Automotive Lead-Acid Batteries – Perspective of the EFB & AGM Technology and Learnings from EU Benchmark

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Motivation of the Study

- **Motivation:**
  - ➢ PENOX wanted to understand the key performances of SLI, EFB and AGM batteries
  - ➢ Data was collected and analysed, and the focus is on understanding the hierarchy of performance-relevant factors, such as general design, plate technology and structure of positive and negative electrodes
  - ➢ PENOX also wants to identify specific “survival” criteria for battery operation
- **Strategy:**
  - Analysis of massive EU database using Python, combined with single-cell testing
  - **Extension to testing of Brazilian Battery technology in 2025**

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Study Overview

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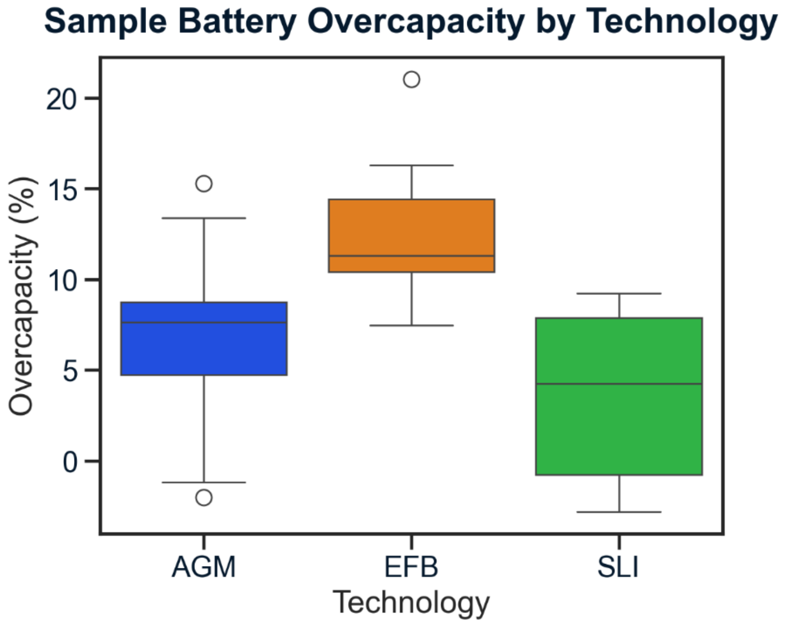
Targets:

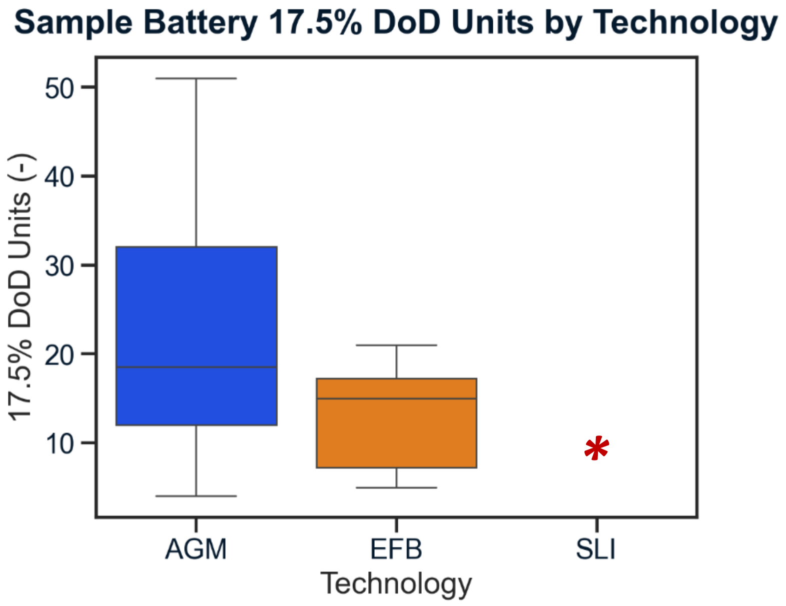
- ➢ Investigate the performance of advanced Automotive batteries in the EU (starting point)
- ➢ Study the main performance limitations, especially regarding:
  - 17.5% DoD units *(EN 50342)*
  - 50% DoD cycles *(EN 50342)*
- ➢ Comparison of lab tests and field-aging, i.e., real-life vehicle application
- ➢ Identify solutions for performance improvements

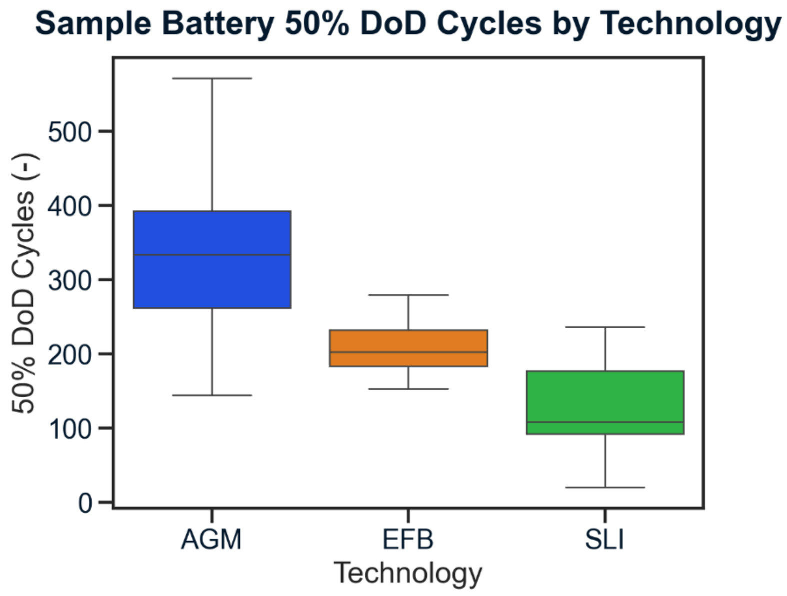
Data Set:

- Technologies: AGM, EFB, SLI
- Manufacturers: Covering > 85% of total market share in Europe
- Lab test data: Ca. 40 test series of usually six or more automotive batteries → Σ > 300 batteries
- Field data (i.e., field returned vehicle batteries): > 150 batteries
- Timeframe: 2018 to 2022 and 2024+

Overcapacity & Cycle Life







- EFB with highest average overcapacity
- SLI with lowest average overcapacity
- Strong overcapacity variation for SLI and especially AGM

