SOC^c vs SOC^e in $LiFePO_4$:

Why Golf Carts Behave Differently Than Home Solar

Executive summary

In lithium-iron-phosphate ($LiFePO_4$, "LFP") batteries, **State of Charge by capacity (SOC^c)** and **State of Charge by energy (SOC^e)** are *not* the same thing. SOC^c tracks how many amp-hours remain; SOC^e tracks how many watt-hours you can still deliver at the voltage you'll actually get under real loads and temperatures. Because LFP's voltage curve is very flat and then drops abruptly at the "low-side knee," high-current golf-cart bursts (e.g., >300 A) can make SOC^e collapse **well before** SOC^c looks low. In practice, a *rest* cell voltage around **≈ 3.280 V** is a pragmatic tipping point for golf-cart use: above that, you're still on the plateau with usable headroom; below it, short inrush spikes more easily push cells into BMS low-voltage cut-off, so the **available energy** (SOC^e) falls sharply even if **remaining capacity** (SOC^c) still looks fine.

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1) Definitions & math (what you're *measuring*)

- **SOC^c (capacity-based SoC)**: fraction of remaining **amp-hours** to nominal capacity.

SOCc=QremainingQnominal\mathrm{SOC^{c}}=\frac{Q_{\text{remaining}}}{Q_{\text{nominal}}}SOCc=QnominalQremaining

- **SOC^e (energy-based SoC; "SoE")**: fraction of remaining **watt-hours**, i.e., the integral of voltage while you draw charge under the *actual* conditions (load, temperature, age).

SOCe=∫V(conditions) dQ∫Vrated dQ\mathrm{SOC^{e}}=\frac{\displaystyle\int V(\text{conditions})\,\mathrm{d}Q}{\displaystyle\int V_{\text{rated}}\,\mathrm{d}Q}SOCe=∫VrateddQ∫V(conditions)dQ

Peer-reviewed work and technical primers distinguish SoE from SoC for exactly this reason: **voltage is not constant**, so percent-Ah (SOC^c) and percent-Wh (SOC^e) diverge as operating conditions vary.

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2) Why LFP's chemistry makes SOC^c and SOC^e diverge

Flat plateau + sharp knee. LFP cells spend most of their mid-range near ~3.2–3.35 V per cell, then exhibit a **rapid voltage drop** ("low-side knee") approaching empty. That non-linearity means the *energy* left (area under V·dQ) can plummet once you roll off the plateau—even if amp-hours aren't yet exhausted. Manufacturer docs and modeling papers highlight (i) the long, flat OCV–SOC region and (ii) the knee/hysteresis and relaxation behavior that make voltage-based estimates tricky.

Rate and temperature sensitivity. Under higher **C-rates**, terminal voltage sags (ohmic + polarization), shifting you sooner into the knee and reducing *deliverable* energy; low temperatures further increase internal resistance and reduce apparent capacity and power.

Voltage relaxation. After load removal, LFP OCV rebounds slowly (minutes to hours), so a quick "rest-voltage check" can still be biased by prior current history—another reason SOC^e under load differs from a simple %Ah tally.

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3) Why "3.280 V at rest" matters for golf carts (and less so for home solar)

- **Where 3.280 V sits.** Multiple OCV–SOC references place mid-plateau around nominal **3.3 V** per cell. A123 documentation notes cells are shipped near ~50 % SOC around 3.3 V; common $LiFePO_4$ charts bracket **3.27–3.32 V** as the transition from mid-plateau toward the onset of the low-side curvature. In practice, **~3.280 V at rest** is a *useful field marker* that you are near the edge of the comfortable plateau.
- **Golf-cart burst currents.** Off-the-shelf golf-cart controllers routinely allow **440–650 A** peaks. Those short inrush spikes impose instantaneous IR-drop and polarization that can pull **one or more cells** to BMS low-voltage cut-off

even when average SOC^c suggests “plenty left,” abruptly ending propulsion and slashing SOC^e.

