How to Monitor, Maintain, and Test Solar Car Batteries

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Why Have Solar Panels and also a Battery?

- The battery allows us to store solar energy during non-racing periods for use during racing periods

- Solar power is variable and the battery allows us to race using the average solar power and maintain a steady racing speed
  - Due to how aerodynamic drag works, a steady speed uses less power to cover a given distance than a variable speed that averages the same

Battery Terms

- ***Resting voltage*** is the voltage when there is no current flowing into or out of the battery
- ***Nominal voltage*** is the spec voltage for the battery
  - When the battery is fully charged, the voltage will be higher than nominal
  - When the battery charge is low, it will be lower than nominal
- ***Charging current*** is current forced into the battery
- ***Discharge current*** is the current pulled out of the battery
- ***Battery capacity*** is how much energy the battery can store
- ***State of charge (SOC)*** is how much (0-100%) of the battery capacity is stored
- ***Battery cells*** are sub-units of the battery
  - Nominal voltage of a cell is determined by the cell chemistry
  - Cell capacity can vary, but the voltage stays the same (for a given chemistry)

Battery Basics

- As the state of charge (SOC) increases, the resting voltage increases
  - Charging the battery requires raising the voltage above the resting voltage
  - Discharging battery causes the voltage to drop below the resting voltage
  - The larger the current, the larger the change from resting voltage
- The battery cells are usually connected in series
  - The same battery current flows through all cells
  - The nominal battery voltage is equal to the nominal cell voltage times the number of cells
- Capacity is measured in Watt-hours (Wh) or Amp-hours (Ah)
  - To convert Wh to Ah, divide Wh by the nominal voltage
  - 5.25 kWh for a nominal 72V battery is about 72.9 Ah
  - A larger-capacity cell is physically larger and heavier

Common Battery Chemistries at SCC

- **Lead acid** — not used much anymore as most teams switched to LiFePO4
  - Low capacity per weight and volume (34-40 Wh/kg)
  - Cannot use as much of the rated capacity
  - Cheapest (initial cost), but lower effective capacity and shorter battery life
  - Generally, has lower charge/discharge currents for a given capacity
- **Lithium iron phosphate (LiFePO4 or LFP)**
  - More capacity per weight (100-150 Wh/kg) — tolerates deep discharge in use
  - More expensive initial cost, but lower lifetime cost
  - Needs Battery Management System (BMS) to protect from fire risk
  - Relatively flat voltage curve as SOC changes means needs to do coulomb counting
- **Lithium-ion**: Lithium NMC (Nickel Manganese Cobalt)
  - Most expensive, but highest capacity per weight (150-200 Wh/kg)
  - Limited to Advanced Division and Cruiser Division
  - Also needs BMS to protect cells from fire risk

Common Battery Voltages

- Lead acid (nominal 2.0V per cell)
  - Commonly packaged in 6-cell units (12 Volts)
  - Can put 4 units in series for 48V system or 6 units for 72V system
- LiFePO4 (nominal 3.2V per cell)
  - Can buy prepackaged batteries (with integrated BMS) or individual cells
  - “12V” is 4 cells (12.8V), “48V” is 16 cells (51.2V), “72V” is 24 cells (76.8V)
  - Can use other numbers (if BMS supports): e.g., 22 cells (70.4V)
- Lithium-ion (nominal 3.7V per cell)
  - Can buy prepackaged batteries (with integrated BMS) or individual cells
  - “12V” is 3 cells (11.1V)

Sensitivity of Battery Life to Daily Use

- Lead acid
  - Prefers 50%-100% SOC
  - Occasionally below 50% SOC is possible, but not recommended
  - Permanent damage can happen below 20% SOC
- LiFePO4
  - Prefers 10%-90% SOC
  - Very slight reduction in battery life outside of that range (if not outside for days)
- Lithium-ion
  - Prefers 20%-80%
  - Slight reduction in battery life outside of that range, especially if for many days
  - Much more reduction in battery life for below 10% SOC