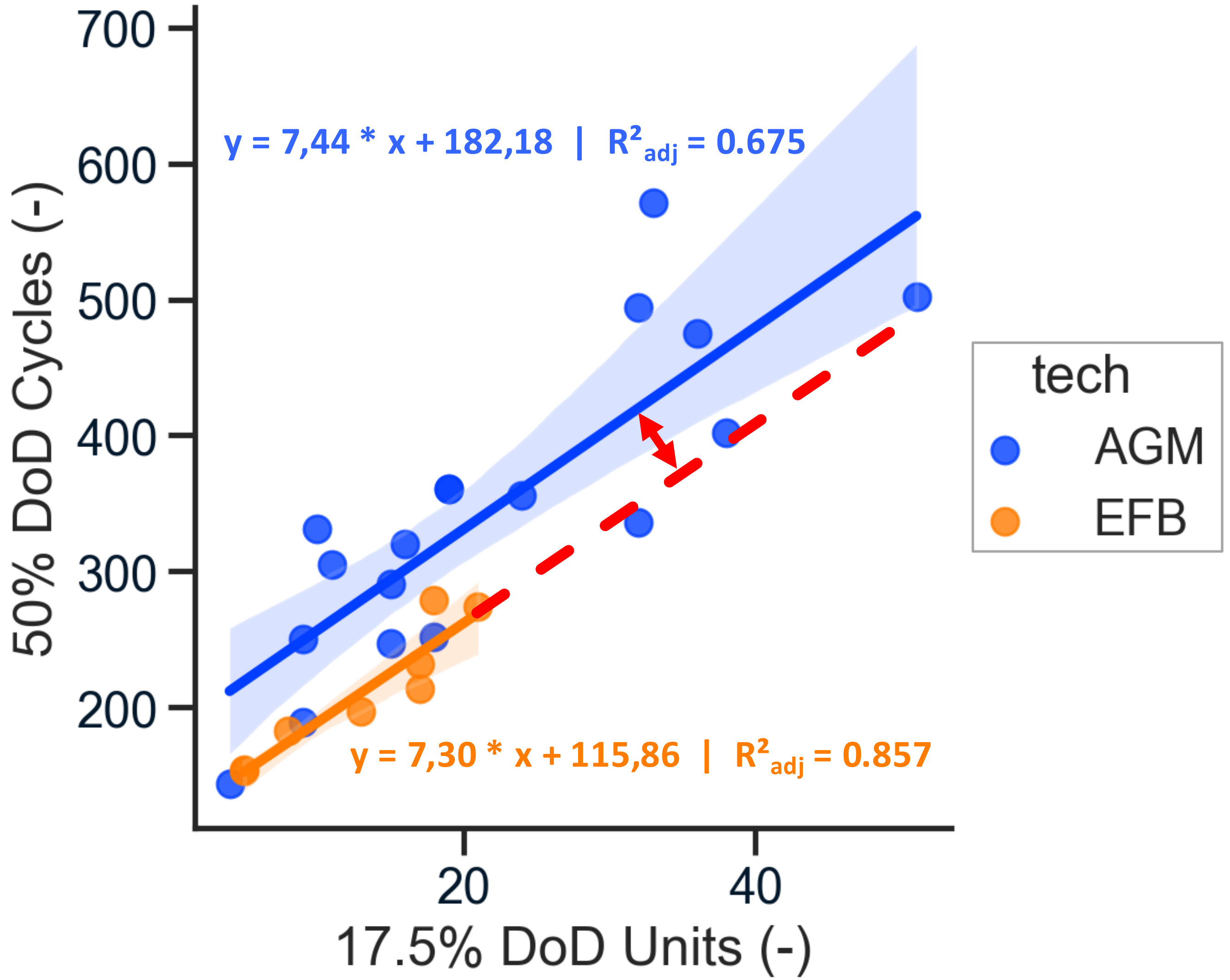
- Strong 17.5% DoD cycle test performance variation for AGM
- Overlap of EFB performance with **low-level** AGM
- **Best-in-class** AGM performs far better than all other types

- Strong 50% DoD cycle test performance variation for AGM
- Overlap between **low-level** AGM and EFB & SLI, and also between **low-level** EFB and SLI
- **Best-in-class** AGM performs far better than all other types

* *Not tested with **SLI** batteries*

50% DoD vs 17.5% DoD Cycle Test Performance

50% DoD Cycles vs 17.5% DoD Units



Lighter colored areas represent 95% confidence intervals

- 17.5% DoD Test performance is well correlated with 50% DoD Test performance for both **AGM** and **EFB**
- Linear regression results in a very similar slope for **AGM** and **EFB** → **parallel-shifted**
- Potential reason for this parallel shift: different average ***plate group compression level*** (**AGM** >> **EFB**)

- EFB until 2021 was not reaching M3 level 50% DOD – meaning 360 cycles @50% DoD
- Start-stop performance of high quality EFB was reaching M3 level

Potential Key-Criteria for Cycle Life

Discussion:

- What are the parameters for a battery to run in specific performance testing?
- PENOX is screening for **“survival” criteria** and wants to improve those by optimising active mass structures (e.g., 4BS structure and optimised porosity)
- Concepts are to establish stable structures and to increase the charge recovery, especially in under-charging conditions (17.5% DoD Testing)

Analysis of ideas:

- Initial capacity stability is expected to be an indicator for 50% DoD cycle life
- Overcapacity is expected to increase the 50% DoD cycle life
- Higher Charge acceptance (CA) is expected to support a high 17.5% DoD cycle life

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Linear Correlations: AGM & EFB

