How random cell-to-cell variation and deterministic pack effects determine pack capacities

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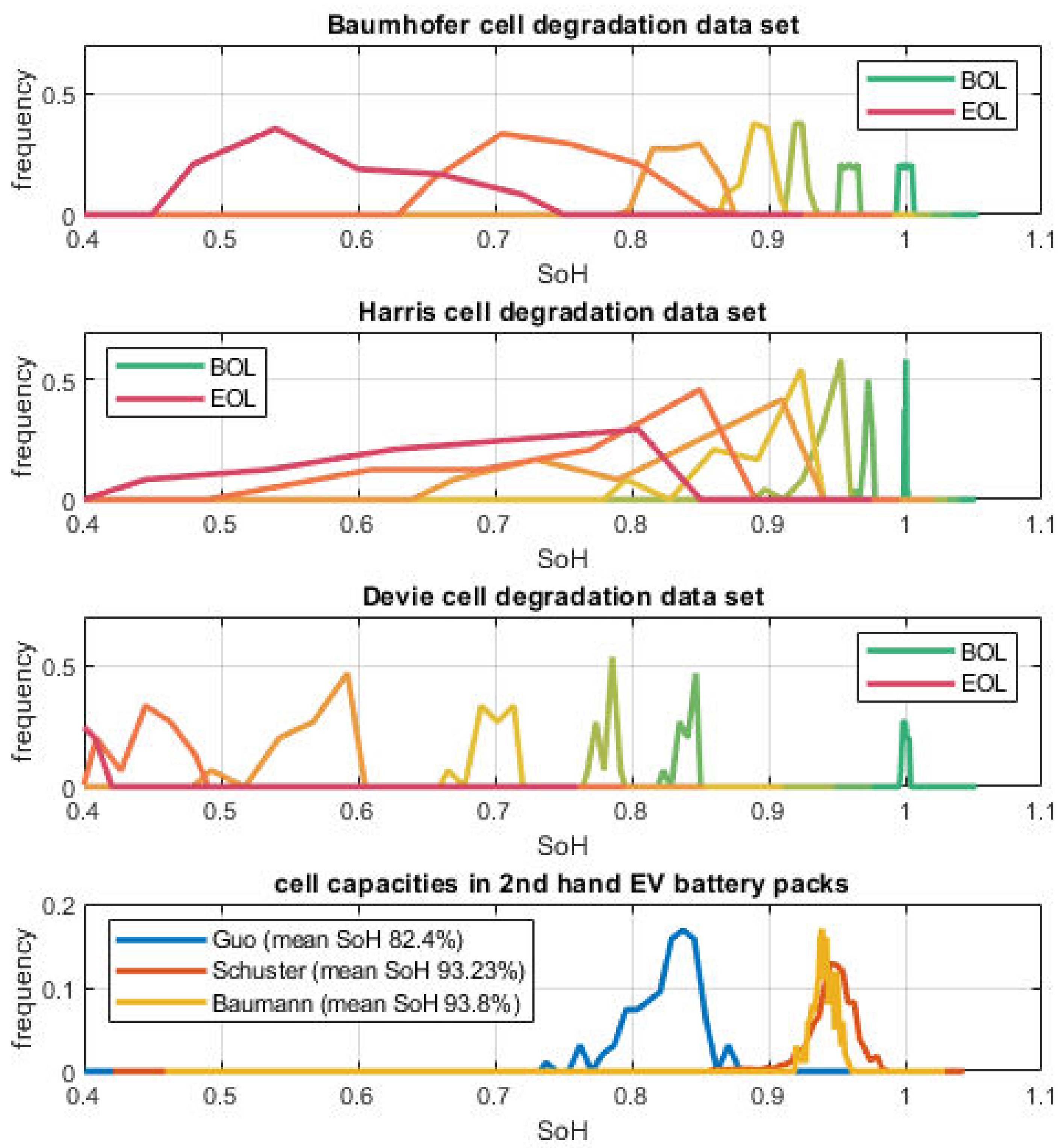
1. Cell-to-cell variation in batteries is larger than single-cell experiments suggest