LiFePO4 is a pretty easy choice over lead acid

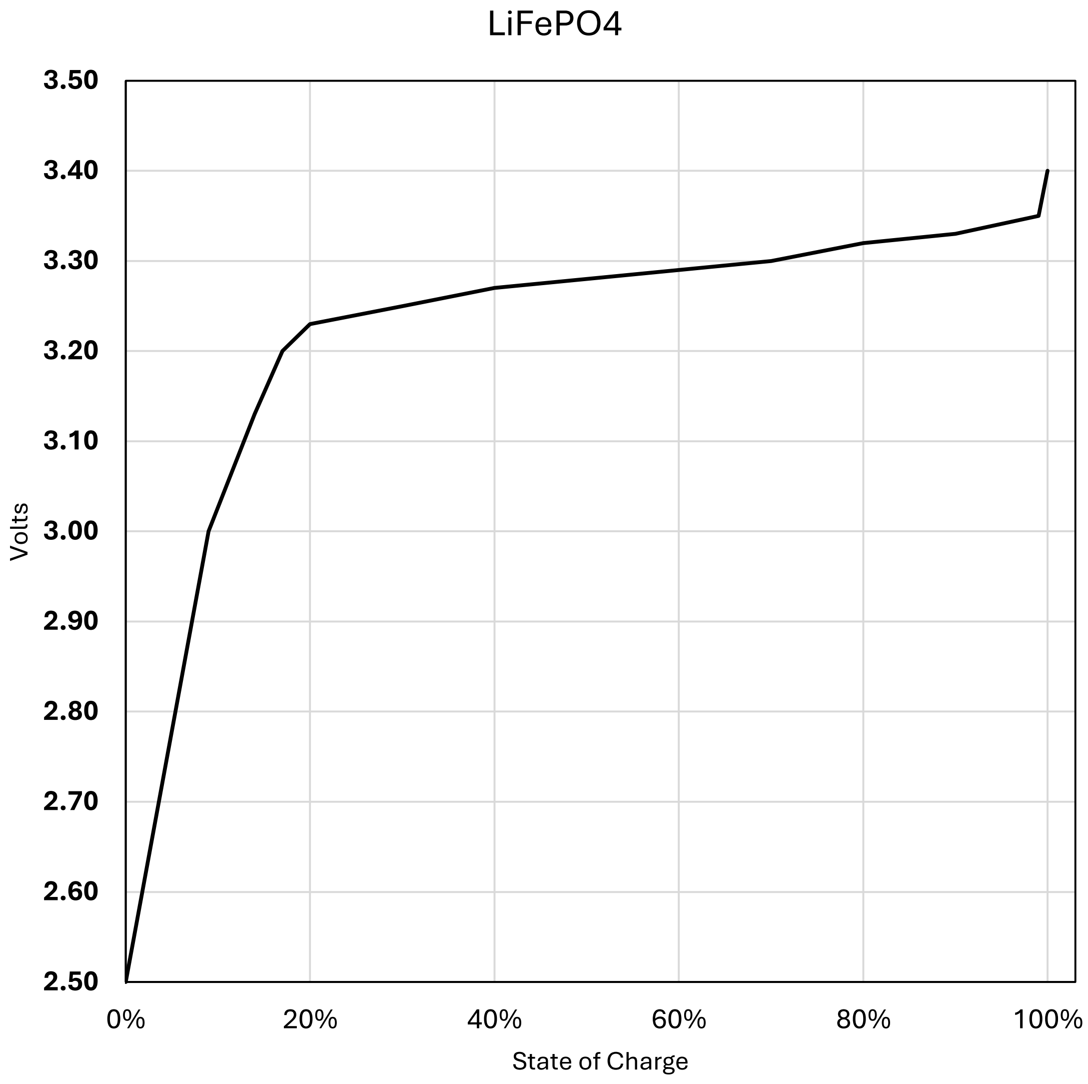
Sensitivity of Battery Life While in Storage

- Lead acid
  - Prefers 100% SOC — with trickle charge to keep it there, if possible
  - Can top off periodically if no trickle charge
- LiFePO4
  - Prefers 40%-60%
  - 20%-80% is minimal reduction in battery life
- Lithium NMC
  - Prefers 40%-60%
  - 30%-80% is minimal reduction in battery life
  - Don't go below 10%