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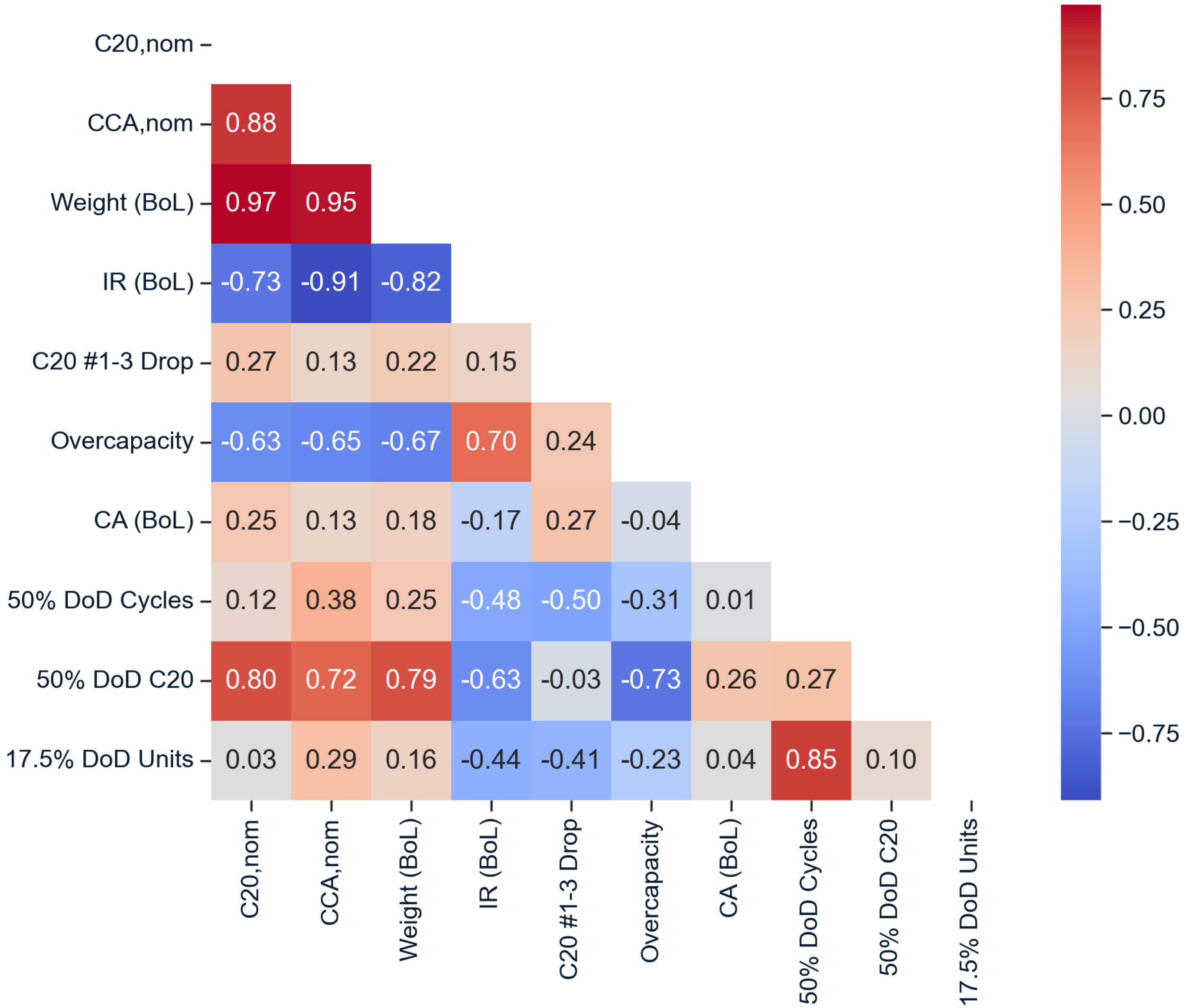
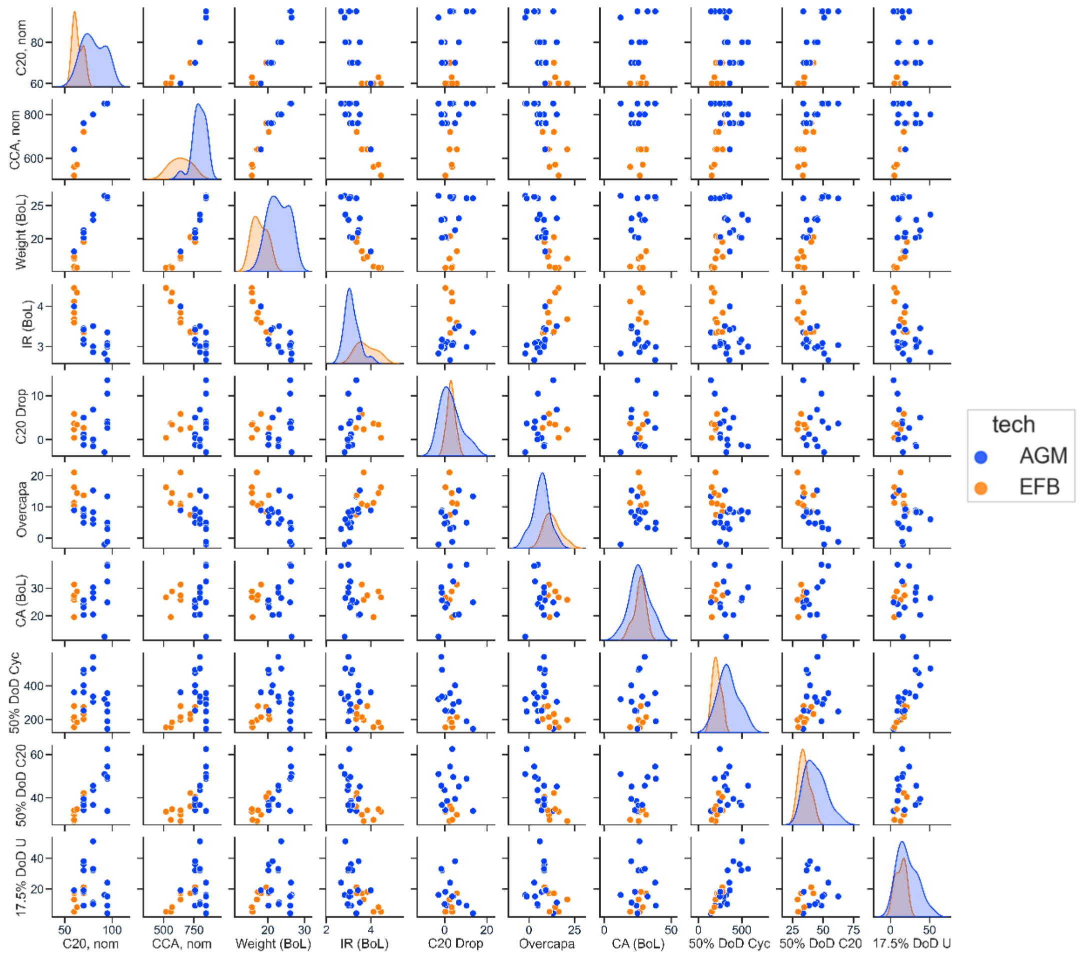
AGM & EFB



AGM & EFB



BoL = Beginning of Life

CA = Charge Acceptance

IR = Internal Resistance

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Correlations – What they mean?

