Benchmarking Automotive Lead-Acid Battery Technologies – A Comparative Analysis of AGM and EFB Systems with New Data Insights

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Motivation

- ABR and PENOX extend the understanding of key performance of SLI, EFB and AGM batteries, using Python-based methods, focused on the Asian ('AS') and European ('EU') markets
- 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 (i.e., PAM and NAM)
- Understanding key differences between these two markets is another primary focus of this study, especially regarding the different battery design principles employed to achieve the same performance targets
- ABR and PENOX prioritize the identification of specific „survival" criteria for a better battery operation

Study Overview

Targets

- Investigate the performance of advanced Automotive batteries in Asia and Europe
- Study the main performance limitations, especially regarding:
  - 17.5% DoD units *(EN 50342 / Asian Test Standard: JIS D 5301)*
  - 50% DoD cycles *(EN 50342 / Asian Test Standard: JIS D 5301)*
- Identify solutions for performance improvements

Data Set

- Technologies: AGM, EFB, SLI
- Manufacturers: Covering > 80% of total market share in Asia and > 85% in Europe
- Lab test data: Around 60 test series of usually six or more automotive batteries

  → Σ > 450 batteries (> 160 from Asia, > 290 from Europe)
- Timeframe: 2018 – 2025

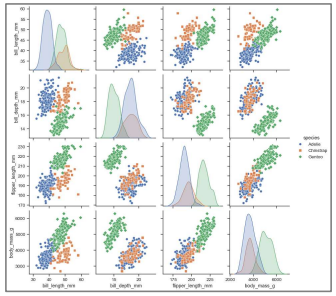
Study Overview

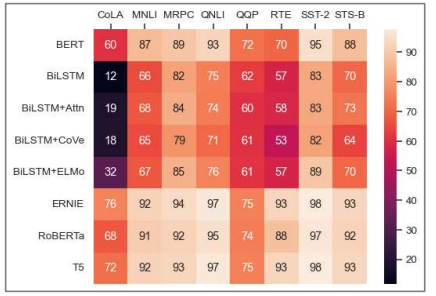
Strategy

- Massive battery test database
- Combined 12V battery and single-cell testing
- In-depth data analysis (in Python™)
- Expansion with a large test series of Asian Battery technology, done in 2025

Methodology

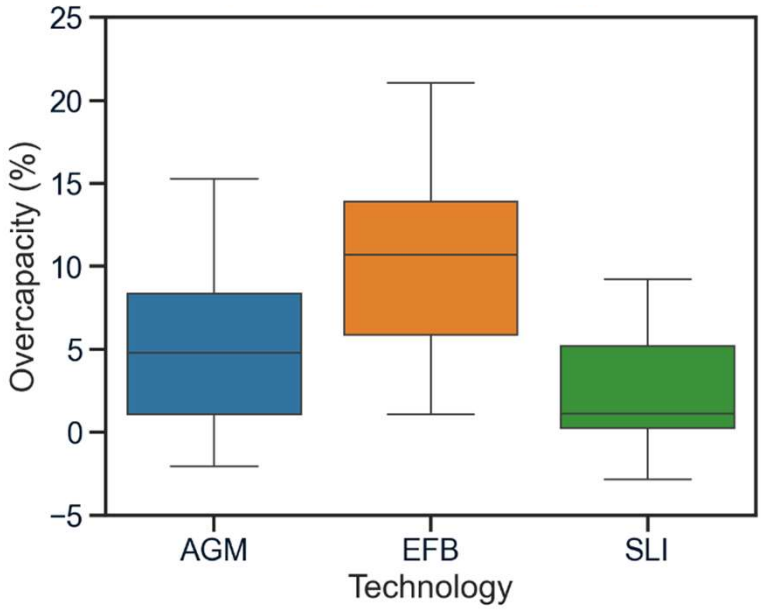
- **Python™** was chosen by PENOX as the main data evaluation tool for this study
- **Advantages include:**
  - Working efficiently with multiple categorical variables
  - Creating advanced visualisations, e.g.:
    - Pairplot
    - Heatmap





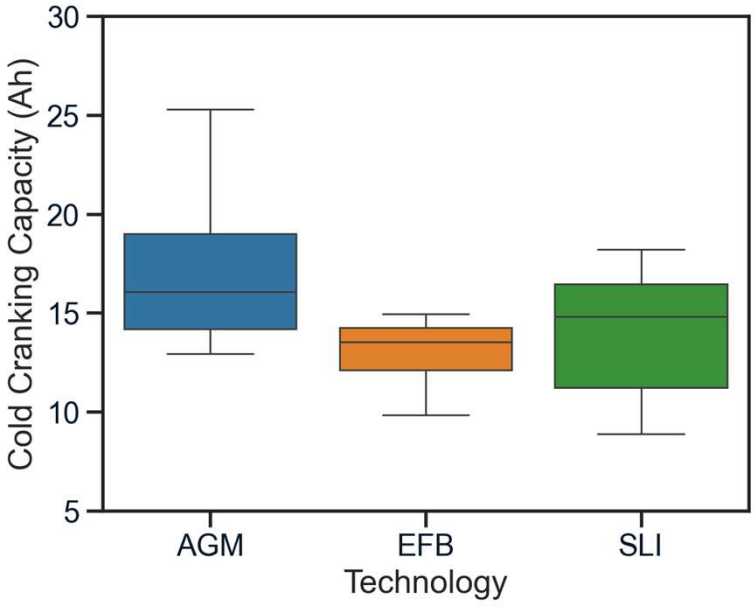
Overcapacity & Cold Cranking Capacity

Overcapacity – General Overview



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

Cold Cranking Capacity (CCC) * – General Overview



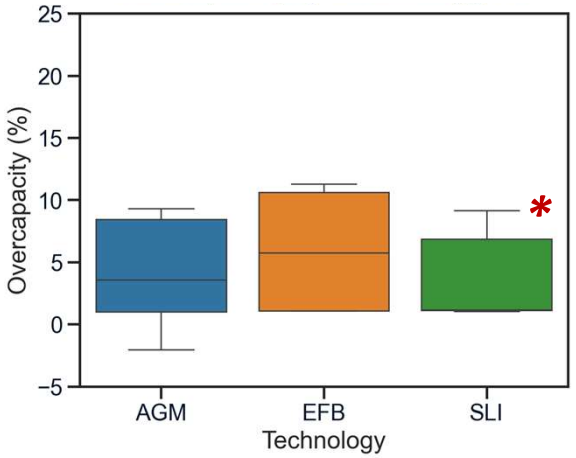
- **AGM** with highest average CCC
- **EFB** and **SLI** with high average CCC
- **AGM** with highest, **EFB** with lowest variation

* *CCC [Ah] = CCA [A] * 10/3600 + (CCA[A]*0,6) * t´(6V)/3600 (Used for all tested batteries)*