Periodically check battery voltage if in storage for a long time

LiFePO4 Voltage vs State of Charge

LiFePO4 SOC	Voltage				Storage
	Cell	4	22	24	
100% Charging	3.65	14.60	80.30	87.60	
100%	3.40	13.60	74.80	81.60	
99%	3.35	13.40	73.70	80.40	
90%	3.33	13.32	73.26	79.92	
80%	3.32	13.28	73.04	79.68	OK
70%	3.30	13.20	72.60	79.20	OK
60%	3.29	13.16	72.38	78.96	Best
50%	3.28	13.12	72.16	78.72	Best
40%	3.27	13.08	71.94	78.48	Best
30%	3.25	13.00	71.50	78.00	OK
20%	3.23	12.92	71.06	77.52	OK
17%	3.20	12.80	70.40	76.80	
14%	3.13	12.52	68.86	75.12	
9%	3.00	12.00	66.00	72.00	
0%	2.50	10.00	55.00	60.00	



BMS (Battery Management System)

- Protects the battery and provides diagnostic data on the cells
- BMS has sense wires to every cell to monitor individual voltages
- Will halt charging by opening the circuit to the battery
  - If current exceeds max charging current, or
  - If highest-voltage cell exceeds max voltage
- Will halt discharge
  - If current exceeds max discharge current, or
  - If lowest-voltage cells drops below min voltage
- Rebalancing: Can use sense wires to pull current out of highest-voltage cell and put it into the lowest-voltage cell
  - Allows for fully charging and discharging even with slight differences in cells
  - Our first BMS had 20 mA rebalancing currents, but our current one goes up to 2 A