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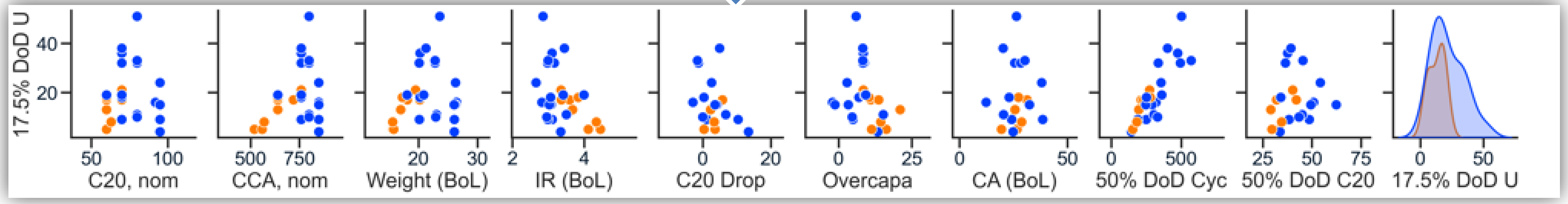
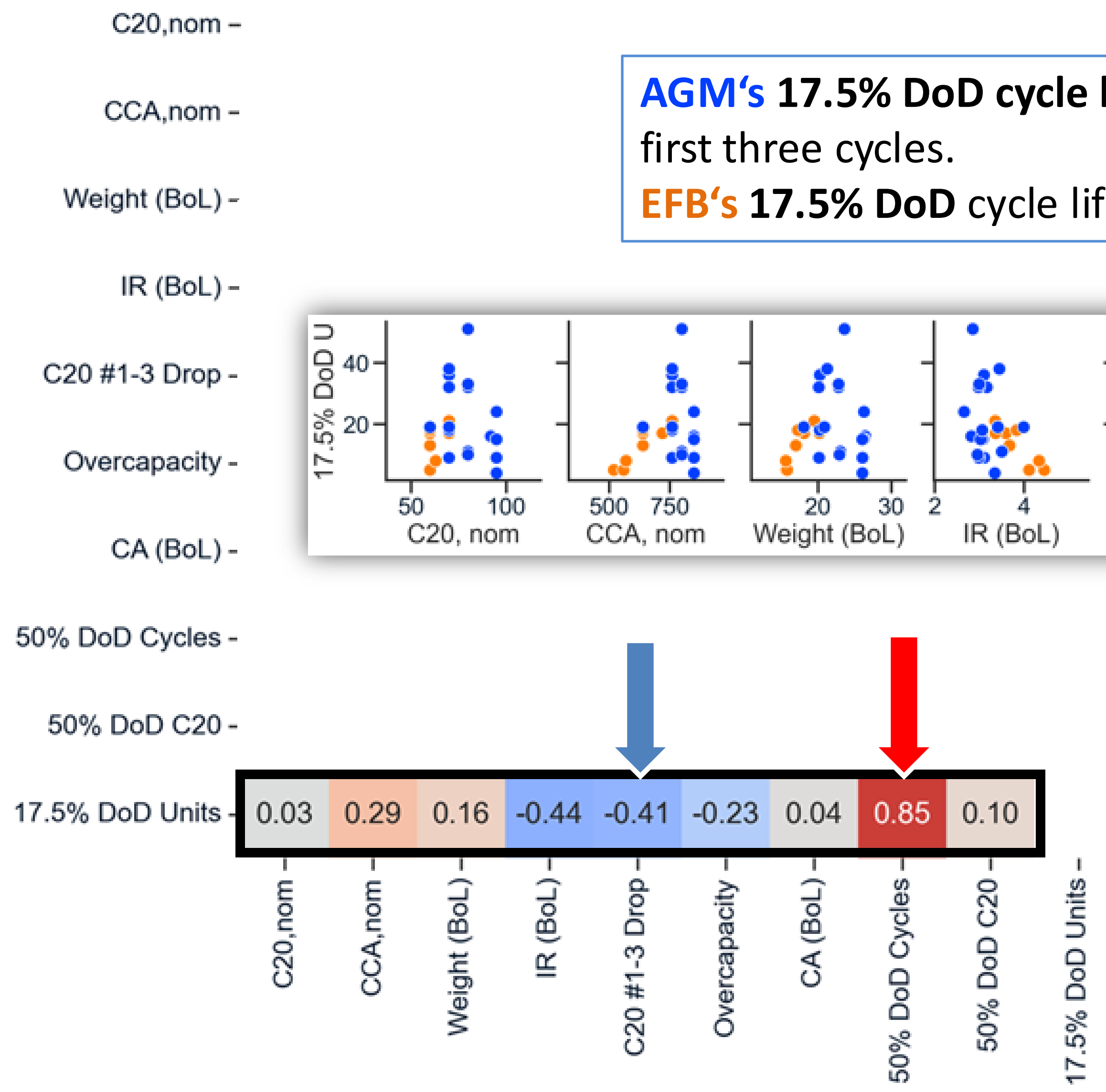
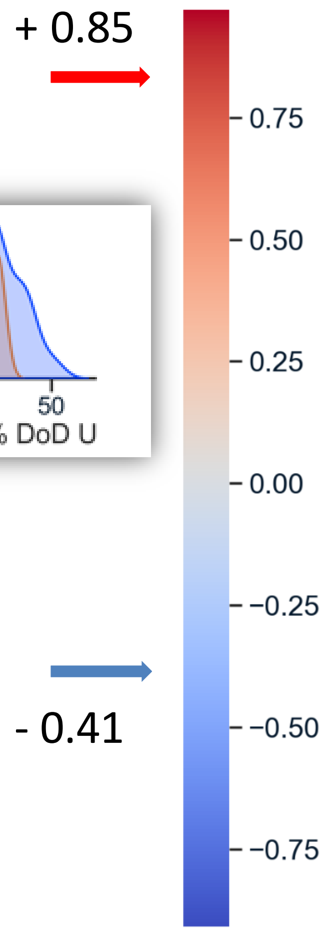
AGM's 17.5% DoD cycle life is <u>lower</u> for <u>dropping</u> „C20 #1-3" in the first three cycles.
EFB's 17.5% DoD cycle life is not showing a trend.