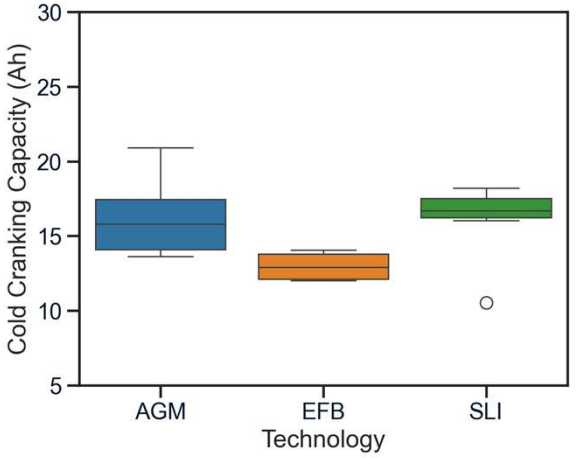
Overcapacity & Cold Cranking Capacity

AS

Overcapacity by Technology

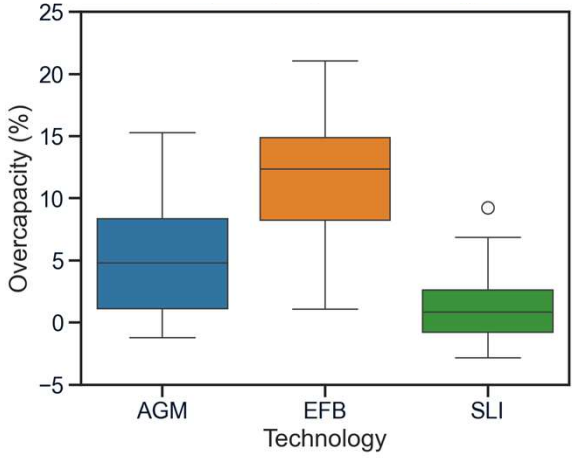


CCC by Technology

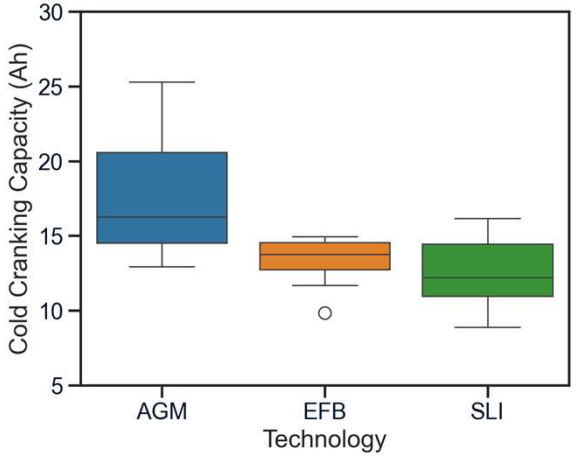


EU

Overcapacity by Technology



CCC by Technology

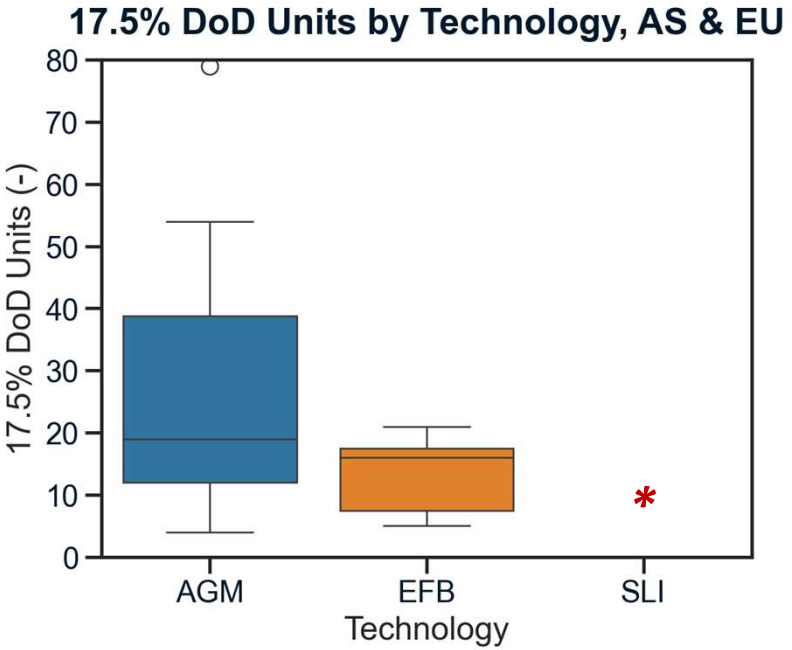


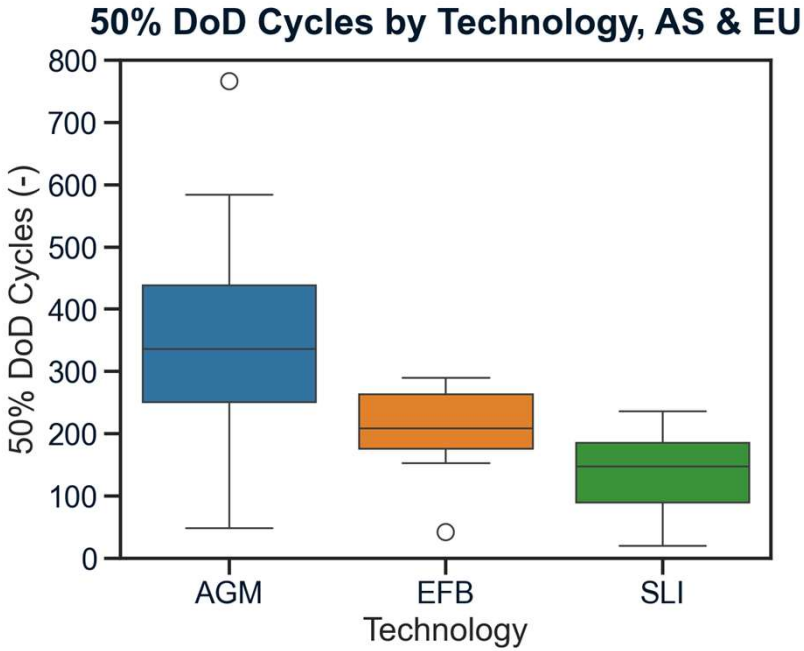
- **AGM** with low difference in overcapacity in AS and EU
- **EFB** with high difference: EU significantly higher overcapacity than AS
- **SLI** with difference: EU lower than AS
- Little difference in overcapacity between **AGM**, **EFB** & **SLI** in AS; all comparable with EU **AGM**, but with less variation

- **AGM** and **EFB** with low difference in CCC between AS and EU
- **SLI** with higher CCC in AS
- EU **AGM** with highest CCC

