EcoMotion – *Sustainability Solutions*

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A Brief Investigation into Battery Degradation
During Normal Cycling Conditions and Standby Operations

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EcoMotion is currently working on several exciting energy resilience projects in the LA area and the Bay area. Specifically, we are "hardening" municipal buildings with solar plus storage. The goal is to deliver energy resilience for critical loads during power outages. We're designing for a four-hour duration minimum, but this can be managed to be much longer as our systems are replenished with solar power.

Here's a new wrinkle: What happens over time as the batteries that anchor the systems lose their capacity? Like normal household batteries and car batteries, they degrade. They lose their punch! Does this mean we will not be able to serve all the critical loads identified over time?

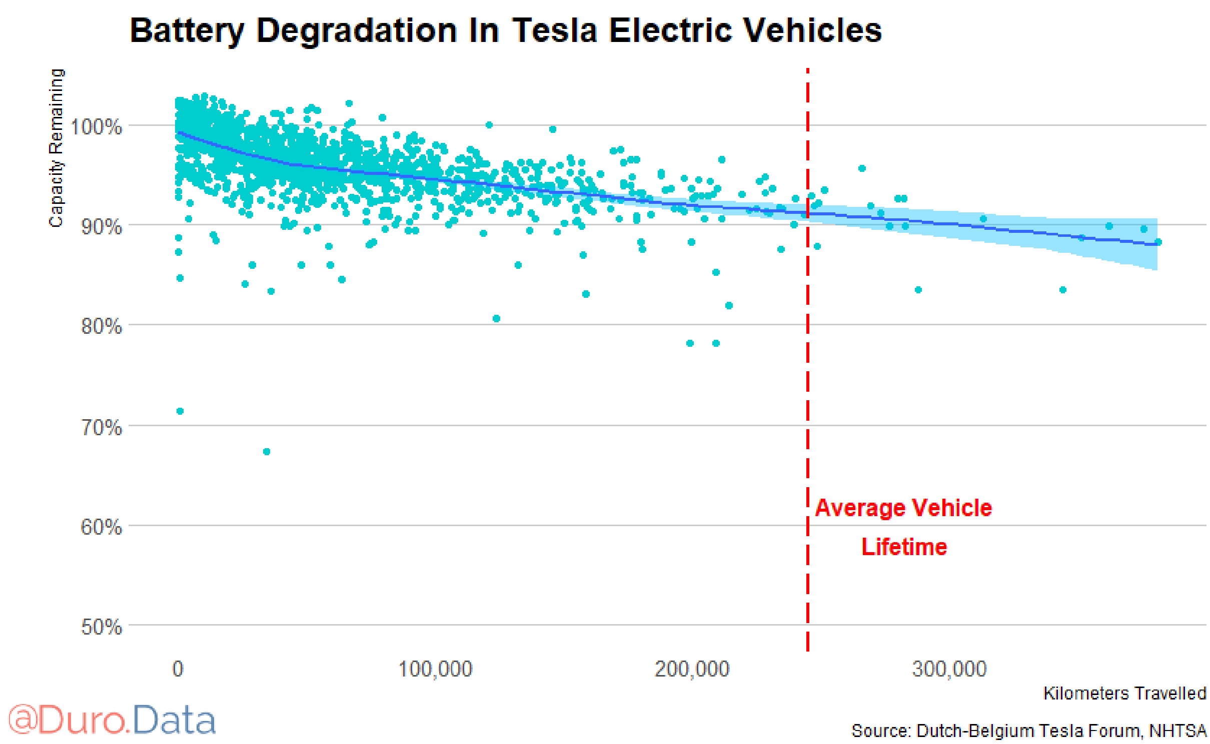
This brief and non-technical investigation delves into the state of battery degradation in two modes: First, and most common, is normal cycling mode. State of California battery incentives currently requires 104 cycles a year. Cycling is used to trim peak demands, which is super important for the grid. Batteries can also charge during off-peak, and discharge during peak periods. That's called energy arbitrage. These financial plays are largely the name of the game in the battery energy storage world.