- **BMS low-voltage thresholds.** Typical LFP protection limits fall around **2.5–2.8 V/cell**. As you approach the knee, small added sag from a 300–600 A pulse can trip cut-off on the weakest cell—despite SOC^c not being zero—because energy-at-voltage (SOC^e) is the gating factor.

Bottom line for carts: Treat **≈ 3.280 V rest** as the practical “yellow line” for **SOC^e**—above it, the pack tolerates inrush more gracefully; below it, expect **disproportionate** loss of usable energy during acceleration and hills as cells flirt with the knee and BMS LVP.

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4) Golf carts vs home solar: contrasting duty cycles

Golf carts (short, heavy bursts >300 A)

- **High C-rate effects.** Studies on LFP show higher discharge rates reduce apparent capacity and shorten the plateau duration; voltage sag under spikes exaggerates the knee. SOC^e drops faster than SOC^c.
- **Controller reality.** 440–650 A controllers are common, and even stock units in the 300–400 A class are typical—so transient IR-drop is the norm, not the exception.
- **Operational implication.** Two packs with identical SOC^c can deliver very different **range** if one is colder, older, or slightly imbalanced—because SOC^e is the quantity that governs “how far you go under *this* load.”

Home solar (lower, steadier C-rates most of the day)

- **Lower discharge rates.** Residential storage typically runs **~0.2–0.5 C** continuous, where voltage sag is modest and pack temperature is managed—so SOC^e tracks SOC^c more closely.
- **Spec example.** Tesla Powerwall is rated 5 kW continuous (PW2) to **11.5 kW** continuous (PW3) on a **13.5 kWh** pack—architected for sustained output

rather than short 600 A surges—so its usable **energy** is predictable against SOC^c at room temperature.

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5) Temperature, controllers, motors & "phantom confidence"

- **Temperature.** Below ~0 °C, LFP internal resistance rises and kinetics slow, leading to less deliverable energy (SOC^e) at a given SOC^c and earlier knee-onset under load.
- **Motor & controller behavior.** High-torque launches demand peak current; IR-drop is worst at low speed/high torque, exactly when you're closest to the knee if cells are below ~3.28 V at rest.
- **Low-mA parasitics & instrumentation.** Milliamps from telematics, converters, alarms, or the controller's standby may barely dent SOC^c, and rest voltage can rebound after use. But **prior** high-rate events leave you thermally and electrochemically closer to the knee; in the next acceleration, SOC^e is what fails first. Relaxation studies in LFP show OCV can drift for **hours**, so "looks fine at rest" can be misleading for the next burst.

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6) Practical guidance (engineer's checklist)

For golf carts

1. **Watch rest voltage**: If any cell reads **≤ ~3.280 V** at rest before a ride, plan for reduced usable energy on hills/starts; avoid hard launches or recharge sooner. (This aligns with the LFP plateau geometry and common BMS LVP bands.)
2. **Right-size the controller** to the pack: Peak current should respect the cell's rate capability and wiring/IR; "bigger" isn't free—600 A surges buy torque but burn SOC^e margin.
3. **Mind temperature**: Cold mornings? Expect less SOC^e at the same SOC^c; pre-warm if possible or drive gentler until voltage stabilizes.

4. **Balance & BMS settings**: Keep cells well balanced; set LVP conservatively (e.g., ≥ 2.8 V/cell pack-level) to avoid knee abuse and nuisance trips under spikes.

For home solar

1. **Use SOC^e for runtime predictions**: Your EMS/EMS-integrated BMS should report SoE (or "usable energy") rather than %Ah alone for accurate hours-remaining.
2. **Operate at moderate C-rates** (typ. 0.2–0.5 C) to keep $SOC^e \approx SOC^c$ and extend life.
3. **Plan around specs** (continuous/peak power) rather than nameplate kWh alone.