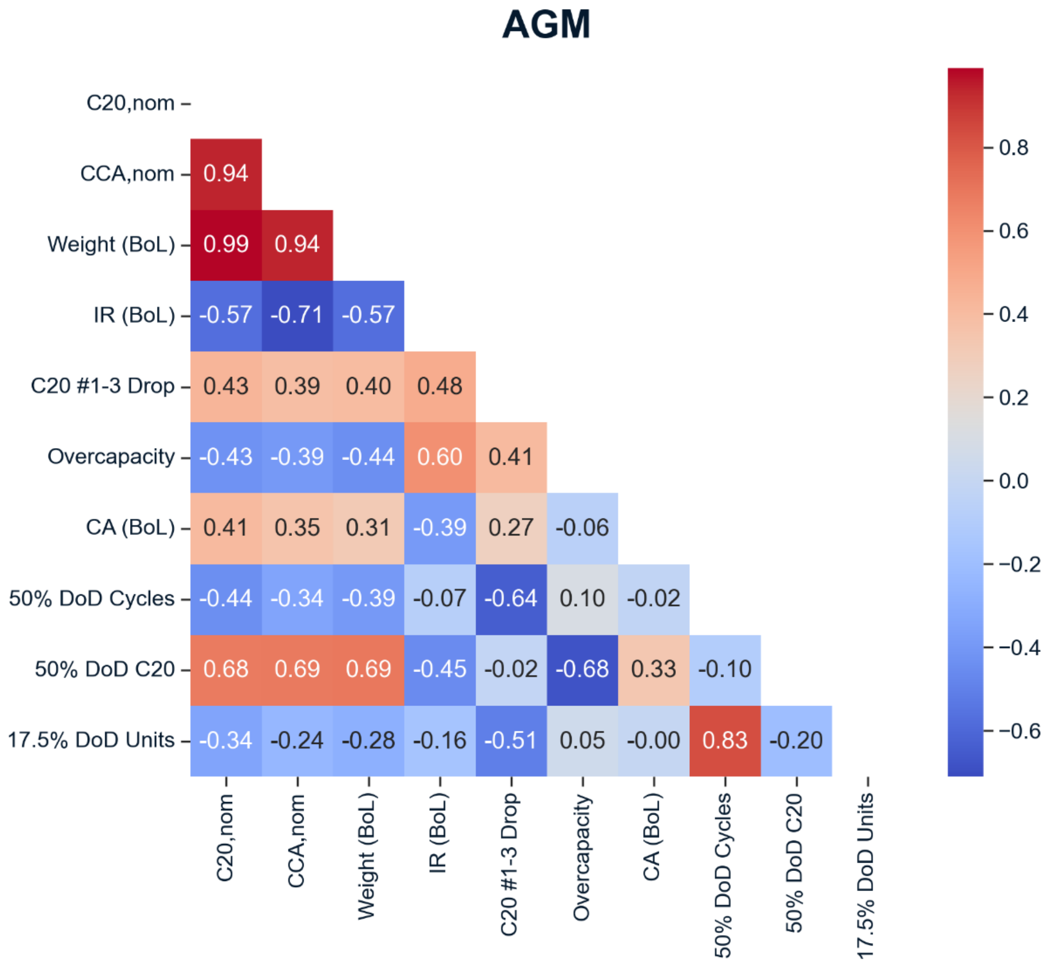


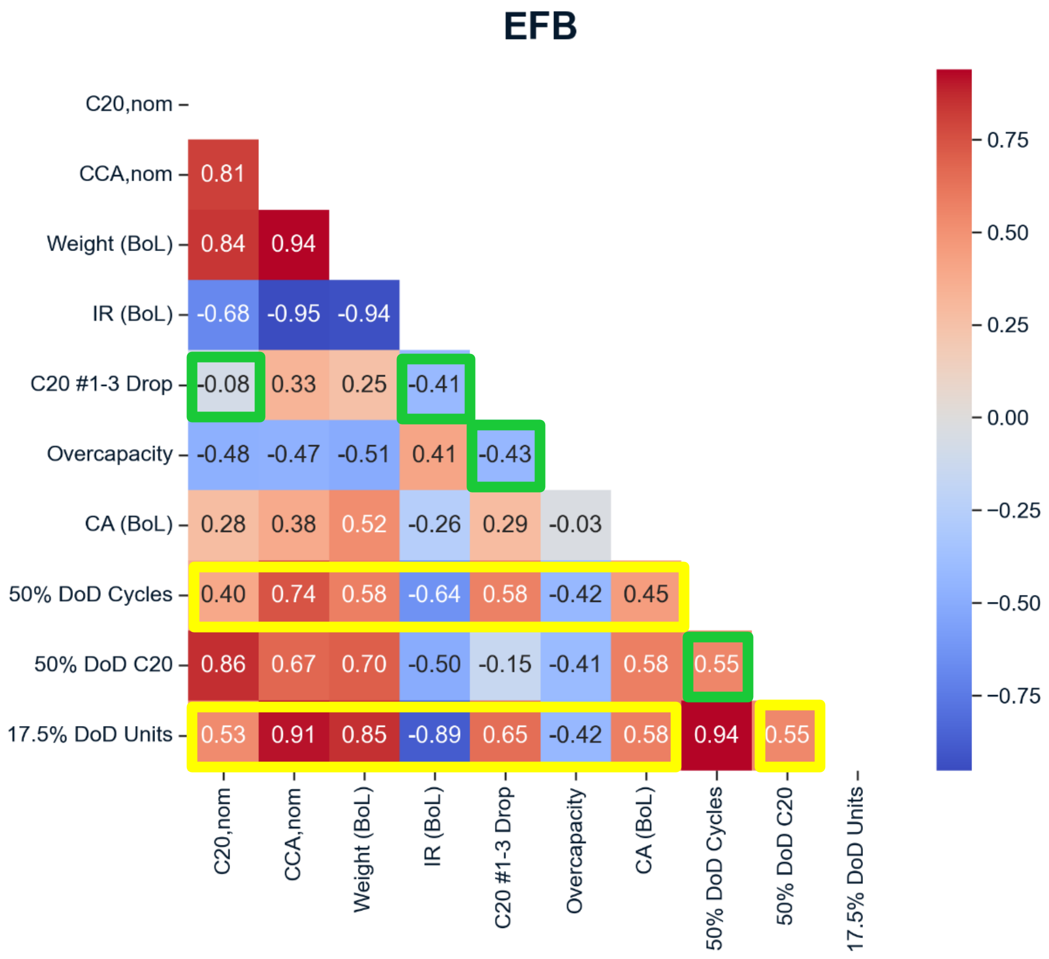
AGM's and **EFB's 17.5% DoD cycle life** is <u>higher</u> for <u>higher</u> 50% DoD cycle life.

Meaning they have similar sensitivities.