A BMS that supports higher rebalancing currents is nice

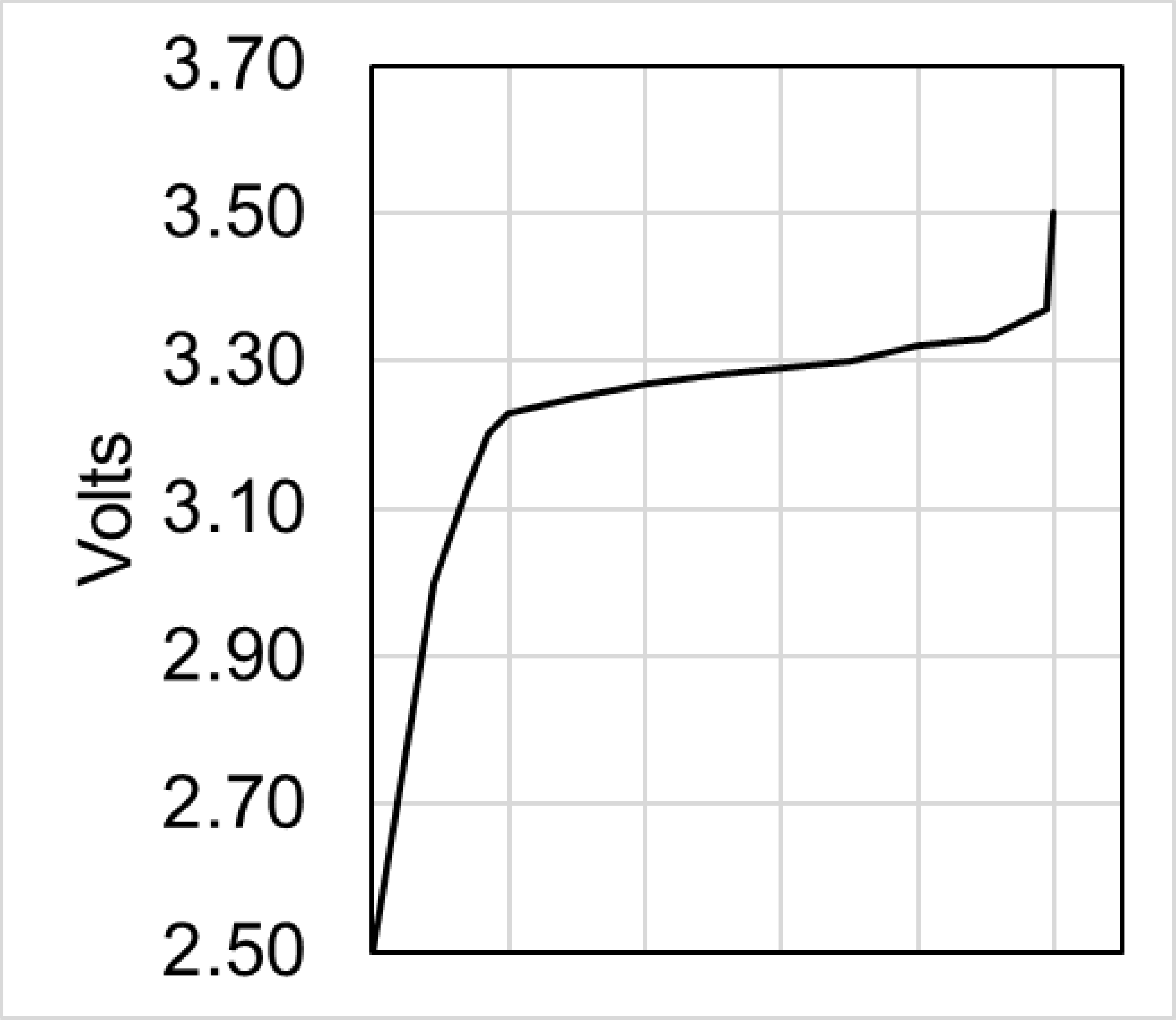
Matched Cells Make for a Better Battery

- Matched cells maximize use of capacity
  - replacing an outlier cell with one that is more similar to the others helps
- Replacing a failed cell may be hard to match the others, but if it is a closer match than the old one, that still helps
  - Even if you have a spare cell from the same manufacturing lot, the cells that have gone through many charge/discharge cycles will have changed
- The higher stress of pushing cells to the limit (on both high and low end) will probably cause the cells to degrade and drift apart from each other faster