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7) Why the "low-side hook" is so abrupt in LFP (the science bit)

LFP's **two-phase ($FePO_4$/$FePO_4$-Li)** intercalation mechanism yields a long plateau as the phases coexist; near depletion, the system transitions out of that two-phase region and cell voltage drops quickly with small additional lithiation changes—the **"hook"/knee**. Equivalent-circuit and OCV-model studies (R_0 + RC polarization) capture the extra sag under load that pushes you prematurely into this knee. That's precisely why **energy-at-voltage (SOC^e)**—not amp-hours—decides whether your cart accelerates or trips LVP.

Footnotes & sources

1. Ma, L. *et al.* "State of Charge and State of Energy Estimation for Lithium-Ion Batteries." **JESTECH** (2021). Defines SOC vs SOE and motivates separate estimation.
2. Hou, E. *et al.* "State of energy estimation of lithium-ion battery…" **Scientific Reports** (2024, open access). Formal definition of SOE as remaining usable energy.
3. gridX knowledge: "What is State of Charge? — SoE vs SoC." (2025). Clear distinction and context-dependency of SoE.
4. Zitara glossary: "State of Energy (SoE)." Short definition emphasizing voltage-aware energy.
5. Texas Instruments, **$LiFePO_4$ Design Considerations** (SLUAAR1, 2023). LFP OCV–SOC profile and plateau/knee considerations.
6. Weng, C. *et al.* "A Unified OCV Model of Li-ion Batteries." **J. Power Sources** (2014). Modeling the flat OCV–SOC region and the knee for A123 LFP cells.
7. A123 Systems, **Battery Pack Design, Validation, and Assembly Guides**. Notes nominal ~3.3 V/cell at mid-SOC and OCV hysteresis.
8. EVE official SOC/voltage guide (2025). Example OCV–SOC mapping showing 3.32 V ≈ ~80 % SOC; illustrates variability across charts.
9. Jackery LFP voltage chart (2025). Example mapping with 3.27–3.30 V around ~60–70 % SOC; underscores curve-flatness.
10. Voicilă, T.-I. *et al.* "Enhanced OCV Estimation in $LiFePO_4$ Batteries." **Batteries** (2025). OCV relaxation persists for hours; knee detection.
11. Huang, Y. *et al.* "Effects of discharge rate on $LiFePO_4$ characteristics." **Applied Thermal Engineering** (2019). Capacity/plateau reduction at higher rates.

12. Luo, H. *et al.* "Lithium-ion batteries under low-temperature environment." **Energies** (2022, open access). Increased resistance & capacity loss when cold.

13. Curtis 1268 platform (manual/datasheet). Golf/utility vehicle controllers widely used; high-current capability.

14. Navitas TAC2 & TSX controllers (440–600 A). Illustrates typical golf-cart peak current envelopes.

15. Typical LFP BMS protection bands: Intercel (pbq) and EVE cell spec indicating ~2.5–2.8 V/cell cut-offs/reconnects.

16. Tesla Powerwall 2/3 datasheets (13.5 kWh; 5–11.5 kW continuous). Representative residential discharge power vs energy.

17. Second-life LFP study (SDSU): Equivalent-circuit (R_0 + RC) impedance framing of load-induced voltage sag.

Closing note

Because **SoE (SOC^e)** is the quantity that determines **usable range and performance**, golf-cart diagnostics and user displays should prioritize **energy-aware** estimates (voltage- and temperature-conditioned) rather than **amp-hour-only** gauges. That's especially true as you approach **≈ 3.280 V/cell at rest**, when small increases in load can trigger the **low-side knee** and cause disproportionate losses in **usable energy**—the thing that actually moves the cart.

We hope this Paper and Research helps everyone understand and live with the idiosyncrasies' of the LiFeP04 Lithium Battery and the related SOC Indicator. The SOC Indicator is simply an ESTIMATE of CAPACITY remaining in the Battery, NOT the ESTIMATE of ENERGY remaining. Enjoy your LFP Battery!

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