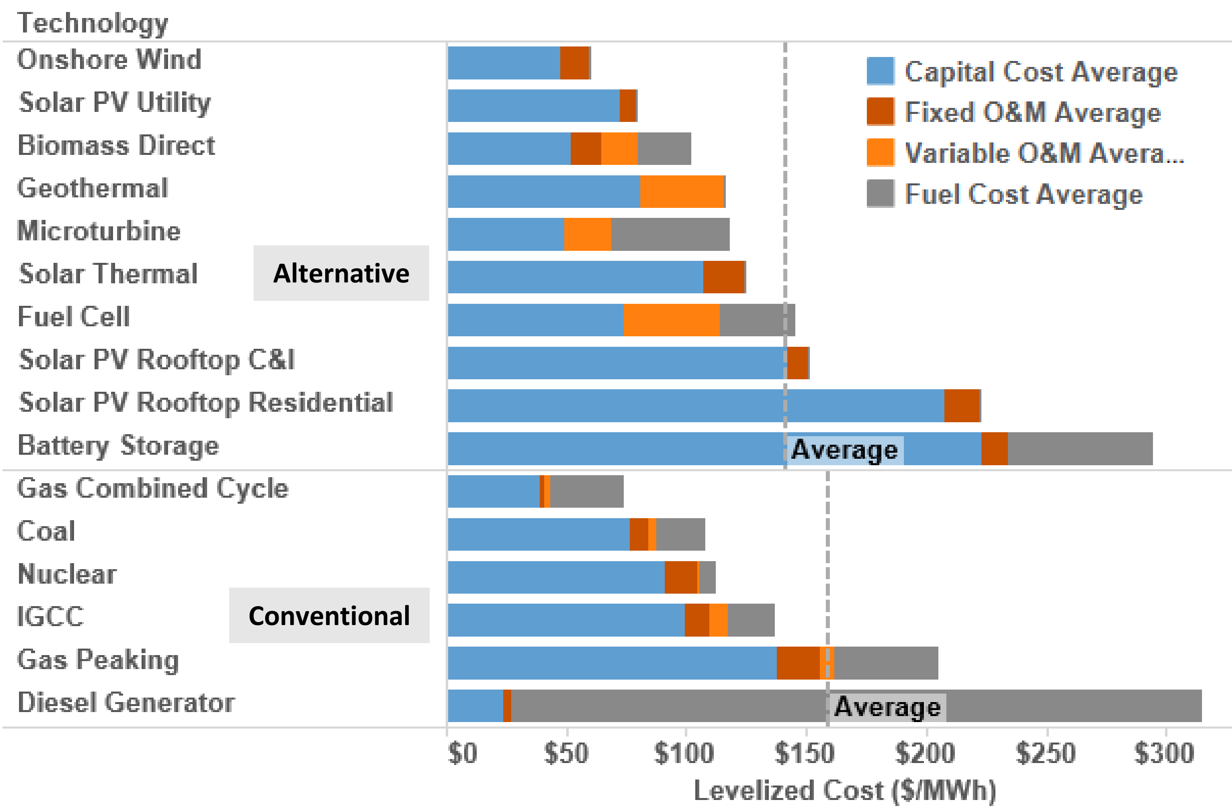


Fig 1. A comparison of the Levelized Cost of Energy for conventional and alternative power technologies[4] (courtesy of Lazard.com)

There are several companies attempting to market batteries for utility level storage[5, 6, 7]. The most prominent of these companies being Tesla. Tesla's product is designed for homes and businesses who want to take advantage of batteries for utility level storage and uses several individual rechargeable Li-ion batteries similar to the ones Tesla uses in their cars to store energy. This paper will focus on the technology of Tesla and compare their claimed performance and goals with charge discharge tests done on batteries of similar chemistry and form factor.

It is clear that battery based technology creates a new paradigm that can fundamentally change power generation and its distribution at all levels including residential, and remote locations. Based on the current status of battery technology, two possible scenarios for the utility level battery technologies are envisioned: 1. Rechargeable Lithium ion batteries (Li-ion) for local and micro-grid level power generation similar to Tesla's vision, and 2. Vanadium Redox Flow batteries (VRF) for a grid level power generation. We also postulate that inclusion of solid state electrolyte in Li-ion batteries is a must for this technology to be adopted for utility level power generation, primarily driven by safety concerns.

a.

Storage	Li-ion	VRF	Pumped Hydro
Pros	• Compact • Zero emissions • Not site specific	• Safety • Zero emissions • Longevity • Cost	• Safety • Longevity • Cost
Cons	• Safety • Longevity • Cost	• Large • Site Specific	• Site Specific • Disruptive • Complex

b.