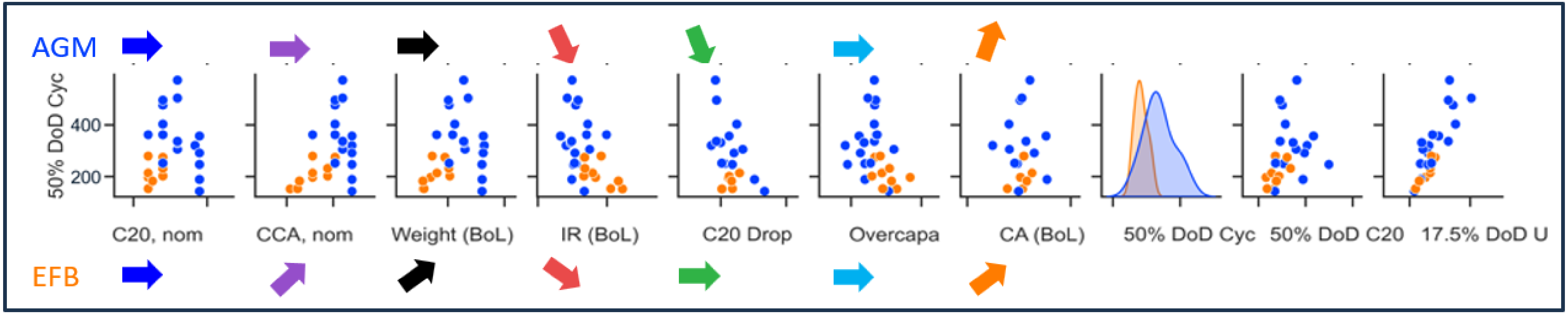
Linear Correlations: AGM vs. EFB





- While many of these linear correlations are comparable between **AGM** and **EFB**, **there are also significant differences, especially concerning 50% DoD cycles and 17.5% DoD units *(marked in yellow)***
- Other main differences are marked in green

Identifying Correlations in AGM and EFB



- Cold cranking (**CCA**): For **EFB**, a higher value correlates with a higher 50% DoD cycle life. This is an indirect effect, as the cold cranking and the charge acceptance (CA) slightly correlate. **AGM** has always had a high CCA—*thus, it may not be scaling*.
- Charge acceptance (**CA**): For both technologies, higher charge acceptance correlates with higher cycle life = charge recovery in 17.5% DoD very important, but also in 50% DoD
- Internal resistance (**IR**): logically relevant for better charge acceptance.
- **C20 drop** (3 initial cycles): is inverse indicative – surprisingly only for **AGM** (due to overcapacity)