This brief, however, looks a bit deeper... and into batteries whose primary mission is to be in reserve for energy resilience. These batteries are not cycled daily. They are on standby for an emergency. They are at the ready, but batteries held in reserve are degrading. Just how fast are they degrading? What is their rate of "self-discharge" as it is called in the industry?

Lithium-ion Battery Degradation

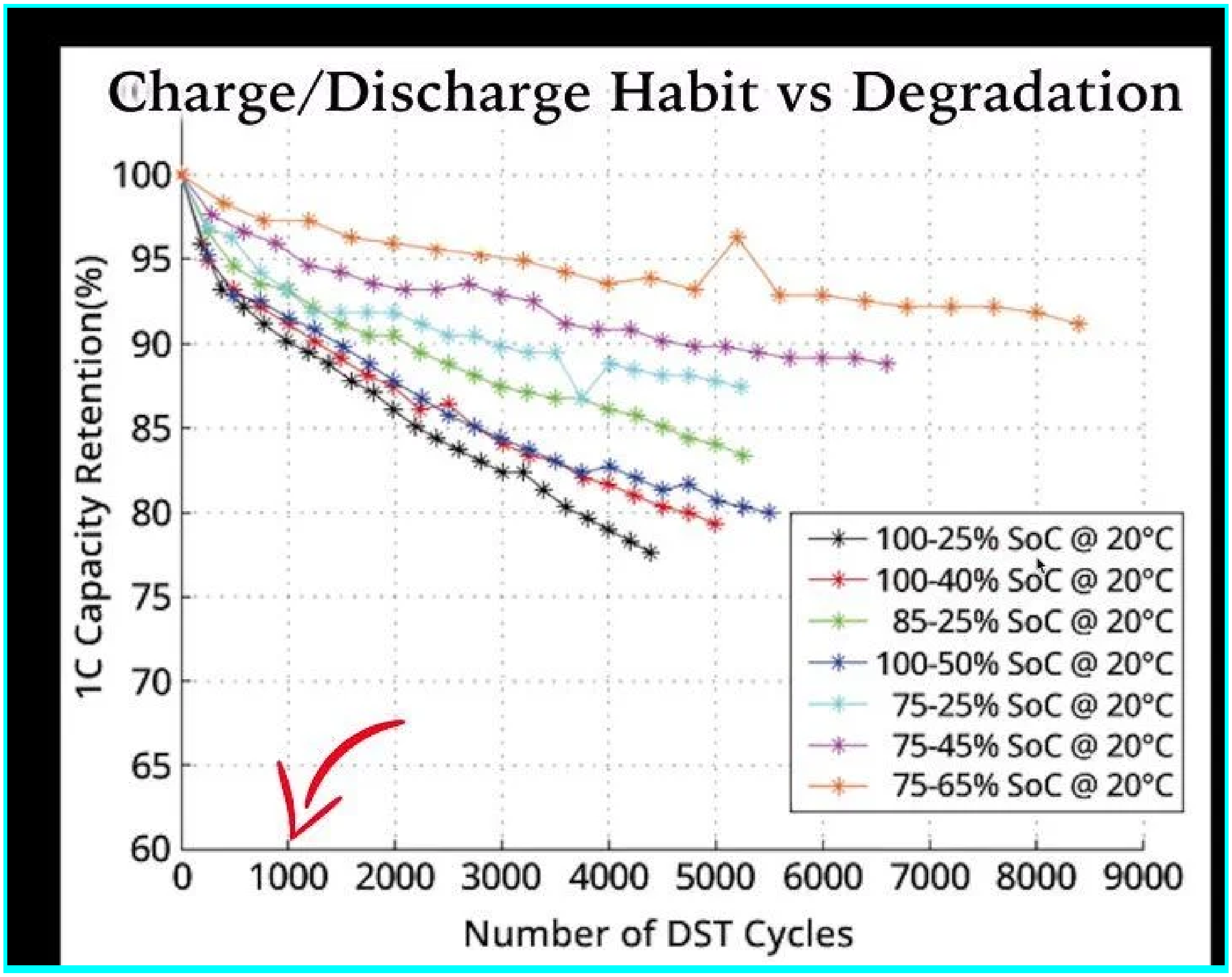
This is alarming stuff. Cadax Electronics, a battery testing firm, reported that a fully charged household lithium-ion battery will lose about 20% of its capacity after a year of typical storage cycling and use. Additionally, lithium-ion batteries slowly discharge – self-discharge – when not in use or while in storage.