Power	Coal	Nuclear	Solar	Wind
Pros	• Cost • Simplicity	• Green • Footprint	• Green • Cost • Simplicity • Renewable	• Green • Cost • Renewable
Cons	• Pollution • Fuel supply	• Complex • Fuel supply • Cost	• Footprint • Efficiency • Unreliable source	• Footprint • Unreliable source

Fig 2. Tables comparing the advantages and disadvantages of different utility level storage and power generation processes. a. A comparison of Li-ion, VRF, and Pumped Hydro technologies for utility level storage. b. A comparison of Coal, Nuclear, Solar, and Wind Power technologies for power generation

Methods and Materials:

Tesla's vision for home power is comprised of three parts. These three parts are the power grid, solar panels or other renewable energy sources located at home, and Tesla's individual rechargeable battery utility level storage solution. During the day or when renewable energy is available, the primary source of power for the house will be the renewable energy source. If this source of power is creating more energy than the house is utilizing, the excess will be diverted into charging the batteries for utility level storage, and if that is fully charged then this power will be put back into the grid for credit from the power company. If this source of power is not enough to meet demands, power will come from the batteries for utility level storage or the power grid if the batteries are fully discharged. At night or when no renewable energy is available, power will come primarily from the batteries for utility level storage or if they are completely discharged, the grid. In this vision, homeowners are the least dependent on power companies, and in some scenarios will be able to feed power into the grid for credit.

The structure of Tesla's home utility level storage solution is comprised of hundreds of individual rechargeable battery cells. The specific batteries Tesla uses are their new 21700 form factor cylindrical cells which are jointly manufactured by Tesla and Panasonic. The structure of cells are different to conventional prismatic cells like those found in other electronics where cylindrical cells have several different anodes and cathodes wrapped around each other and each attached to their respective current collector. In Tesla's utility level storage solution these individual batteries will be connected in groups of series and parallel connections to get the desired power output. The cooling system of Tesla's home utility level storage solution is interwoven between the individual rechargeable cells much like in Tesla cars. This system is able to cool the individual batteries over a larger surface area than if Tesla used a large prismatic cell that could only be cooled from the outside. From there, the electricity from the batteries is fed into an inverter which makes it usable in the home. One Tesla home utility level storage module has a capacity of 13.5 kWh and currently a system can be scaled to 10 modules.

a. b. c.

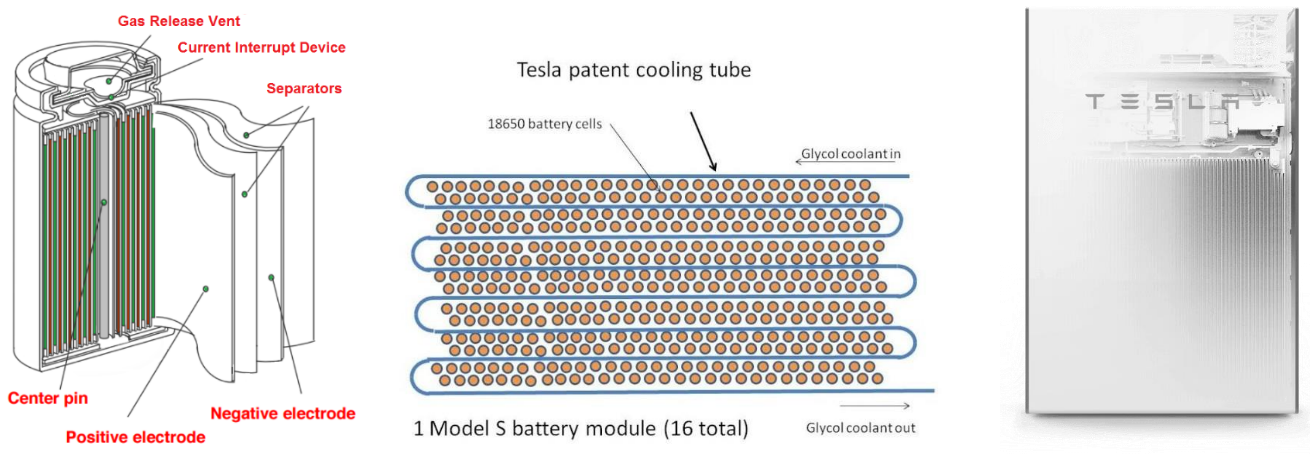


Fig. 3.Demonstration of different Tesla technologies implemented in their utility level storage solution. a. A cross section diagram of a Tesla cylindrical cell[8] (courtesy of electricbike.com) b. A simplified diagram of Tesla's battery cooling system[9] (courtesy of insideevs.com). c. a partial internal view of Tesla's utility level storage module[7] (courtesy of tesla.com).

Since the individual battery cells used by Tesla in their home utility level storage solution are not readily available, for the purpose of this research, several charge discharge tests were carried out on batteries with similar characteristics to those planned for Tesla's utility level storage solution. In rechargeable batteries, the use of different cathode materials will change the capacity and other performance characteristics of the battery. Tesla itself uses conventional Li-ion technology but there are other variations of lithium based rechargeable batteries which have also shown promising results for utility level storage. That is why three different lithium based chemistries from different suppliers were chosen for these tests. The three batteries that were tested in this research were a Nanophosphate $LiFePO_4$ cell in a 26650 form factor made by A123 Systems[10], a LiNiMnCo cell in a 26650 form factor made by AA Portable Battery Corp.[11], and a Li-ion cell in an 18500 form factor made by Panasonic[12]. The capacities of these batteries are 8Wh, 14.4Wh, and 7.344Wh, respectively based upon their specification sheets.

a. b. c. d.