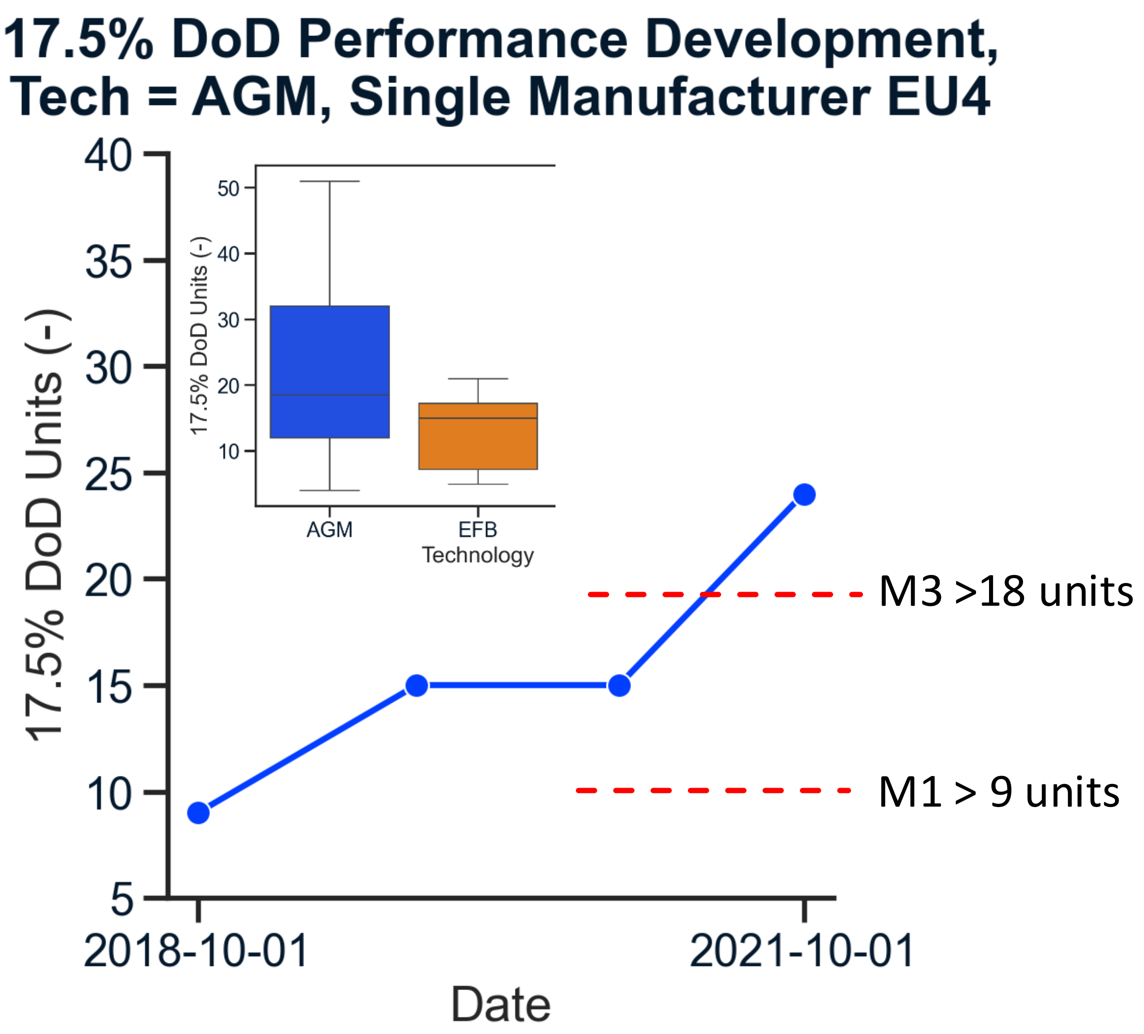
Key-Points for Cycle Life

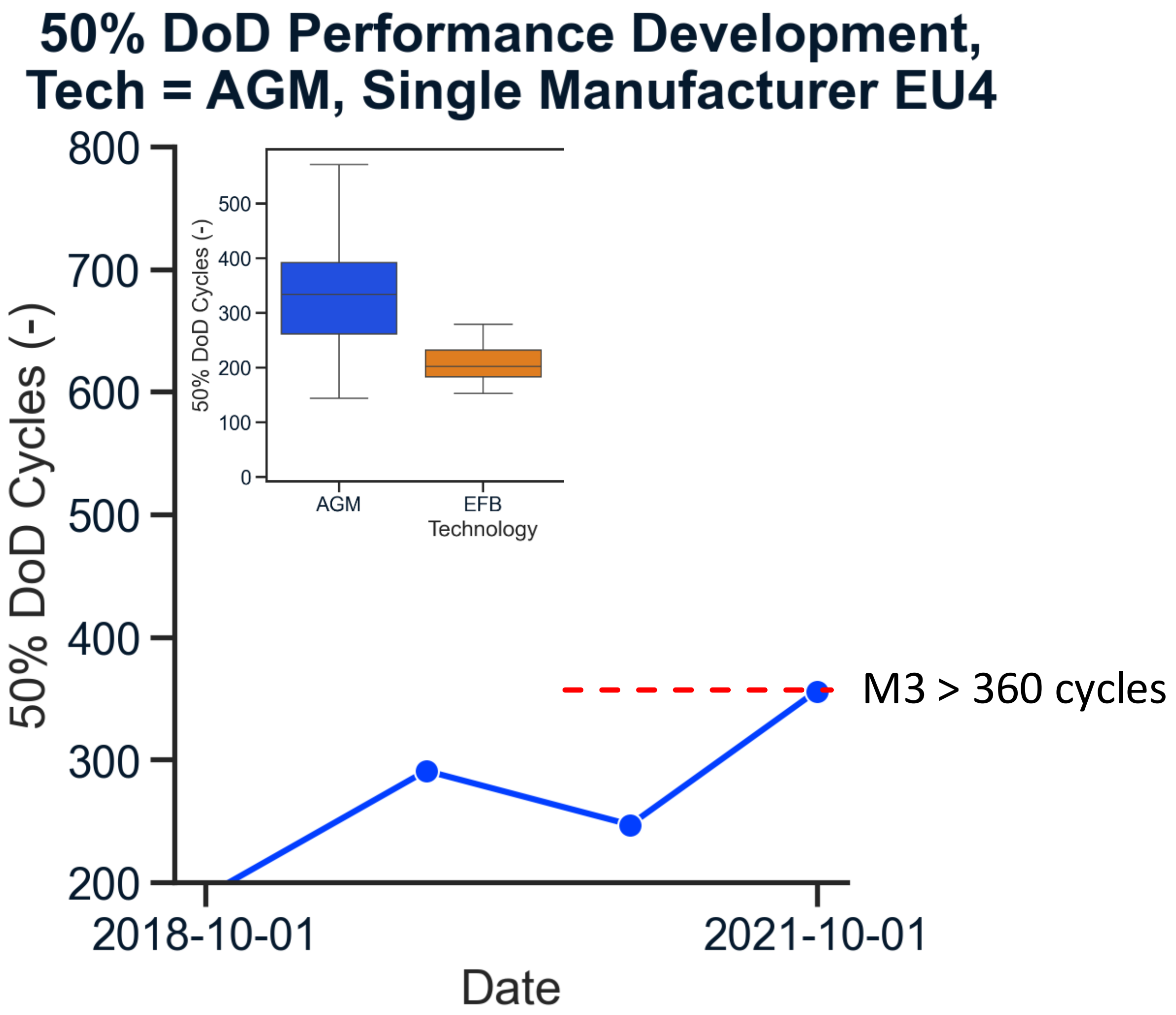
Learnings:

- In 17.5% DoD cycling, it is important that after the end of the unit, the state of charge is not dropped too low. Therefore, charge recovery based on high charge acceptance is key.
- Expanders play a relevant role in preparing the negative electrode for high charge acceptance.
- Proper mixing and curing are essential for the function of the expander in NAM.
- RL in PAM is beneficial to protect the NAM from over formation
- Modern thin grid technology is sometimes more difficult to allow for a proper mass-to-grid adhesion. However, a strong adhesion is the base of a low internal resistance of the mass-to-grid interface.

- 50% DOD cycling is driven by similar parameters – and thus not only a stable PAM structure is required, but also a NAM which supports the recharge in cyclical operation.

Cycle Test Performance Development Over Time





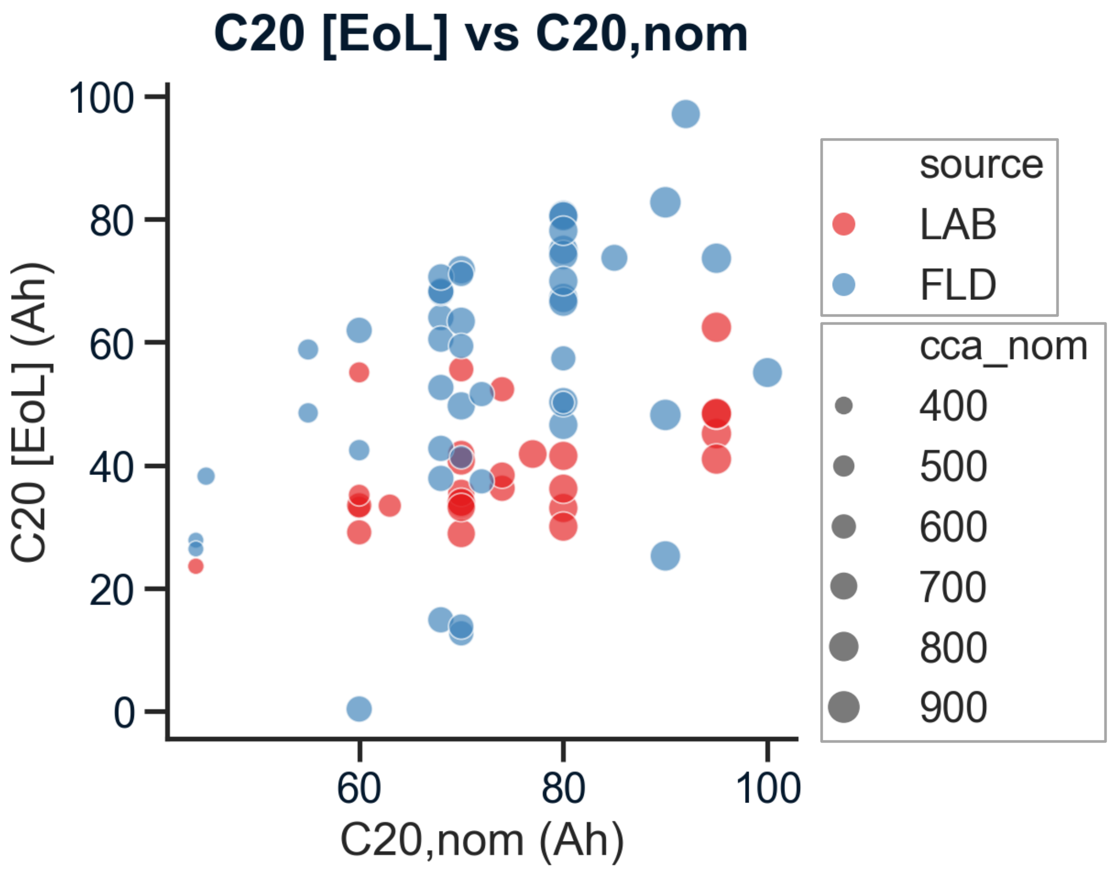
- Example for the technical evolution of **AGM** and the correlation between 17.5% and 50% DoD cycle life