* *Median hidden by quartile Q1 line*

17.5% DoD & 50% DoD Cycle Life





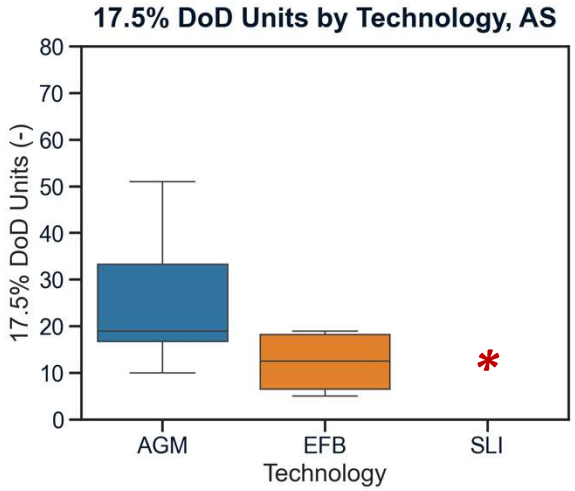
- Strong 17.5% DoD cycle test performance variation for **AGM**
- Overlap of **EFB** performance with **low-level AGM**
- **Best-in-class AGM** performs far better than all other types

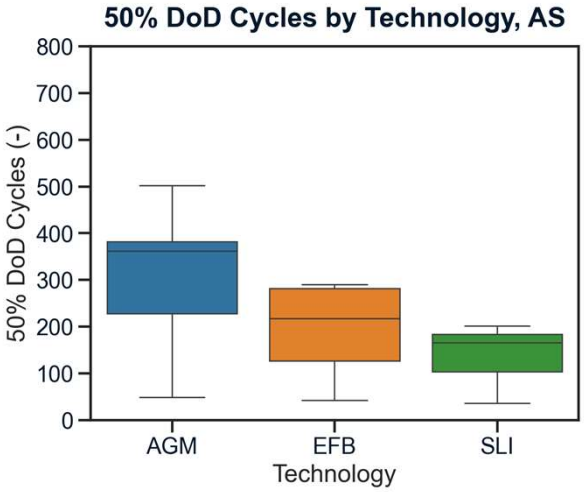
* *Not tested with **SLI** batteries*

- 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

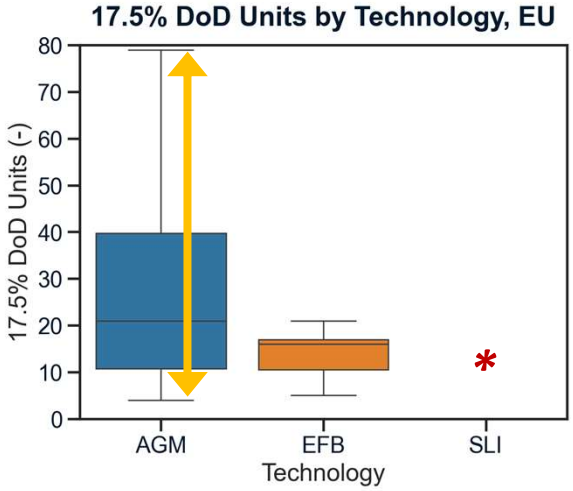
17.5% DoD & 50% DoD Cycle Life

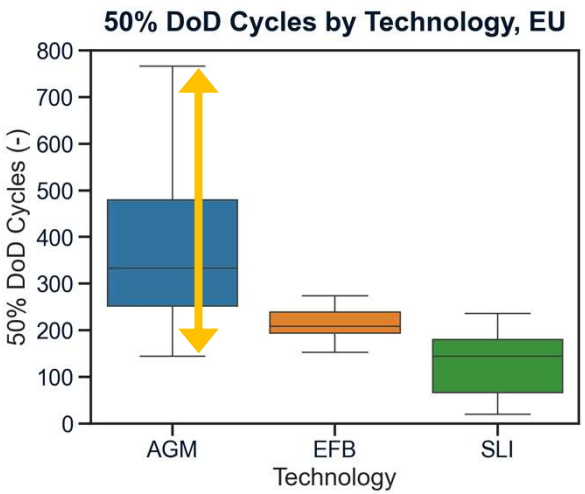
AS





EU





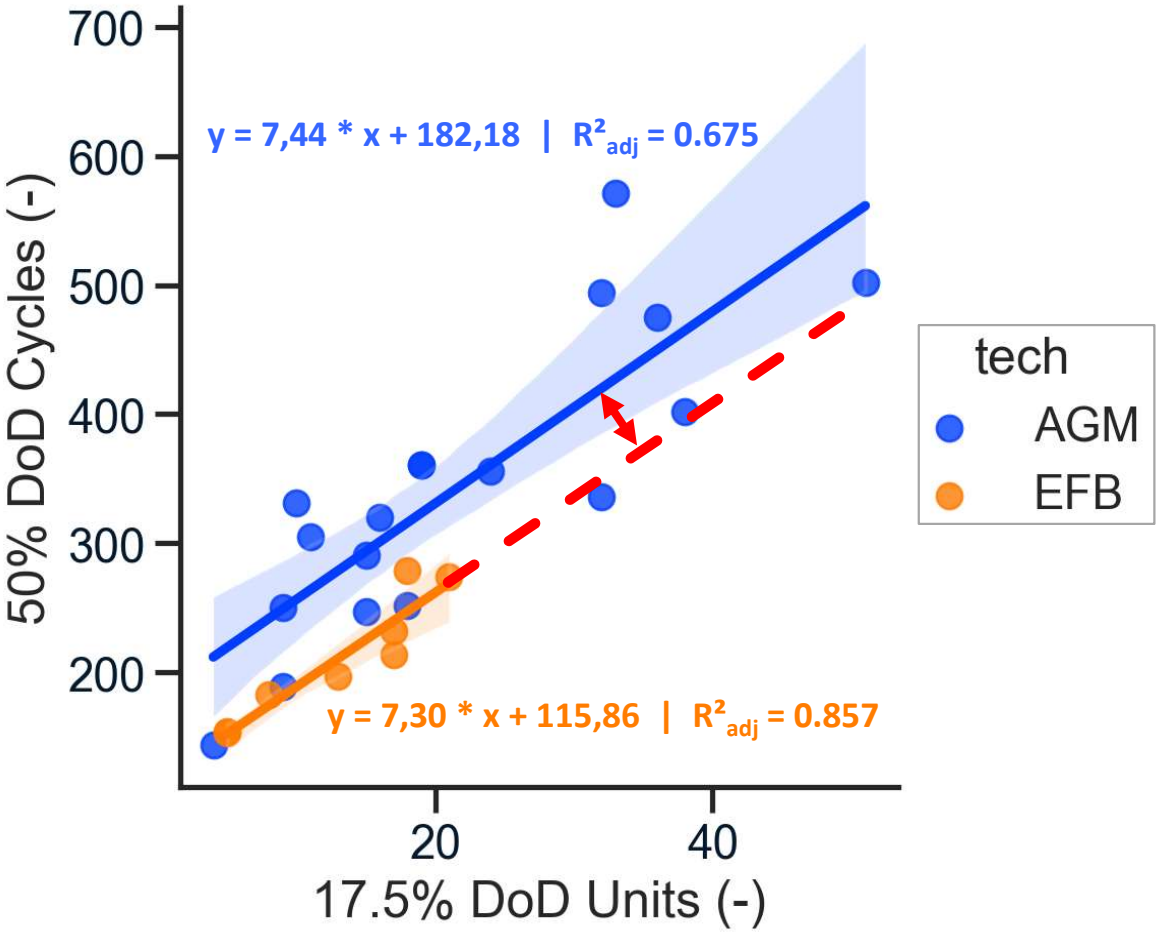
- **AGM** with very high variation in EU
- **EFB** with a very low difference AS vs EU
- In both AS and EU, **AGM** > **EFB**