Fig. 4. Individual rechargeable batteries compared in this research. a. Nanophosphate $LiFePO_4$ cell in a 26650 form factor made by A123 Systems[10] (courtesy of batteryspace.com) b. LiNiMnCo cell in a 26650 form factor made by AA Portable Battery Corp.[11] (courtesy of batteryspace.com). c. Li-ion cell in an 18500 form factor made by Panasonic[12] (courtesy of batteryspace.com). d. Tesla's 21700 form factor Li-ion cell produced with partner Panasonic[13] (courtesy of electrek.co).

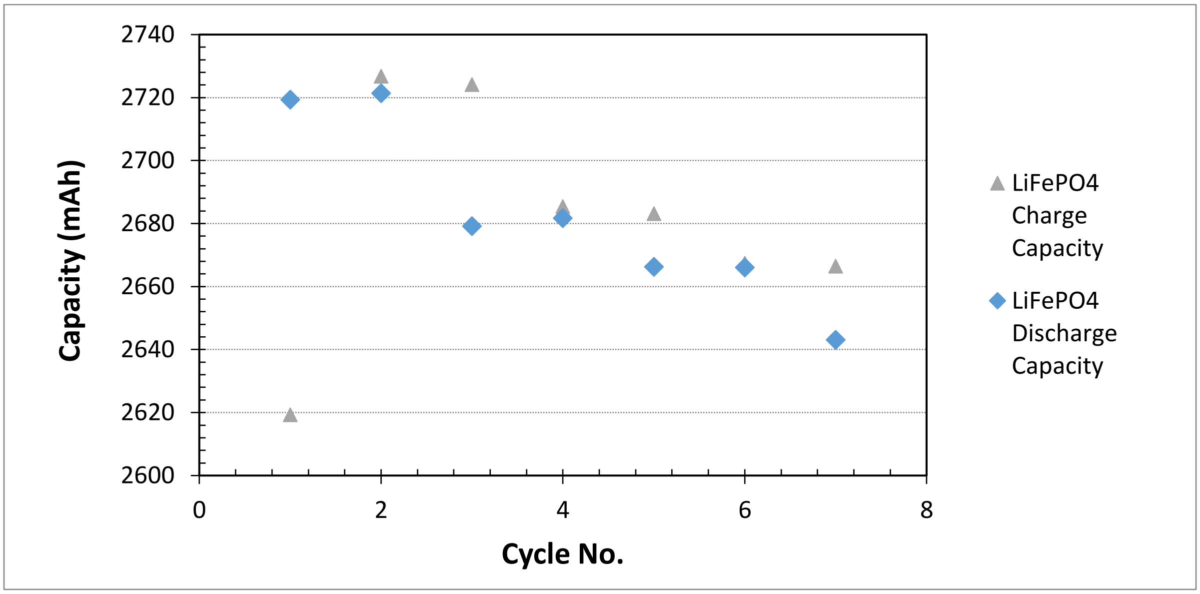
The charge/discharge tests performed on these "pseudo-Tesla" batteries were specifically chosen to test viability for utility level storage and some of the conditions these batteries may face in real life scenarios. The first test was a measure of the charged and discharged capacity of each of these individual batteries. The goal of this test is to examine the degradation in capacity over time of these batteries to effectively estimate their lifecycle in a utility level storage solution. This test was performed at a rate of 1C. A charge rate of 1 C defines that a battery will fully charge in one hour for a given current value. Therefore 1C can be 1 Ah or 1 mAh or 100 mAh or other values depending on the capacity of the battery. In the above example, a 1Ah battery will fully charge in 1 hour with 1 A current, and so on. The second test was a measure of charge/discharge time at a constant charge rate of 1C and different discharge rates from 1-5C. The goal of this test was to examine whether or not the batteries could be discharged at different rates depending on the power demand.

In addition to being a measure of viability for utility level storage, these performance tests help to estimate the levelized cost of energy (LCOE) for these batteries. For the LCOE of utility level storage and power options not tested in this specific research, other reports will be cited. For the batteries tested in this research LCOE will be calculated using cost of the battery unit per kWh, effective cycle life, round trip efficiency, and depth of discharge. The equation for this is $\$\boldsymbol{kWh} = \frac{\$\boldsymbol{T}}{\mathbf{C*E*DoD}}$ where \$kWh is LCOE per kWh[14], \$T is the cost of the battery unit per kWh, C is cycle life, E is efficiency, and DoD is depth of discharge. These costs do not include the inverter and any other management devices necessary for connecting the utility level storage modules to the house and managing their use. In the equation these would be added to the cost of the battery unit but are the same for each technology so they can be neglected. Efficiency will be taken from these batteries' specification sheets and depth of discharge for all batteries is set to 80%.