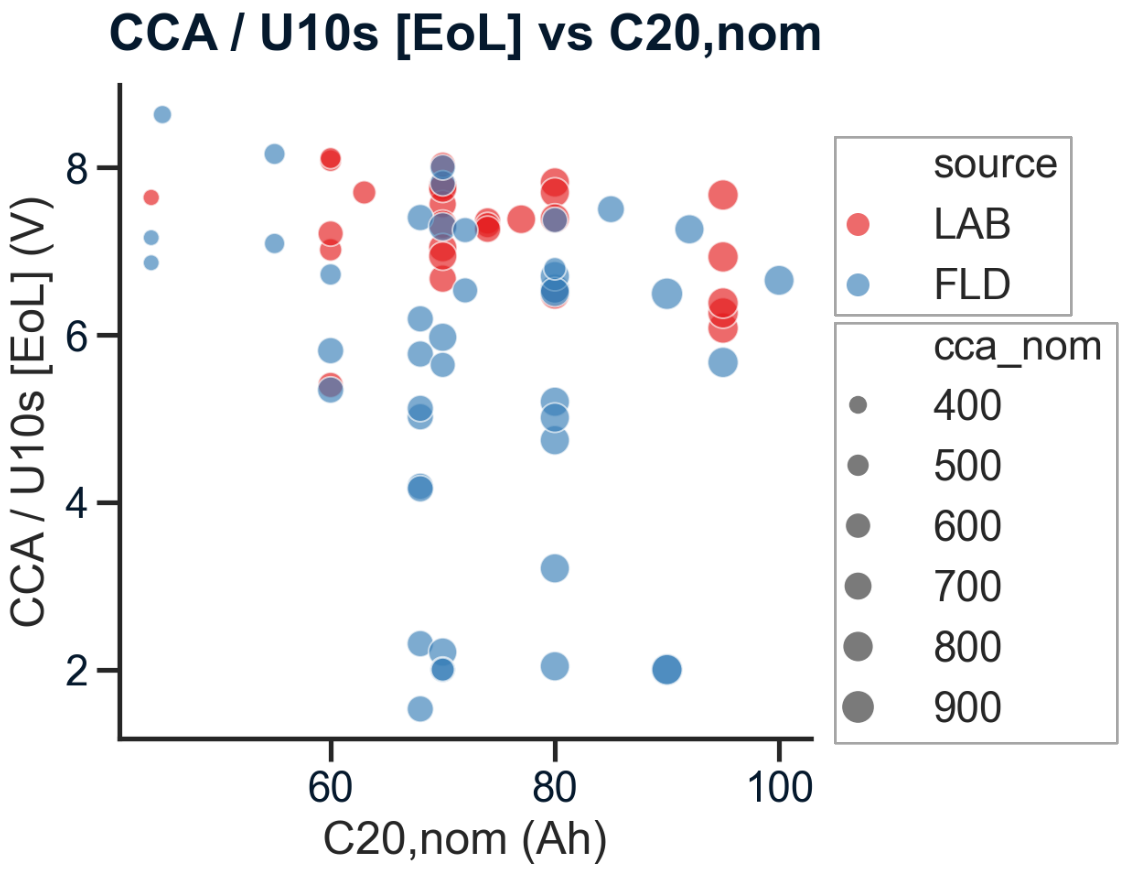
Trends relevant for Brazil and South America

- **EFB** and **AGM** Technology show different performance correlations
- Use of specific **EFB** and **AGM** expanders by PENOX is increasing the 17.5% DoD cycle life
- 17.5% DoD and 50% DoD cycle life are coupled – *if you observe a different result, there might be an issue in the battery test or a specific problem.*
- *Reaching about 120 to 150 cycles 50% DoD equals about 7 to 9 units 17.5% DoD*
- To improve 50% DoD from < 100 cycles to >100 cycles is typically the most difficult step
- PENOX has recently seen positive trends in cycle life—the M1 level passed, and the M2 level was reached. A formal study with ABR will start later in 2025. ***We need test batteries from partners.***

- **Attention:** Charge acceptance (CA) is relevant to recovering capacity in the 17.5% DoD units. Any decrease in charge acceptance caused by a mass-to-grid disturbance, such as process oil on grids (often observed in some thin grid technologies) or an ohmic barrier caused by Ca-oxide layers (too high Ca-content in alloy), is critical.

Lab vs. Field – What can we learn?





- **Significant differences between the lab and field data!**
- Lab battery C_{20} [EoL] (after 50% DoD test) at around ~ 50% $C_{20,nom}$, while field data is significantly higher
- Also significant difference in CCA / U10s [EoL] data: lab data at ~ 7 V, while field data is significantly lower

EoL = End of Life

Summary & Outlook

- Screening of Battery benchmark data allows for a better understanding of technology
- "*Survival criteria* can be extracted and materials adjusted to function
- Evolution of different technology over time becomes visible
- Best practices for technology, choice of oxides, and different additives and expanders

- Comparison of regions, e.g., EU vs. South America and the specific technologies is possible
- This allows e.g., better expander mixes and adjusted functional oxides (e.g., RL+)

- PENOX is running laboratory testing with a new generation of expanders, including the learnings from the benchmark data – *to be presented soon*

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Thank You for your Attention!

aBR Austrian Battery Research Laboratory GesmbH.