Eking out the max capacity of the cells will reduce capacity faster

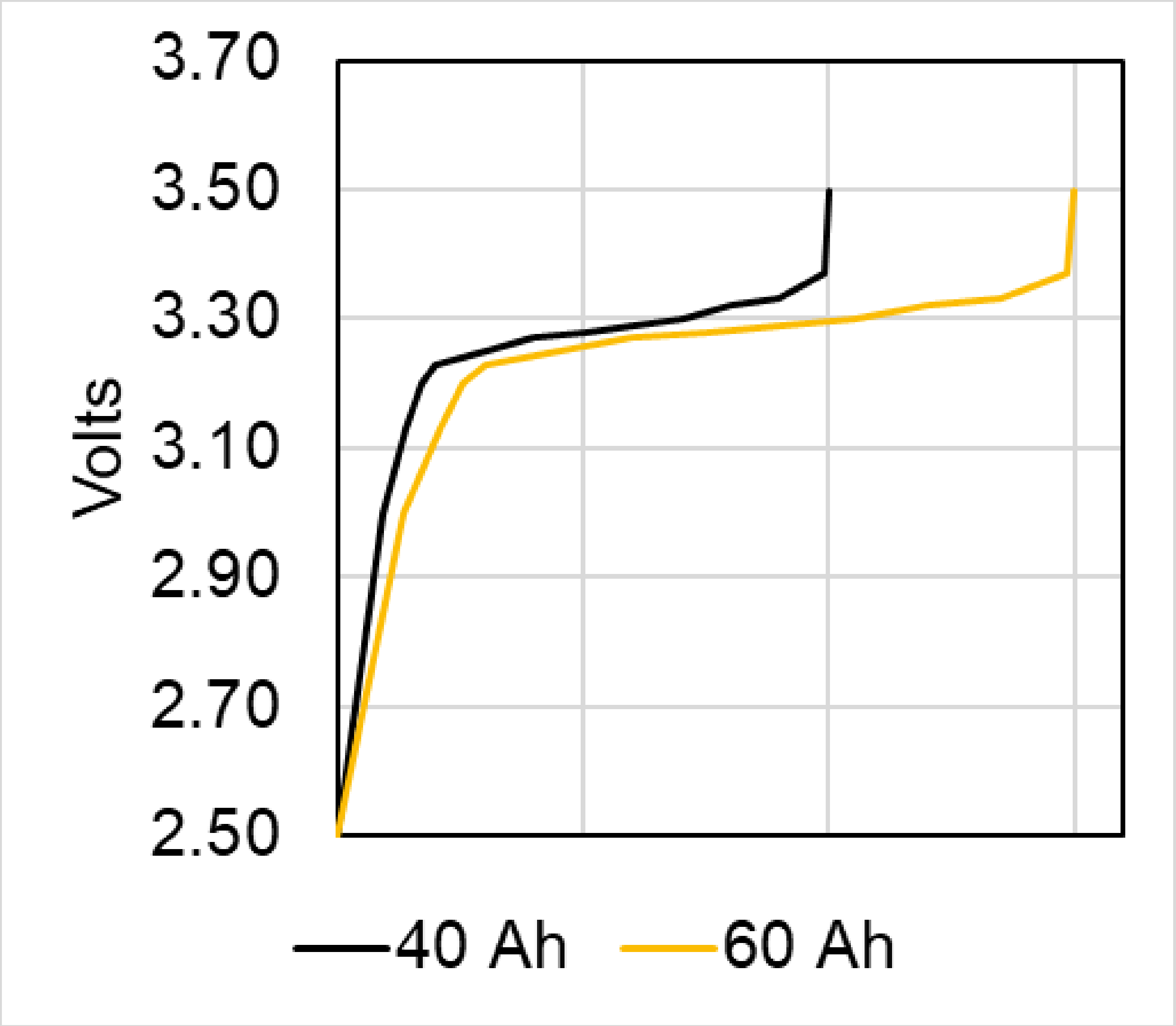
LiFePO4 Voltage vs State of Charge

- X-axis is energy stored — proportional to number of electrons stored
  - If two different batteries had slightly different storage capacities, then they would hit 100% SOC at different number of electrons
- At SOC nears 100%, the voltage climbs a lot