Results:

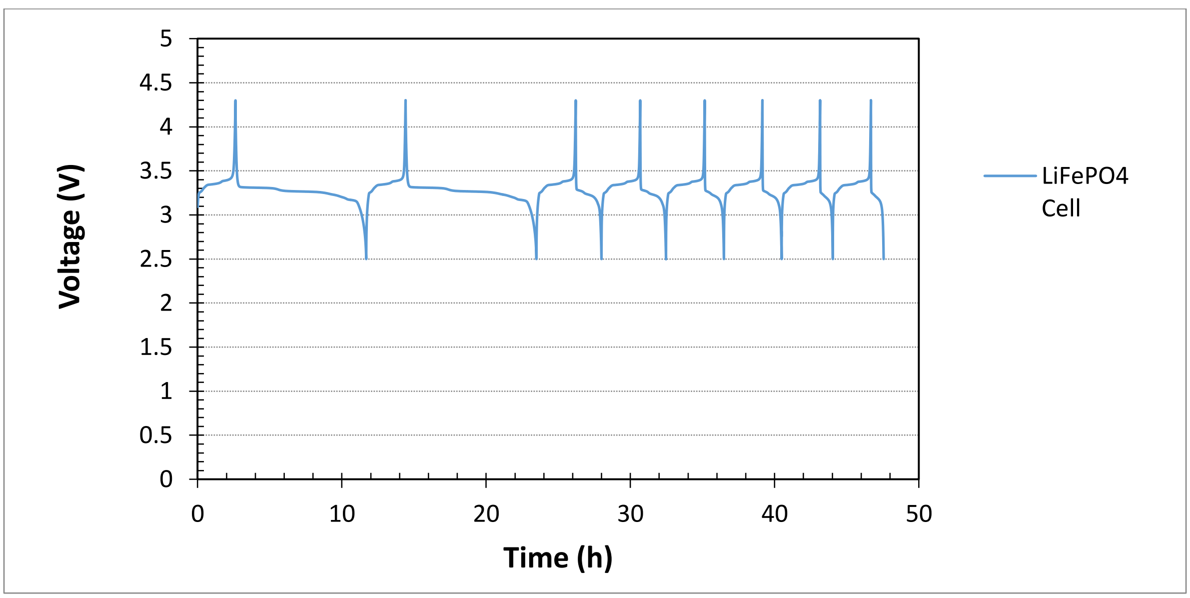
It is well known that all batteries degrade in performance over time irrespective of the technology used to make them. In the first test done to measure charge/discharge capacity over a series of 7 cycles at 1C charge/discharge rate it was found that the capacity of the Nanophosphate $LiFePO_4$ cell decreased by 0.48%. Examining the charge discharge graphs provided in the specification sheet for this battery, Fig. 5c, allow the extrapolation of results over seven cycles to a general trend over time based upon the shape of the provided graph. Using the combination of the experimental data and the trend from the specification sheet it is expected that this battery will last around 1500 cycles before its capacity will drop below 80%[15]. If it assumed that this battery is integrated into a utility level storage system, it would last just over 3 years until significant capacity loss and would be in need of replacement assuming a maximum charge/discharge rate of 1C. In the charge/discharge rate tests, the battery held up to a maximum discharge rate of 5C exhibiting normal charge/discharge curves. The LCOE of this battery was determined to be \$0.98 per kWh with a total cost per kWh of \$1168.27, a cycle life of around 1500 cycles, an efficiency of 99%, and a depth of discharge of 80%.

a.



2740
2720
2700
2680
2660
2640
2620
2600
Capacity (mAh)
0
2
4
6
8
Cycle No.
LiFePO4 Charge Capacity
LiFePO4 Discharge Capacity

b.



5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Voltage (V)
0
10
20
30
40
50
Time (h)
LiFePO4 Cell

c.