- **AGM** with very high variation in EU
- **EFB** with a significantly higher spreading in AS
- In both AS and EU, **AGM** > **EFB** > **SLI** *- but in AS, generally more overlap*

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

50% DoD vs 17.5% DoD Cycle Test Performance

50% DoD Cycles vs 17.5% DoD Units



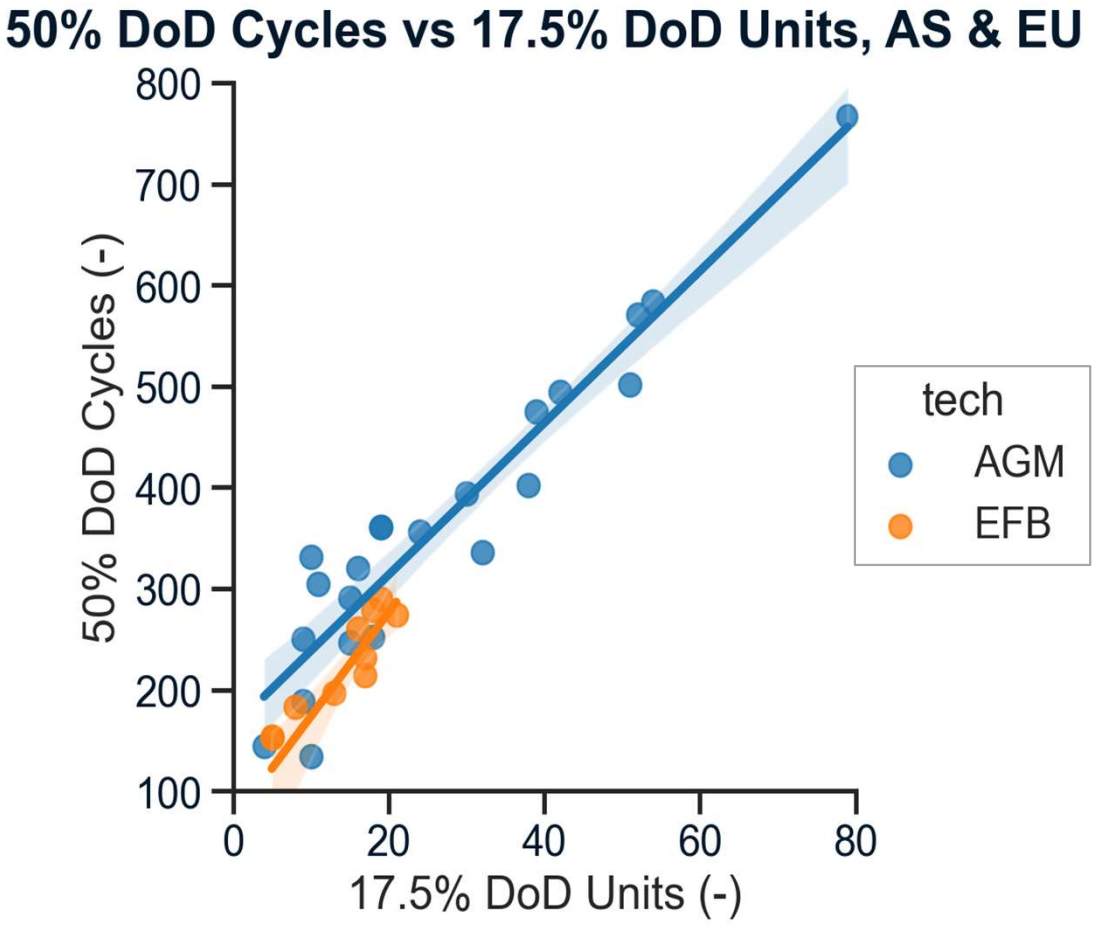
Lighter colored areas represent 95% confidence intervals

Main Findings from our ELBC 2024 Work

- 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**)