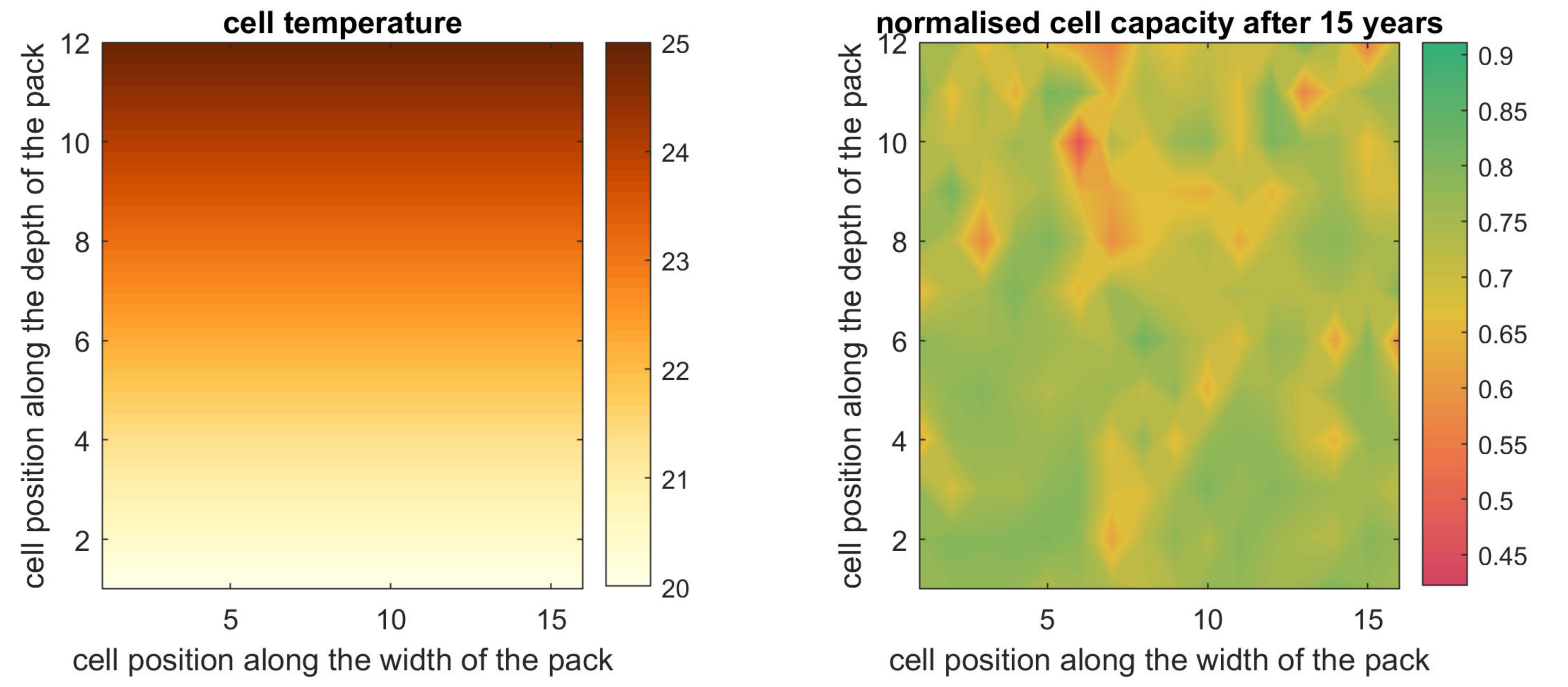
Researchers have analysed cell-to-cell variation by individually cycling cells in identical ways [1, 2, 3]. They found that cell-to-cell variation starts small but increases with degradation as indicated by the width of the green, yellow, amber and red histograms on the top 3 figures. Other researchers acquired battery packs from used electric vehicles and measured the cell capacity of each cell [4, 5, 6] as shown on the bottom figure. The cell-to-cell variation of these packs is larger than what could be expected based on the single-cell experiments. For instance, at 93.5% SoH, the standard deviation of Baumhofer's data set is less than 0.5% while the EV packs have a standard deviation of 0.75% and 1.48%.



2. Pack capacity is determined by random cell-to-cell variations and deterministic thermal offsets

One explanation for the larger cell-to-cell variation in used EV battery packs is the non-homogeneous load that each cell receives in real-life batteries. For instance, imperfect cooling systems result in a thermal gradient along the battery pack. This means that some cells are always hotter, and therefore degrade faster than other cells. The effect of thermal gradients could be analysed simply by increasing cell-to-cell variation. However, whereas cell-to-cell variation is random, and thus "weak" cells are spread randomly across the battery pack, the effect of the thermal gradient is deterministic because cells in hotter locations will degrade faster. This matters greatly, because the capacity of the battery pack as a whole is limited by the weakest element of the series-string, while differences in capacity between parallel-connected elements average out.

We fitted degradation models to single-cell degradation experiments (including thermal effects) and did various simulations of battery packs with given thermal gradients, to analyse the interplay between the random inherent cell-to-cell variation and the static offset due to a thermal gradient. An example result is shown below, where the left figure shows the thermal gradient we assumed, and the right shows the normalised cell capacities after 15 years. As can be seen, cells with lower capacities tend to be located in hotter parts of the pack, but this is not a one-on-one relation due to the random cell-to-cell variation.