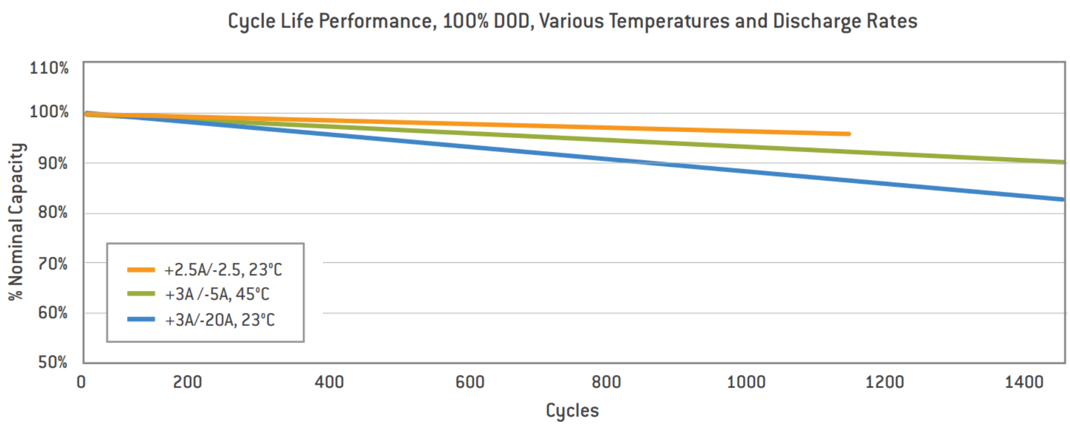
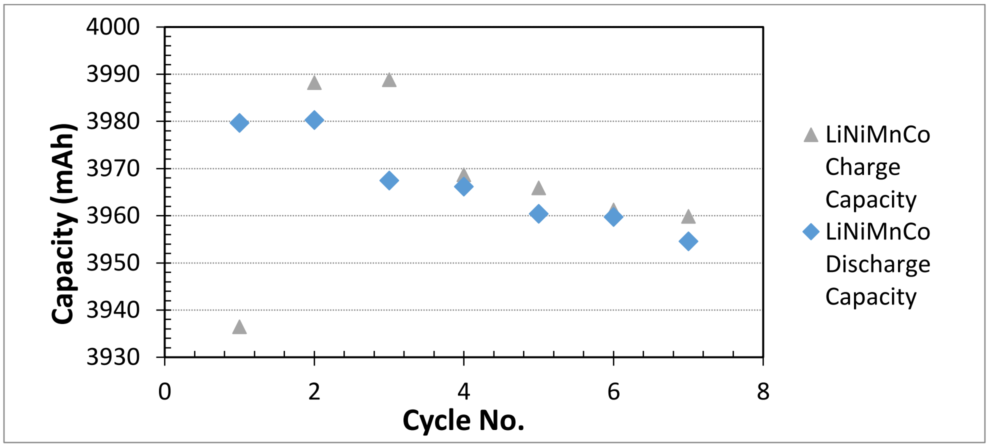


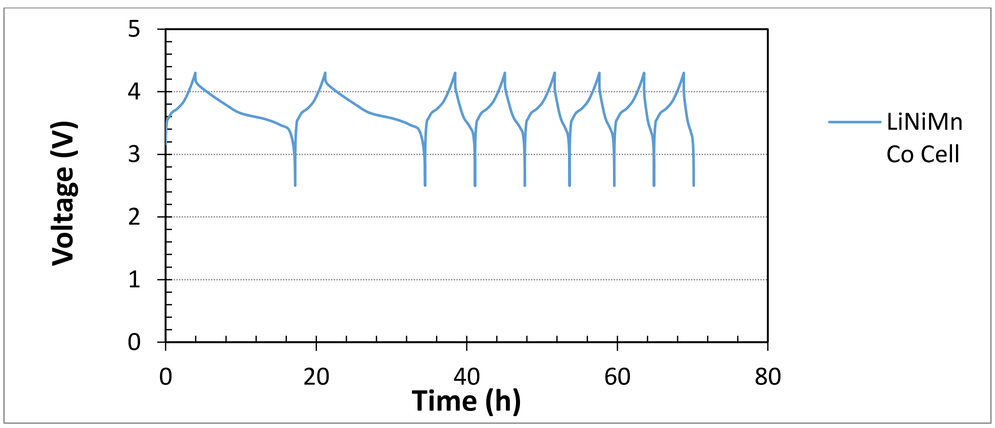
Fig 5. Performance Graphs for the Nanophosphate $LiFePO_4$ cell. a. Charge and discharge capacity over consecutive cycles at a charge/discharge rate 1C. b. Charge/discharge curves at a constant charge rate 1C with varying discharge rates from 1-5C. c. Capacity over consecutive cycles provided in the battery's data sheet[15] (courtesy of batteryspace.com).

The LiNiMnCo cell yields similar results. In the first test done to measure charge/discharge capacity over a series of 7 cycles at 1C charge/discharge rate it was found that the capacity of the LiNiMnCo cell decreased by 0.63%. Using the experimental data and the trend from this battery's data sheet, Fig. 6c, it is estimated that this battery will last around 500 cycles before its capacity will drop below 80%[16]. If it assumed that this battery is integrated into a utility level storage system, it would last almost 3 years until significant capacity loss and would be in need of replacement. In the charge/discharge rate tests, the battery held up to a maximum discharge rate of 5C exhibiting normal charge/discharge curves. The LCOE of this battery was determined to be $1.00 per kWh with a total cost per kWh of $497.224, a cycle life of around 500 cycles, an efficiency of 99%, and a depth of discharge of 80%.

a.



b.