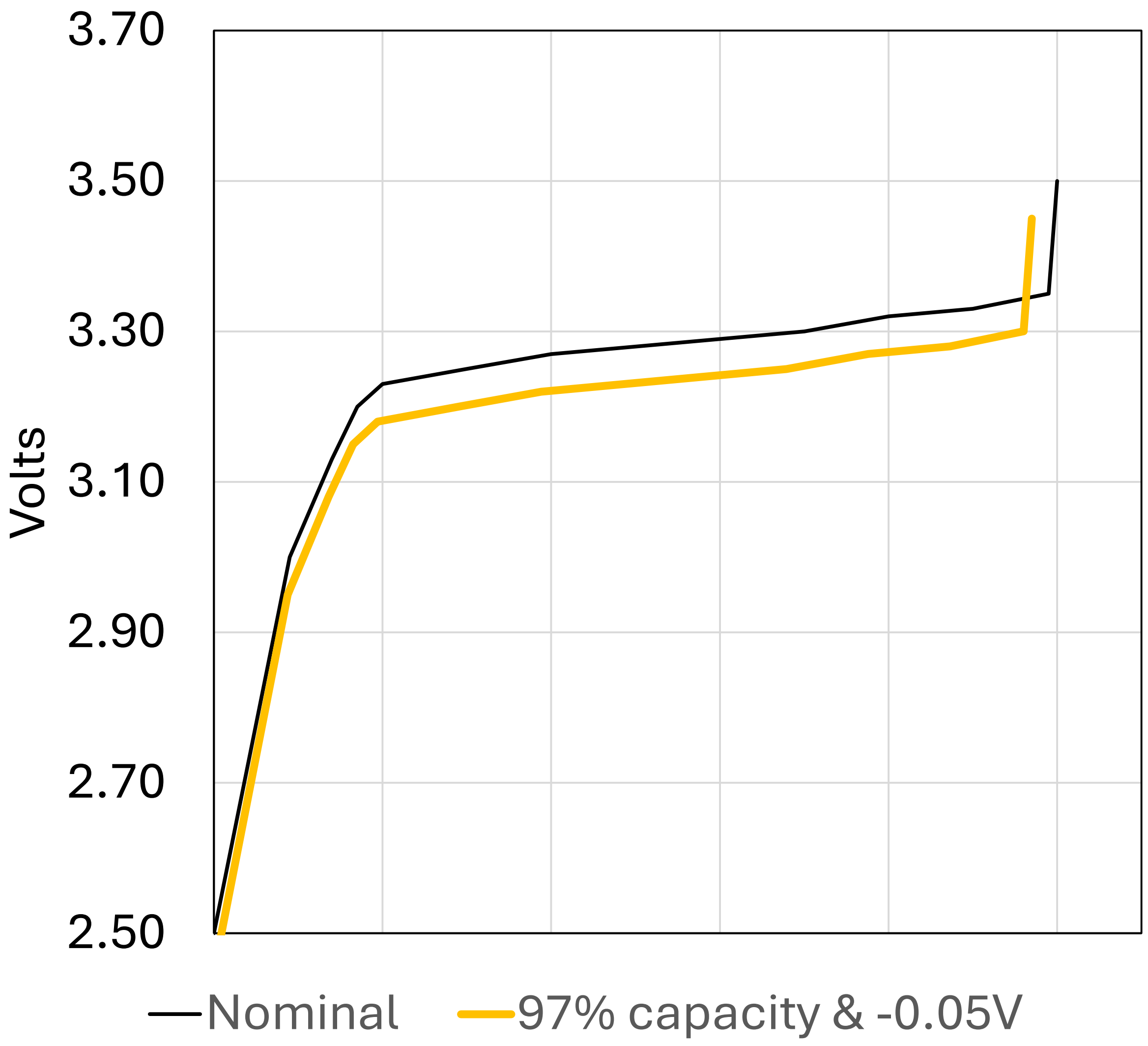
Cell Capacity Should Match

- Cells should all be the same capacity
  - Overall battery capacity is set by the lowest capacity cell
- Suppose you had a cell with 40 Ah capacity in series with a cell that had 60 Ah of capacity
- If you were charging from empty at 20 Amps, the first one would hit 100% SOC after two hours, but the second one would only be at 67% SOC
  - Since the same current flows through both, you have to stop charging while the second one only has 40 Ah too



Suppose the Cells Are Not Balanced

- Capacity differences stretch and shrink along X axis
- Internal resistances differences shift up or down along Y axis
- Suppose a cell only has 97% of rated capacity and slightly higher internal contact resistance so its voltage is 50 mV lower
- The battery would stop charging at 97% rated capacity
- BMS rebalancing could allow full charging by moving current out of that one to the others



Implications of Setting the Battery Thresholds

- If you set your battery high-voltage threshold a couple of volts lower, you are putting less stress on your battery
  - Cells will last longer
  - Cells will probably stay well-matched for longer
- The charge controller effectively sees the average voltage, so if you set the desired threshold too high, there is a greater chance that the worst-case cell exceeds the safe level before the average is at the desired voltage
- In Carlsbad, as we approached being fully charged, total voltage was increasing by a volt every 20 seconds (cell voltage increasing by 0.05V every 20 seconds)
  - Setting the battery high-voltage threshold a couple of volts lower means you lose 40 seconds of solar power