50% DoD vs 17.5% DoD Cycle Test Performance

Data Extrapolation: 17.5% DoD Tests (manually stopped) ≥ 30 Units *



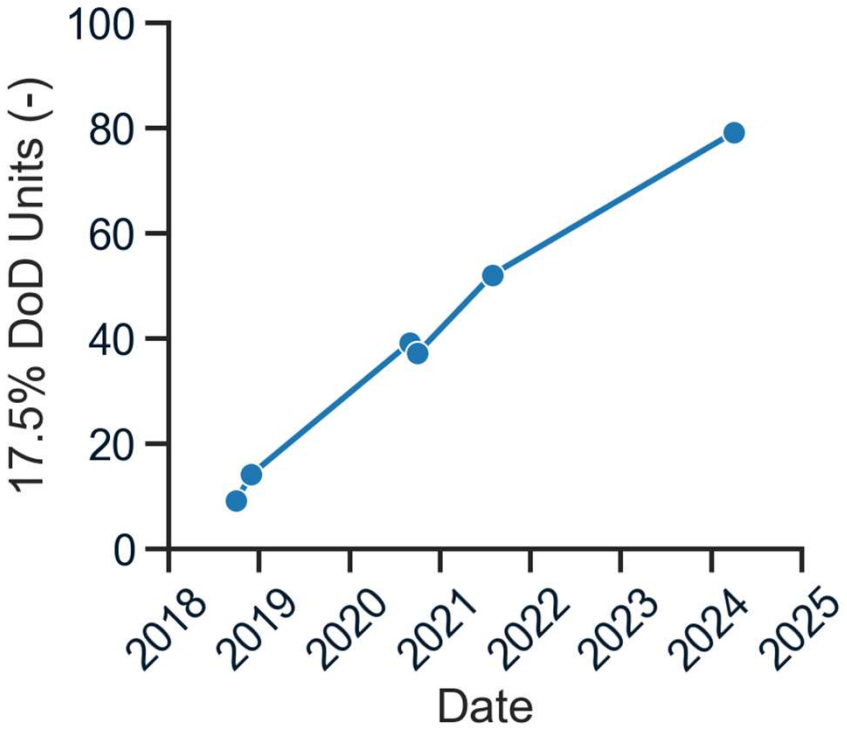
Comparison AS vs EU

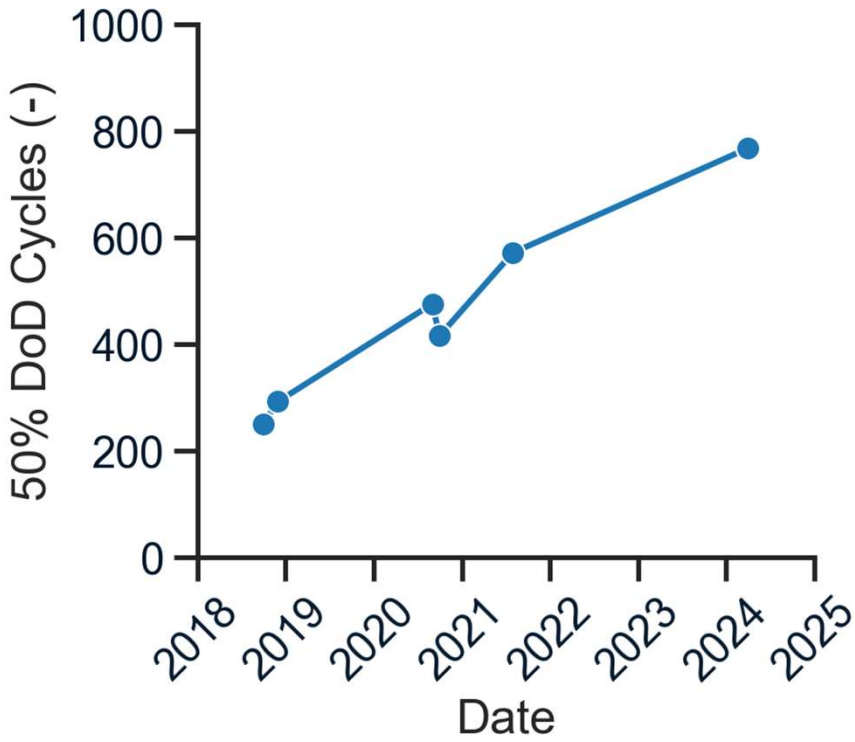
- Also between AS and EU, 17.5% DoD Test performance is well correlated with 50% DoD Test performance for both **AGM** and **EFB**
- Linear regression results in a similar slope for **AGM** and **EFB** → **shifted**
- Potential reason for this shift: different average ***plate group compression level***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

* = *Based on the strong linear relationship between 17.5% and 50% DoD test results shown on the previous slide*

Cycle Test Performance Development

AGM Performance Development, Single EU Manufacturer





- Historical Asian battery test data exists from 2014 and 2019 - 2021
- ABR and PENOX are currently running additional tests with batteries from several Asian manufacturers

Potential Key Criteria for Cycle Life

Discussion:

- What are the parameters for a battery to run in specific performance testing?
- ABR and PENOX are screening for **'survival criteria'** and want 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)

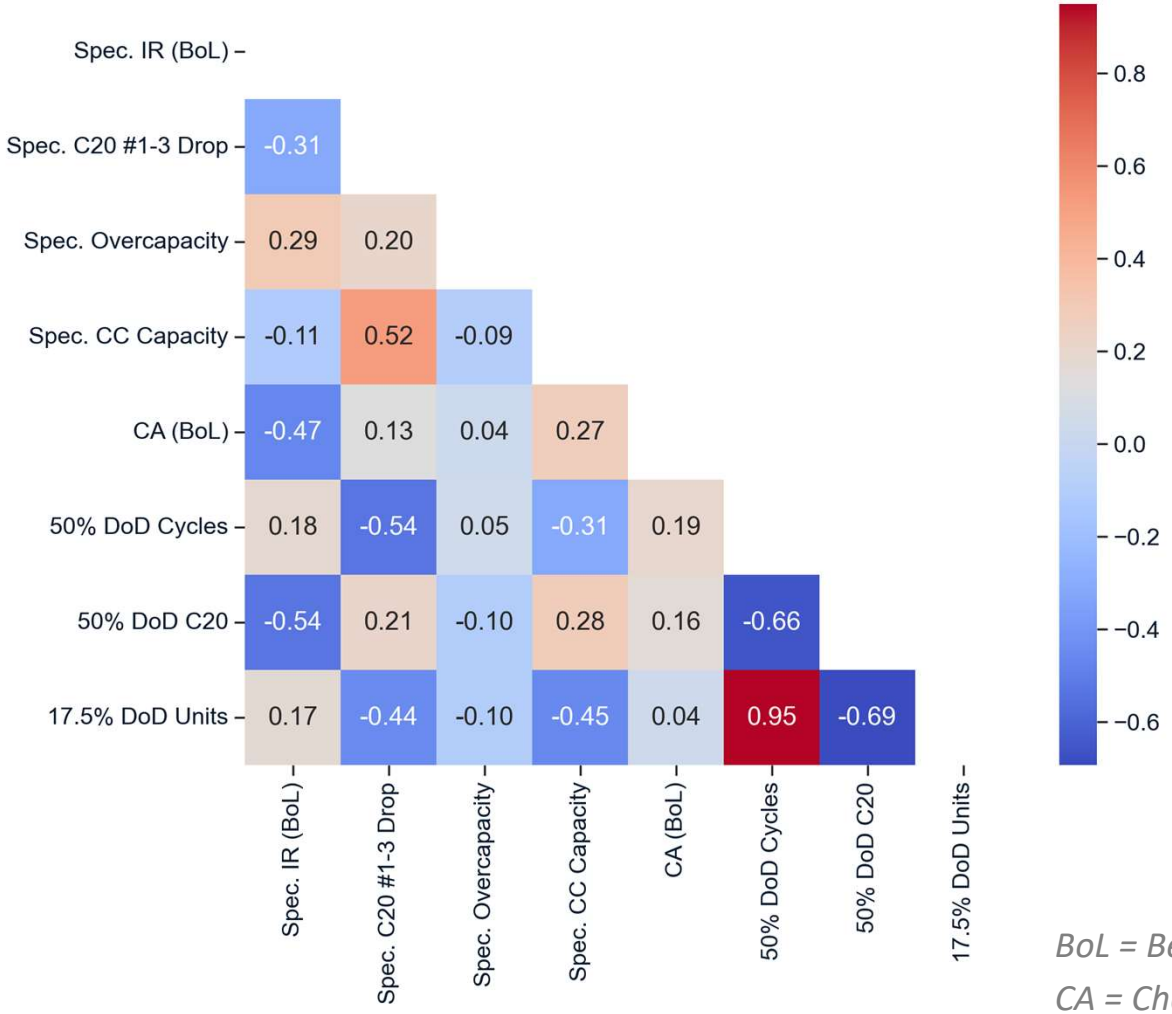
Analysis of ideas:

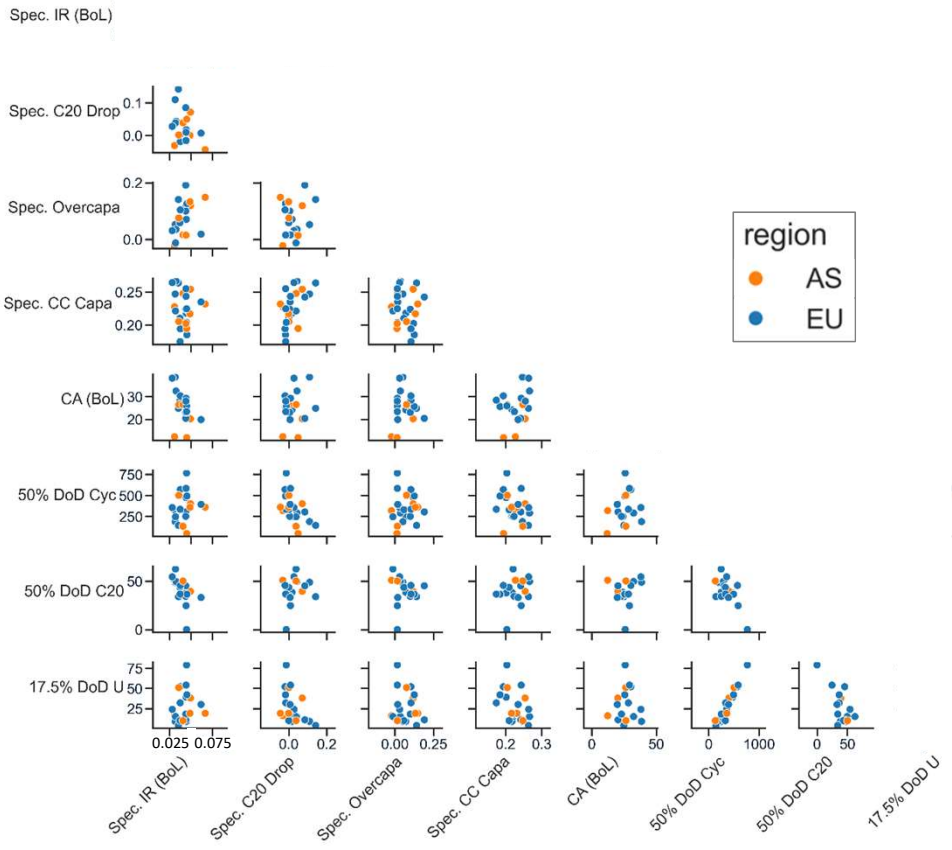
- Initial capacity stability is expected to be an indicator for 50% DoD cycle life
- Overcapacity is expected to increase the 50% DoD cycle life
- Higher charge acceptance ('CA') is expected to support a high 17.5% DoD cycle life