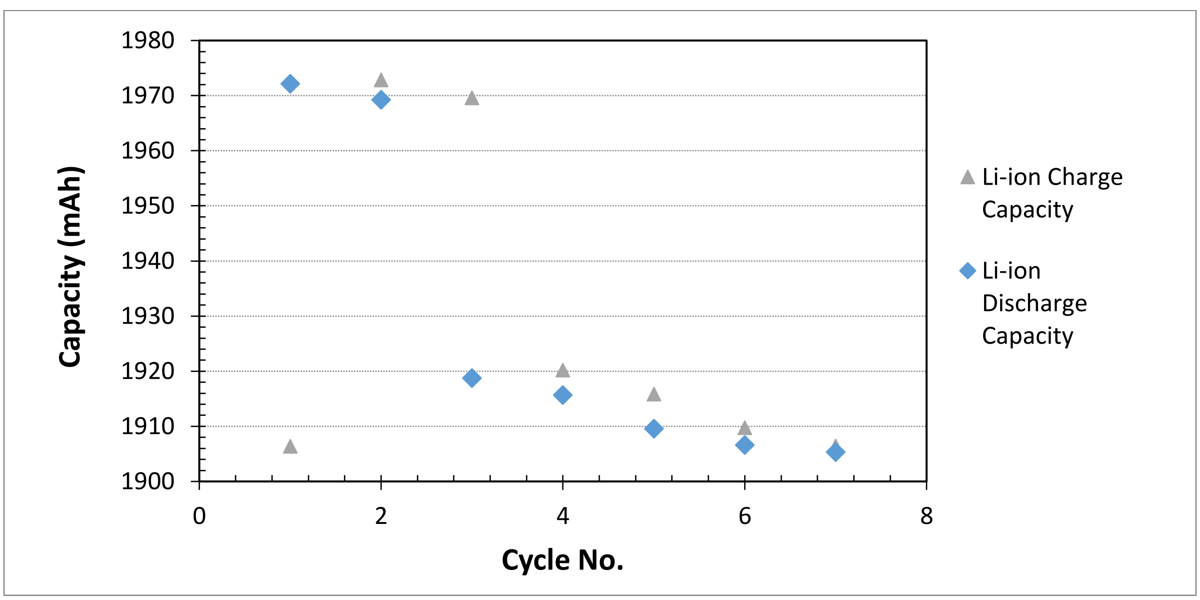
c.

4.3 Cycle Life	Under the temperature (22.5±2.5) ℃,after standard charging, set aside 1.0h, and then constant current discharging at 0.5C_5A to 3.0V, after discharging, set aside 0.5h, and then the next one charge & discharge cycles. One cycle is defined as once charging and once discharging for the cell, doing so 600 times.	After 600 cycles, the remaining capacity /original capacity ≥80%

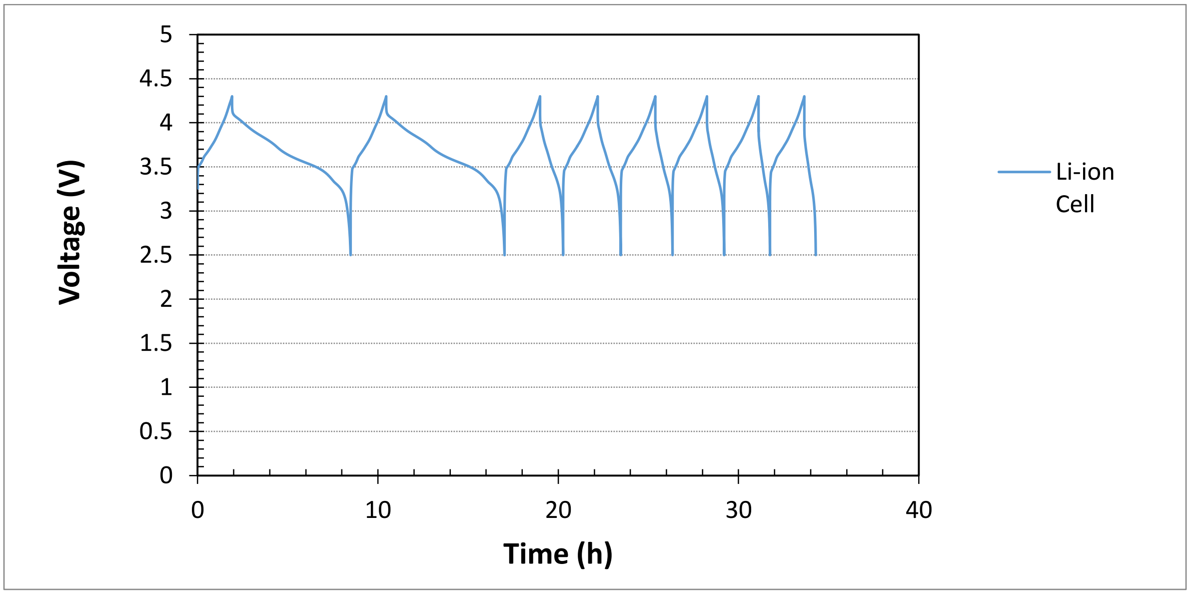
Fig. 6. Performance Graphs for the LiNiMnCo cell. a. Charge and discharge capacity over consecutive cycles at a charge/discharge rate 1C. b. Charge/discharge curves at a constant charge rate 1C with varying discharge rates from 1-5C. c. Lifetime capacity statistics provided by the battery's data sheet[16] (courtesy of batteryspace.com).