Eking out the max capacity of the cells only adds seconds of charging time

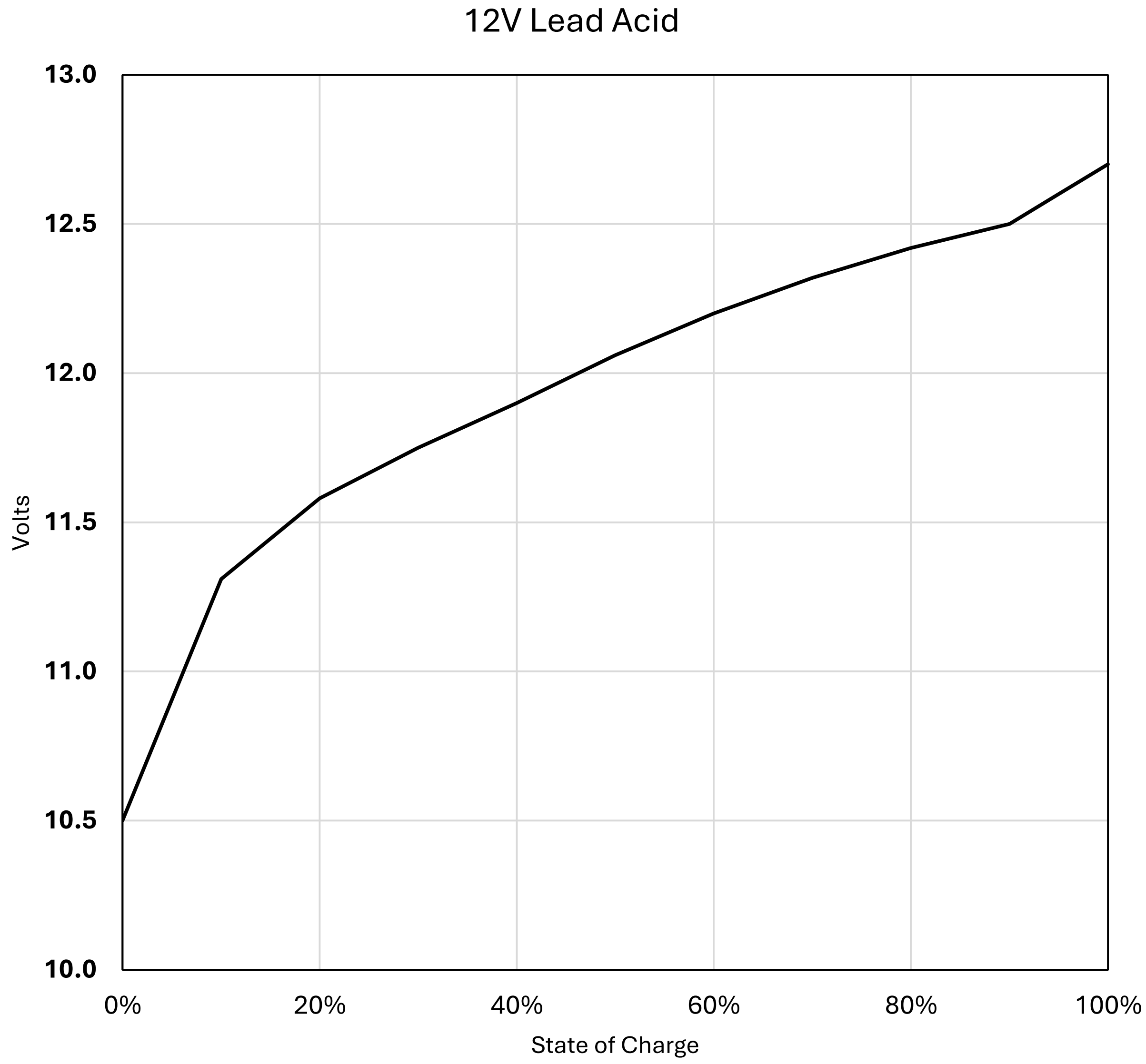
Conclusions

- LiFePO4 is a pretty easy choice over lead acid
- Periodically check battery voltage if in storage for a long time
- A BMS that supports higher rebalancing currents is nice
- Eking out the max capacity of the cells will reduce capacity faster
- Eking out the max capacity of the cells only adds seconds of charging