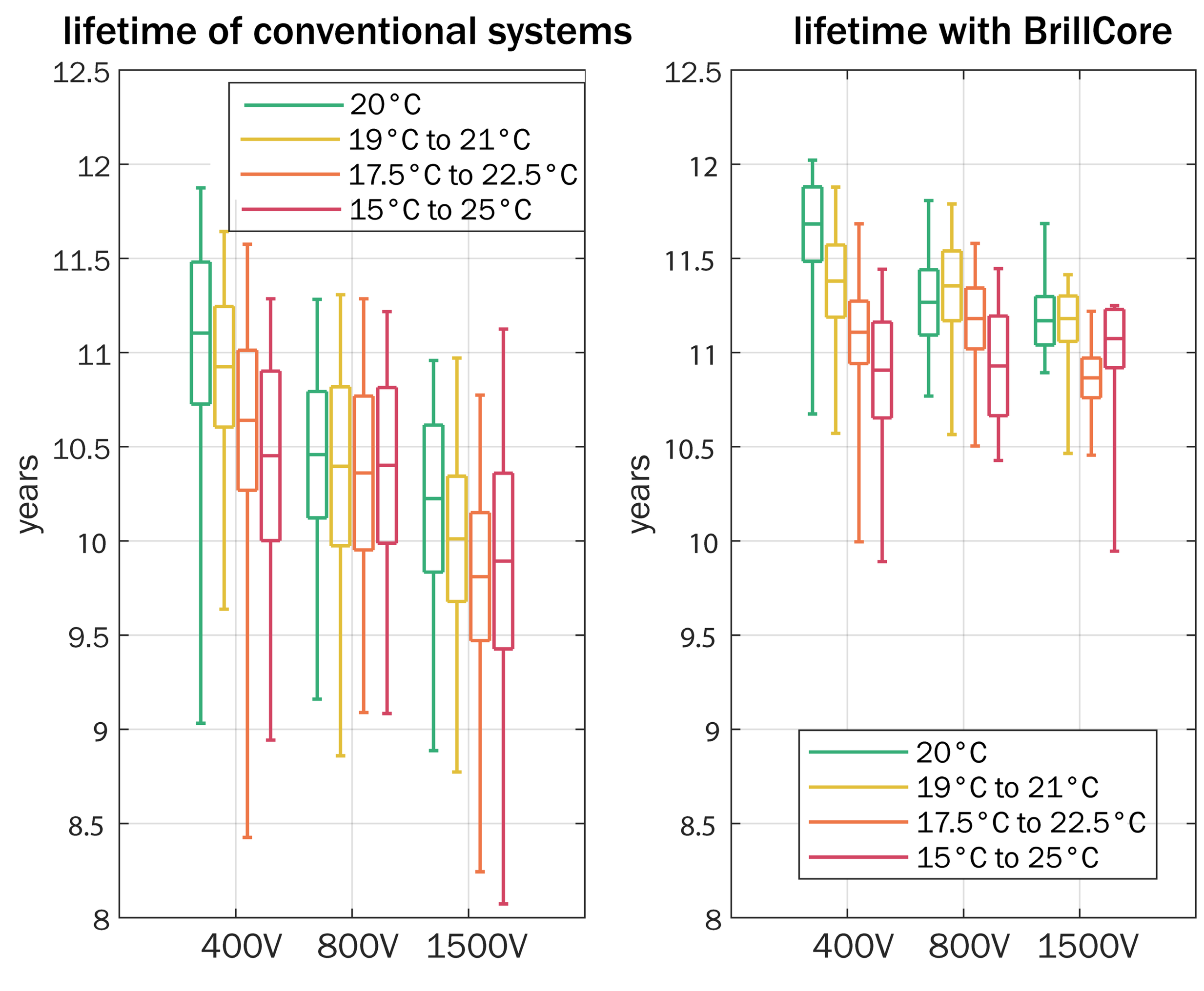


3. Larger thermal gradients and longer string lengths cause problems without modular control

Because a series-string is limited by the weakest element, the effects of random variation become worse when batteries go to higher voltages, while the deterministic effects become worse when thermal gradients are larger. We analysed these two factors by simulating packs of different thermal gradients and series length, going up to 1500V which is a common voltage for grid-scale batteries. For each scenario, we show the boxplot of the pack lifetime (70% remaining pack capacity) after simulating 1000 batteries. The colours show results for different thermal gradients.

By integrating power-electronics into a battery pack, Brill Power's BrillCore active loading technology draws power from each module relative to its capacity. This means that a string is no longer limited by the weakest element and hence the string capacity, and therefore lifetime, is increased. For example a 1500V system with 5 degrees thermal gradient has a 13% longer lifetime using BrillCore. These benefits will be even greater if fewer than 12 cells are connected in series to every BrillCore module.

Additionally, the spread in string lifetimes is reduced because BrillCore can alleviate the impact of a few bad cells, thus mitigating the statistical effect of the "left tail" with a few cells that have short lifetimes. For the 1500V system with 5 degrees, the standard deviation of lifetimes is reduced by 85%, increasing the minimum expected lifetime by 2.5 years (33.6%). This can have a large implication for warranties, reliability and up-time.



Conclusion

Due to random cell-to-cell variation and deterministic effects of thermal gradients, the lifetime of battery packs is uncertain. As strings go to higher voltages, or thermal gradients increase, not only does the average lifetime decrease, but the uncertainty in lifetime increases, causing a double effect on warranty lifetime, reliability and up-time. Using Brill Power's BrillCore technology, these effects can be mitigated, increasing the commercial lifetime of batteries.

References

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