- *Technology excellence outperforms 'tweaking' by underrating a weaker design*

Linear Correlations Overview

AGM, Manufacturer = AS & EU





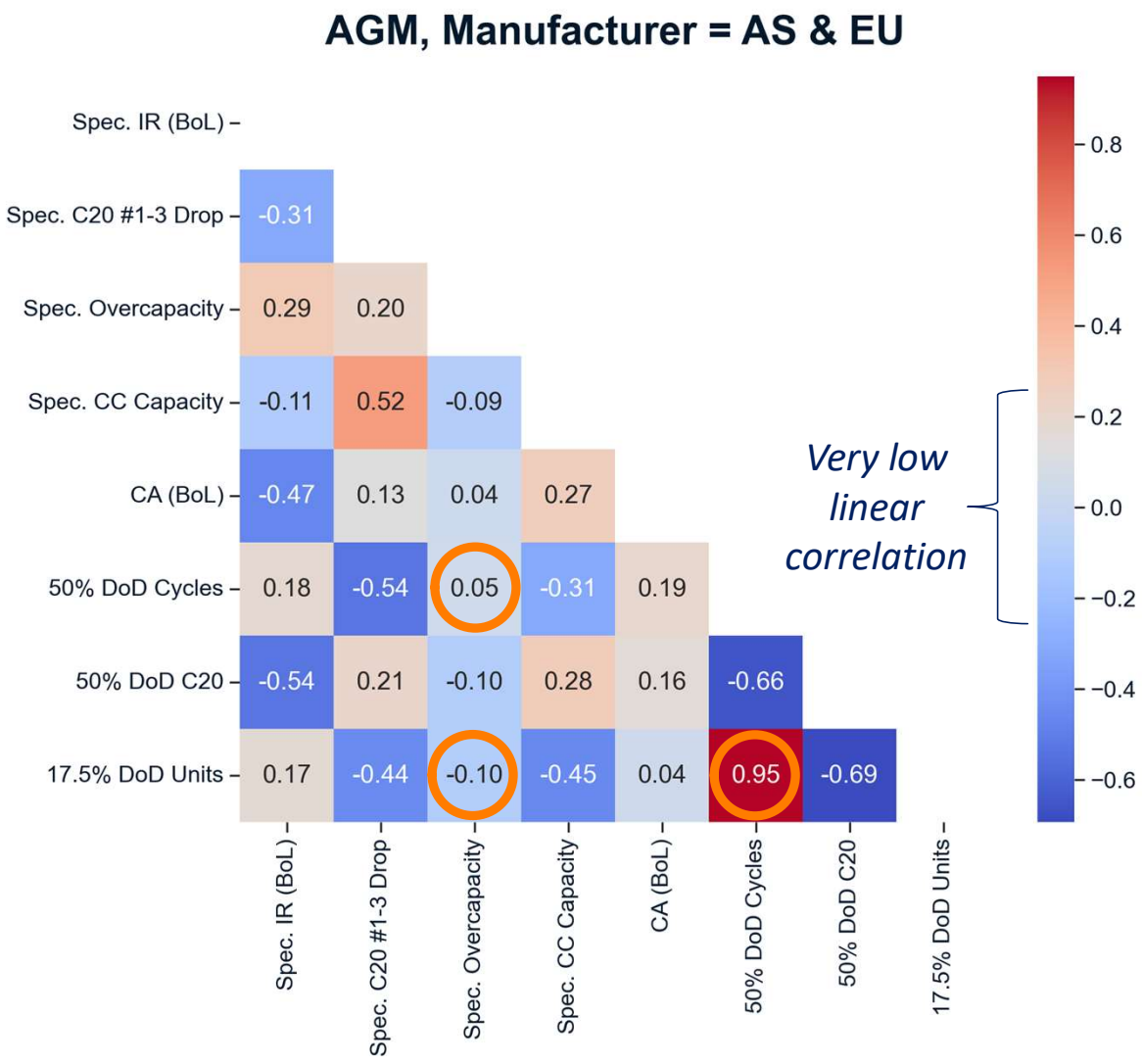
BoL = Beginning of Life

CA = Charge Acceptance

IR = Internal Resistance

Spec. = Normailzed to $C_{20,\,nom}$

Linear Correlations Overview

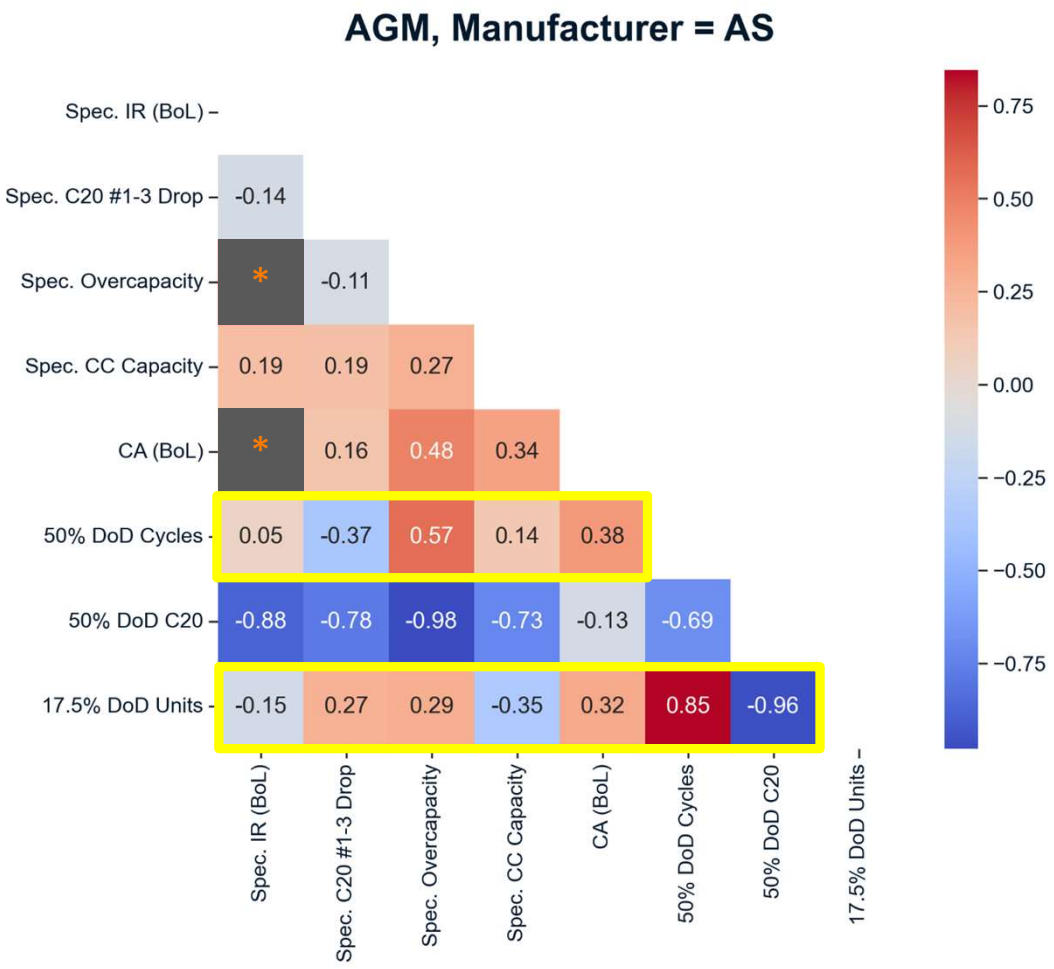


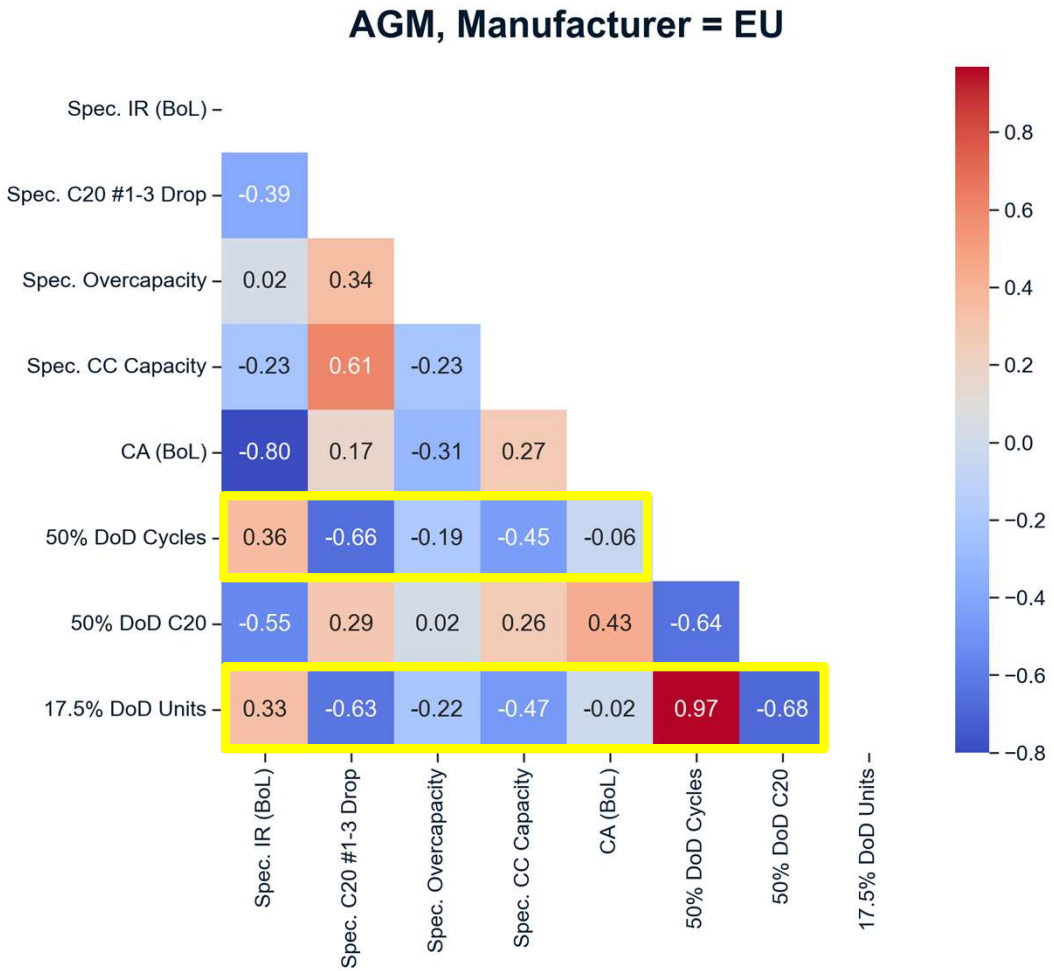
Very low linear correlation

- Checking for **linear *(i.e., Pearson)* correlation**:
  - **Red** = Positive correlation
  - **Blue** = Negative correlation
- **SLI** and **EFB** are excluded from this graph, as this part of the study focuses on the evaluation of differences between **AGM** batteries from AS and EU
- **Examples of how to interpret these values:**
  - **17.5% DoD** and **50% DoD** cycle test performance are strongly correlated
  - **17.5% DoD** units and **50% DoD** cycles are not strongly correlated with **overcapacity**
- *Data for this mix of **AS** & **EU** batteries is interesting to evaluate, but effects may get masked if these battery types strongly differ regarding these linear relationships*