Anyone with a smartphone, laptop, or indeed whole electric car knows that lithium-ion batteries degrade over time. For electric vehicles, Tesla reports 10% battery degradation after 200,000 miles. In one study, the Tesla Model 3 lost 7% of its battery capacity after 24,000 miles. Each time that you charge and discharge the battery loses a little capacity.



When not in use, batteries of all kinds gradually lose capacity. Rechargeable batteries for standard household electronics that sit idle for over a year, often die. They self-discharge to a low enough voltage that it is not possible to recharge... or if they do recharge, they may well have a severely diminished life.

Battery performance is strongly affected by operating conditions, notably temperature. Experts describe that degradation is a non-linear phenomenon driven by different storage temperatures as well as the range of discharge, the State of Charge (SOC) levels. Battery capacity degradation is higher at higher temperatures, however, a higher state of charge results in less degradation. Poor internal ventilation will increase degradation rates due to increased heat. Good rule of thumb: keep 'em at 75% in cool temps and cycle only in the higher ranges of the SOC, for instance 45% - 85%.



Five Battery Degradation Factors

1. Battery Chemistry
2. Number of times that the battery is cycled
3. The SOC discharge range
4. How rapidly the battery is charged and discharged
5. The operating environment (ambient temperature)

There are other battery degradation factors: The use of fast-charging increases degradation. Self-discharge may also increase as batteries age. Another variable is the routine depth of discharge, to what depth does the state of charge go? How far down do you draw the batteries: 45%, 25%, or 10%?

Tesla has what it calls its Energy Retention Warranty. For Power Walls, it warrants the batteries' capacity at 70% in terms of energy retention at ten years. The same warranty covers the 776 kW Tesla MegaPack... but for 15 years with a "no defect and energy retention" warranty.

Industry expert Matt Harper concurs that the degradation of 30% over ten years for lithium-ion batteries is an indicative value. “Yes,” says Matt, “and even north of that if the batteries are being cycled heavily.... could be 50 – 60% degradation after ten years.” Thus, there are two options: You overbuild battery capacity from day one, or you augment the battery pack over time.

Tesla’s Hornsdale battery farm in Australia has gaps between batteries to accommodate more batteries over time as the original batteries degrade. By interweaving the new batteries with the old, they can tap into the same power electronics. There are complexities in running different aged batteries through the same gear. Linking together new and old batteries can be limiting as strings of batteries often perform at the level of the weakest link in the chain/string.

From Kirk Stokes at MBL Energy, I get a somewhat more optimistic perspective. He’s been working with Samsung batteries for some time and explains that its warranty is likely indicative of battery performance. As long as you meet certain operating criteria and live within certain operating ranges, Samsung and at least one other major that MBL uses offer warranties that reflect a 2% per year loss, or 20% over ten years.

So what are the warranty criteria? First off, temperature control. Between 50 – 100 degrees Fahrenheit. All batteries, to maintain their warranties, must have climate-controlled enclosures. The second major criteria is based on the throughput of kilowatt-hours, in and out. This is tracked by the software. There is a limit on the number of kWh each month. Exceed the limit and void the jeopardize, if not void the warranty. In this case, the warranty does not limit the number of cycles or the depth of discharge.

I asked Matt Harper the question of whether a battery that cycles degrades faster than one that does not cycle. “Yes,” says Matt, “cycling definitely increases degradation, but it depends.” If you cycle in the 40 - 55% state of charge (SOC) range, a battery can last a long time. If you drain the battery to 0% or leave it topped off at 100%, there’s a lot of degradation. For this reason, cell phones are typically shipped with their batteries half full.