Backup

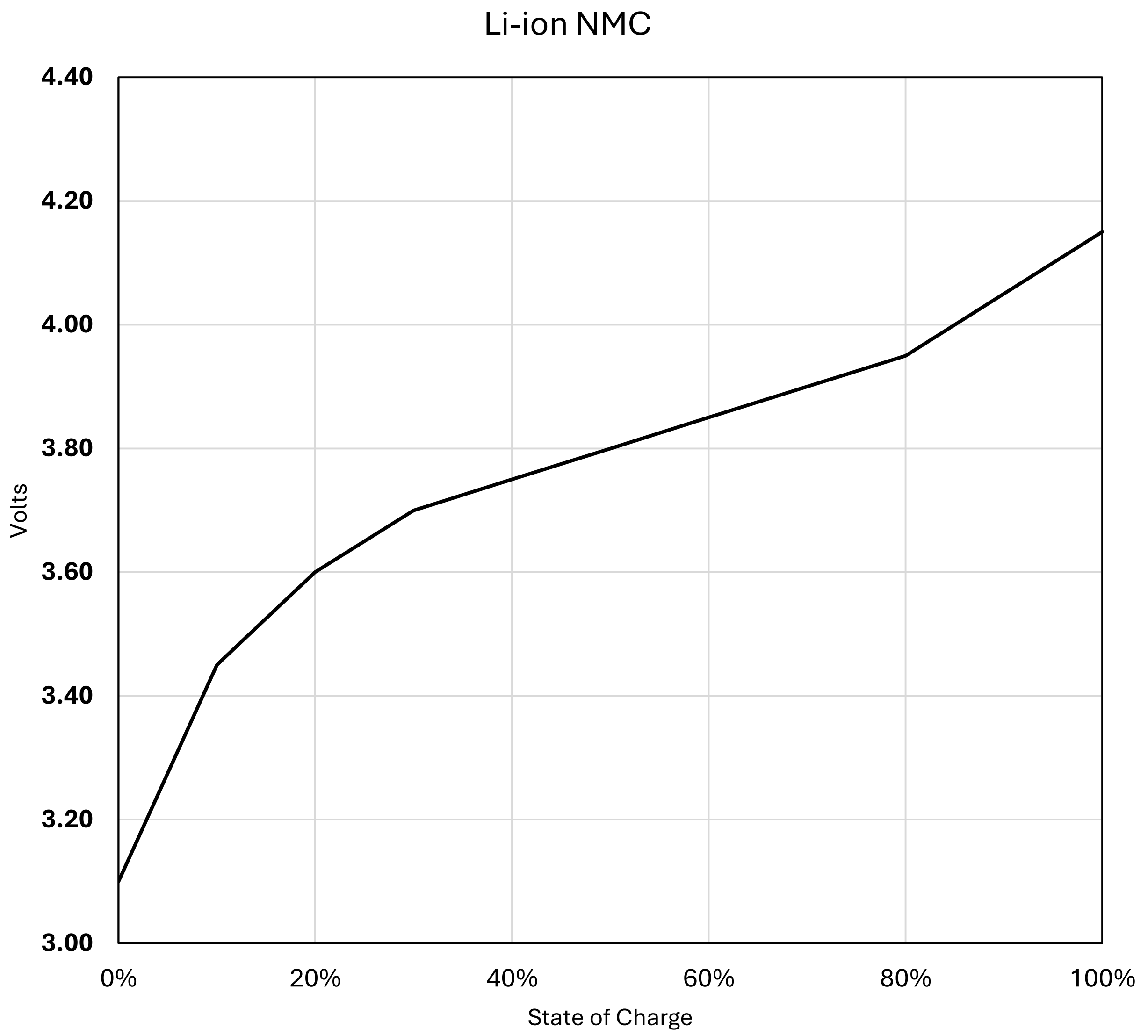
Lead Acid Voltage vs State of Charge

Lead Acid SOC	Voltage			
	Cell	6	24	Storage
100% Charging	2.43	14.60	58.40	Best
100%	2.12	12.70	50.80	Best
95%	2.10	12.60	50.40	OK
90%	2.08	12.50	50.00	OK
80%	2.07	12.42	49.68	
70%	2.05	12.32	49.28	
60%	2.03	12.20	48.80	
50%	2.01	12.06	48.24	
47%	2.00	12.00	48.00	
40%	1.98	11.90	47.60	
30%	1.96	11.75	47.00	
20%	1.93	11.58	46.32	
10%	1.89	11.31	45.24	
0%	1.75	10.50	42.00	



Lithium-Ion Voltage vs State of Charge

Li-ion NMC SOC	Voltage			Storage
	Cell	6	36	
100% Charging	4.20	14.60	100.80	
100%	4.15	12.70	99.60	
90%	4.05	12.50	97.20	
80%	3.95	12.42	94.80	
70%	3.90	12.32	93.60	OK
60%	3.85	12.20	92.40	Best
50%	3.80	12.06	91.20	Best
40%	3.75	11.90	90.00	Best
30%	3.70	11.75	88.80	OK
20%	3.60	11.58	86.40	
10%	3.45	11.31	82.80	
0%	3.10	10.50	74.40	



Battery Chemistry

- The cell voltage is different for different types of cell chemistries
  - A chemical reaction at anode (negative terminal) gives up an electron — which then runs through the car’s circuits and back to the battery — and then a different chemical reaction at the cathode (positive terminal) incorporates an electron.
    - Positive ions flow through electrolyte inside the battery from anode to cathode
  - Charging reverses those chemical reactions by forcing reactions to run the other way
    - Requires raising the voltage higher than resting voltage
    - The higher the charging current, the more the voltage needs to be raised to get enough positive ions to the anode to take the electrons
    - As the battery approaches 100% SOC, it becomes harder for the few remaining positive ions to make it to the anode to accept an electron — voltage can climb dramatically even as charging current drops