→ **Thus, AS and EU have also been evaluated separately side by side**

Linear Correlations Overview





* *Under review.*

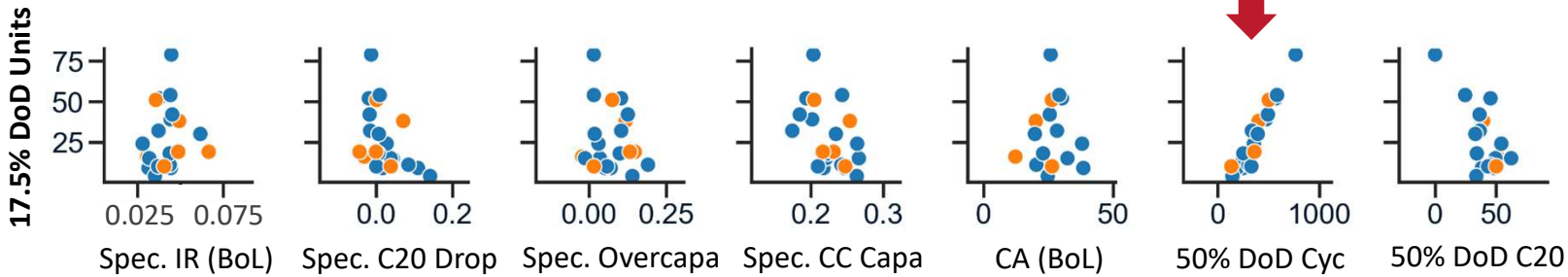
BoL = Beginning of Life
CA = Charge Acceptance
IR = Internal Resistance
Spec. = Normailzed to $C_{20,\,nom}$

Linear Correlations Evaluation

Meaning of Correlations

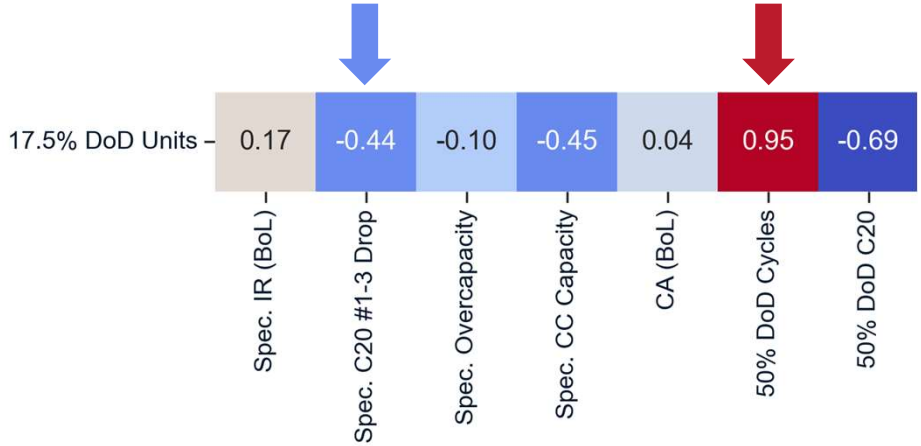
AS‘s and EU‘s 17.5% DoD cycle life is **higher for higher** 50% DoD cycle life, with excellent linear correlation

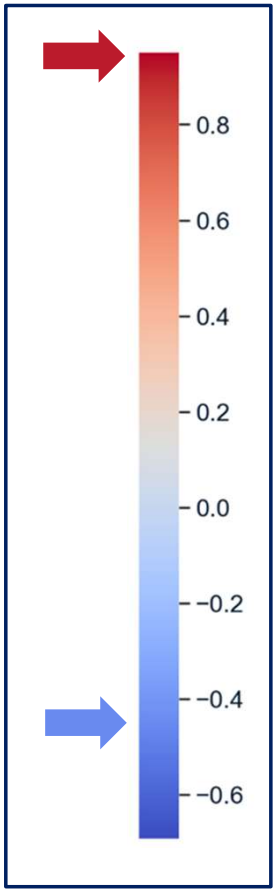
Pairplot Excerpt (AS & EU)



AS‘s and EU‘s 17.5% DoD cycle life is **lower for higher** 50% DoD cycle, with weaker linear correlation

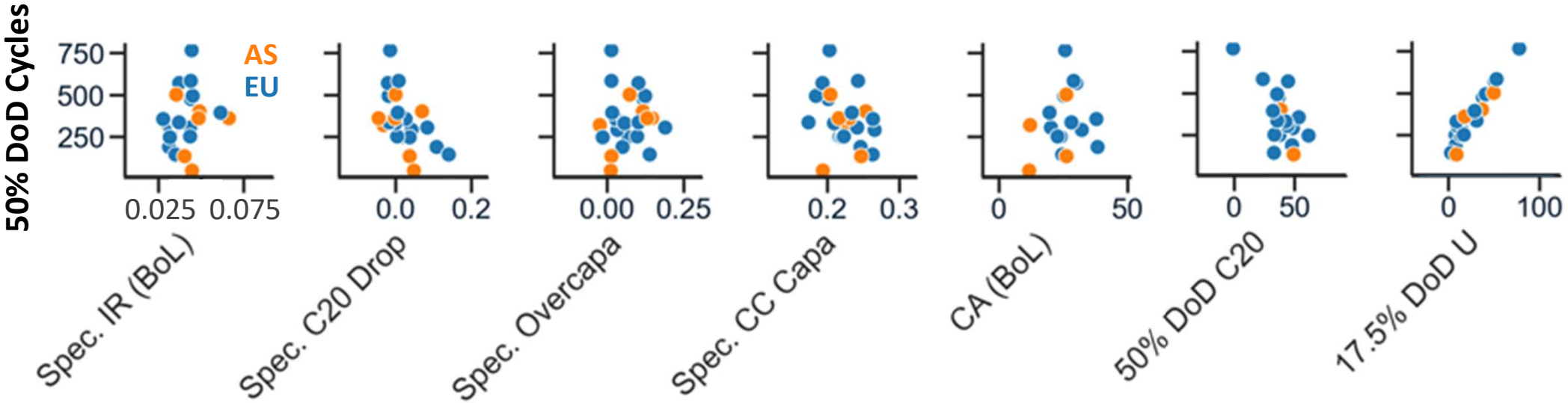
Heatmap Excerpt (AS & EU)





Linear Correlations Evaluation

Identifying Correlations in AGM Batteries from AS and EU: 50% DoD Cycle Life



Summary

- Screening of battery benchmark data allows for a better understanding of technology
- In several parameters, the trends are similar, e.g. the shift of AGM and EFB in cycle life
- However, the pattern of overcapacity between technologies is significantly different
- While the amount of overcapacity found for Asian and European AGM batteries is similar, the data shows that it is only beneficial for the cycle life of Asian batteries.
- This indicates that Asian and European battery manufacturers follow different design concepts and strategies
- **'Survival criteria'** can be extracted and materials adjusted to function
- Evolution of different technologies over time becomes visible

Outlook

- Understanding of best practices for technology, choice of oxides, and different additives and expanders (tear down and materialographic analysis, including laser microscopy)

- This allows PENOX to develop advanced expander mixes and functional oxides that are adjusted to survival criteria identified (e.g. charge acceptance)
  - Plate-internal (i.e., active mass) conductivity
  - Structural reversability

- ABR and PENOX are running laboratory testing of Asian batteries

  – to be presented soon (Whitepaper)

Thank You for your Attention!