Self-Discharge Rates

Self-discharge is a phenomenon in batteries in which internal chemical reactions reduce the stored energy charge of the battery without any connection between the electrodes or an external circuit. “Calendar aging” is an important factor where the idle periods are shorter than the operational periods. Self-discharge decreases the shelf life of batteries and causes them to have less than a full charge when actually put to use. Like closed-circuit discharge, a fancy term for normal cycling operations, self-discharge tends to occur more quickly at higher temperatures.

The information presented in the table below is focused on small batteries, not large commercial building-sized batteries. These are 1.2 – 3.6 volt batteries versus 450 volt Tesla PowerPack for Model S, but perhaps their relative values are indicative.

<u>Monthly</u> Self-Discharge Rates for Various Battery Types

Lead acid	3 - 20%
NiCad	15 - 20%
NiMH	30%
Lithium-ion	2 – 3%

From the literature, I find that there are widely differing degradation rates for lithium-ion batteries. One source suggests a standard self-discharge rate of 0.35 – 2.5% per year. Another source suggests 1.5 – 2% per month. One source suggests that the shelf-life of lithium-ion batteries is only 3 – 6 years. EcoMotion assumes replacements of commercial energy storage systems after 10 years, aligned with their warranties. In 2003, it was reported that the typical range of capacity loss in lithium-ion batteries after 500 charging and discharging cycles varies from 12.4 – 24.1%, and average capacity lots of 0.025 - 0.048% per cycle.

One insight from Kirk Stokes at MBL Energy is that for new batteries that are stored in a warehouse, or that are onsite, and in each case in conditioned environments, the warranty clock does not start until the batteries are placed in service. That's up to two years, with a warranty that the battery will still maintain its nameplate capacity.

The Merits of Flow Batteries

Something to consider in this discussion is that vanadium redox flow batteries experience virtually no degradation. They will maintain their capacity throughout their life. They do need to be maintained like an engine, with routine maintenance of mechanical and other parts, and yes, their carbon electrodes degrade over time. Flow batteries need to be maintained too. Just like a car engine, the flow battery is a mechanical device... you've got to replace the water pump at 10 years and the tanks at 10 years. There is also some degradation of the electrodes themselves. Compared to lithium-ion, flow batteries have far superior lifecycle economics.

Note that the lower power density of flow batteries means that they will certainly not replace lithium-ion batteries in cars, phones, etc. where space and weight issues rule supreme. Flow batteries weigh 2 – 3 times more, and take up nearly twice as much room as lithium-ion batteries. For large-scale stationary projects, they are perfect with nearly 0% self-discharge. You can also cycle vanadium flow batteries down to 0 and up to 100.

Conclusion

- Compared to traditional lead-acid batteries, lithium-ion batteries have terrific benefits. They can operate in a wide range of temperatures, they can charge and discharge quickly, and they have no memory effect. Yet, they degrade quite dramatically.

- The degradation of lithium-ion batteries is real.

- For EcoMotion's energy resilience projects, we need to size for degradation and make sure that our vendors will too. At this time, EcoMotion's best shot is that the batteries will be at 70 - 80% capacity after 10 years and just prior to replacement. That's 2 - 3% degradation per year. We need to be very clear on the amount of degradation and make plans to augment the battery size or the critical loads accordingly.

- Lithium-ion batteries operate and will have the longest life if they cycle in the 25 – 95% range. That's perfect for energy resilience programs that have a "carve-out" of battery capacity in reserve. We leave the 25% in the tank so to speak, and cycle above that in terms of depth of discharge. Thus we maintain battery life, and maintain the 25% reserve for emergencies.

- Some developers fully understand degradation and live with it. Kirk Stokes states that his company does not upsize battery size, they just help customers understand degradation and how to adapt to less capacity in time. This is interesting. Seems that you either invest 20 - 30% more upfront to be covered throughout the ten-year cycle... or end up 20 - 30% short on power for your critical loads.

EcoMotion welcomes comments and corrections to this policy brief. Please do so by reaching out to Ted Flanigan at TFlanigan@EcoMotion.us.