The Li-ion cell, which is the most similar to the cells used by Tesla, is the most surprising. In the first test done to measure charge/discharge capacity over a series of 7 cycles at 1C charge/discharge rate it was found that the capacity of the Li-ion cell decreased by 3.39%. Using the experimental data and the trend from this battery's data sheet, Fig. 7c, it is estimated that this battery will last around 300 cycles before its capacity will drop below 80%[17]. If it assumed that this battery is integrated into a utility level storage system, it would last almost 1 years until significant capacity loss and would be in need of replacement. In the charge/discharge rate tests, the battery held up to a maximum discharge rate of 5C exhibiting normal charge/discharge curves. The LCOE of this battery was determined to be $3.09 per kWh with a total cost per kWh of $735.14, a cycle life of 300 cycles, an efficiency of 99%, and a depth of discharge of 80%.

a.



b.


Voltage (V)
Time (h)
Li-ion Cell
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40

c.

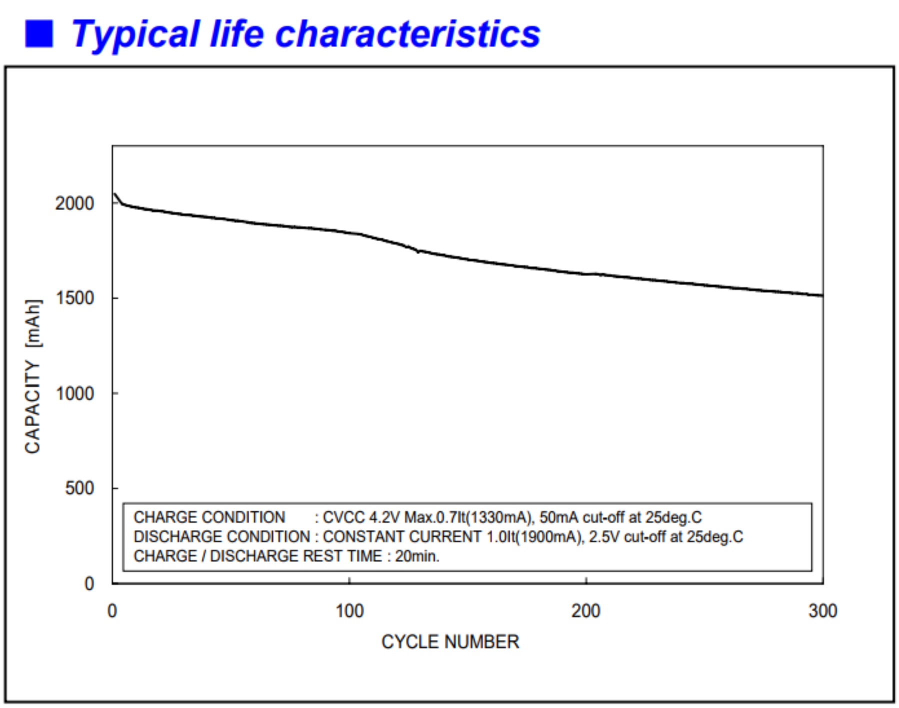

Typical life characteristics
CAPACITY [mAh]
CYCLE NUMBER
0
500
1000
1500
2000
0
100
200
300
CHARGE CONDITION : CVCC 4.2V Max.0.7It(1330mA), 50mA cut-off at 25deg.C
DISCHARGE CONDITION : CONSTANT CURRENT 1.0It(1900mA), 2.5V cut-off at 25deg.C
CHARGE / DISCHARGE REST TIME : 20min.

Fig. 7. Performance Graphs for the Li-ion cell. a. Charge and discharge capacity over consecutive cycles at a charge/discharge rate 1C. b. Charge/discharge curves at a constant charge rate 1C with varying discharge rates from 1-5C. c. Capacity over consecutive cycles provided in the battery's data sheet[17] (courtesy of batteryspace.com).

Discussion:

The significance of this data is a show of the performance and cost characteristics of currently available lithium based individual rechargeable batteries. And from this data it can be concluded that these batteries available to consumers at consumer prices are unsuitable for home utility level storage it terms of performance and cost. The only battery that was able to meet the performance goals for longevity predicted by Tesla was the Nanophosphate $LiFePO_4$ cell. Under a maximum charge/discharge rate of 1C this battery would last around 1500 cycles until serious capacity loss which accounts for just over 3 years of use. For any utility or household appliance this is not a long enough to be considered an acceptable lifetime. Assuming longevity is not a problem to the consumer, the performance characteristics of these batteries is acceptable showing that in high demand every battery was able to discharge at a 5C rate. While constant discharge at this rate will ultimately reduce the life of the battery it did not seem to cause too much extra stress shown by the normal shape of the charge/discharge curves. In terms of cost every battery proved too expensive for use in utility level storage. With the cheapest battery being the Nanophosphate $LiFePO_4$ cell at \$0.98 none of the batteries were below the maximum LCOE of \$0.12 that would ensure cost effectiveness of the energy storage. The most interesting dataset came from the Li-ion battery produced by Panasonic. This battery had the lowest performance in terms of longevity with a cycle life of 300 cycles and the highest LCOE at \$3.09. The reason that this is so interesting is that Panasonic is also a partner in the manufacture of batteries for Tesla's future home utility level storage system. However while they are made by the same manufacturer, it is important to consider the difference in projected performance for these two batteries and difference in cost between consumer and manufacturer. Assuming Tesla's performance goals are met, their batteries for utility level storage will have a cycle life of around 1000 cycles. It would be expected that these batteries would also be able to handle discharge rates of 5C so this is not a concern. In terms of cost, Tesla has been doing a lot of research into lowering the manufacturing costs of their batteries. While the cost of consumer available Panasonic Li-ion batteries as tested is around $700 per kWh, Tesla has plans to manufacture batteries at a low cost of $100 per kWh[18]. Using these projected performance characteristics and assuming efficiency of 99% and 80% DoD the LCOE for Tesla's projected batteries would be $0.12. While this is equivalent to the average cost of power from the grid which would make it cost neutral, there are a couple things that raise the price. Assuming Tesla wants to make money on their utility level storage products they will have to increase their selling price to over their production cost in turn raising the LCOE. In addition auxiliary parts besides the batteries such as cooling battery management and an inverter will add to the cost. Although this makes Tesla's home utility level storage product too expensive for current home utility level storage applications, ongoing research into will continue to improve the longevity of their batteries which will reduce the LCOE. In addition the increased use of large amounts of Li-ion batteries will drive the production costs lower allowing Tesla to sell their products at lower costs. In the near future, Tesla's solution for home utility level storage may be entirely practical as a means to save money and the environment.

The key problems that remain with batteries for utility storage are cost, longevity, and safety. Battery research continues to focus on these areas but unfortunately at the current state of battery technology, many promising battery technologies are ruled out because of one or more of these factors. Power plants are expected to last for decades without replacements. The same has to be expected of batteries if they are to be used for utility level storage. At a current average cycle life of around 1000 cycles for many battery chemistries, charging and discharging every day will cause them to seriously degrade at around three years after their first use (assuming 1 charge / discharge cycle per day). The safety of batteries is also a large concern. Conventional Li-ion technology has a reputation for causing fires and explosions. On a utility level scale these events could be catastrophic.

In the future batteries will continue to improve in all aspects of performance and safety. The ideal battery of the future would be safe with no risk of fire, compact with high specific energy, last for tens of thousands of cycles, and be cost effective all at the same time. Recent research into all solid state batteries look to improve the safety of batteries especially to puncture[19]. All solid state batteries are safer, lighter, and a hot topic of battery research especially in the EV market. Decreasing the size and weight of batteries has always been a large focus of the consumer electronics market. More compact batteries would also be beneficial to utility level storage especially in home based systems. Advancements in newer battery chemistries like Li-S with a specific energy of 2500 Wh/kg[20] already meet performance specifications of the future but run into problems of safety and longevity. Current research into solid state materials and construction methods continue to make these batteries safer and longer lasting.

The longevity of batteries has been a real challenge especially as other performance characteristics continue to improve. As more resources are committed to improve construction methods and stability of high performance batteries, batteries that sacrifice performance in favor of cycle life like current VRF technology ($0.05 per kWh)[21, 22] and NiMH ($0.03 per kWh)[23,24] will fall out of favor. This goes without mentioning the improvements in performance in VRF technology in recent years. As performance characteristics improve so will cost. Assuming the use of the same materials in more efficient ways, technology such as Li-S which is currently not cost effective ($0.17 per kWh)[25] will start to become cost competitive with improved cycle life. In an ideal world, the best battery for utility level storage would have the safety, longevity, and low cost of VRF technology, as well as the high specific energy and solid state of Li-S chemistry.

Just as important as it is to look at the performance benefits of batteries for utility level storage, it is also important to look at the impact they will have. Widespread integration of batteries for utility level storage would revolutionize the power industry and possibly the cost of power. Shifting the load off of peak times will allow power plants to run much more efficiently and minimize the amount of power lost. Energy storage by batteries will allow obtaining predicable power output from unpredictable power sources, such as wind turbines and solar panels. The battery based electrical utility, in principle, is much safer to meet the peak electricity demand than that based on natural gas which can be dangerous when any leak occurs. The widespread use of battery technology for utility level storage will result in improvement in battery technology for a wide spectrum of products including mobile consumer electronics, electric vehicles and many others. As the battery technology is widely adopted, batteries will get safer, smaller, cheaper, and longer lasting. With the current pace of progress in battery technology, the goal of reaching an ideal battery is not farfetched.

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