ADVANCED RECHARGEABLE & LITHIUM BATTERIES ASSOCIATION

Safety is a priority for the battery industry:

Risks associated with the design requirement for individual cell replacement

RECHARGE position paper

April 2023

No matter what the design, application or technology, all batteries are electro-chemical devices optimised to store and release energy according to the applications' demand. Due to the energy released and chemical properties, batteries must fulfil a series of international, European and national safety requirements during their production, transport, storage, use and end-of-life management. Safety is, hence, a key priority for RECHARGE and the advanced European rechargeable and lithium battery industry.

The safety risks, which are attached to the provisionally agreed Article 11 of the Batteries Regulation, are serious, particularly when it comes to the replacement of cells inside batteries. Nearly every unqualified change of components, such as the replacement of individual cells of a battery pack, causes the loss of conformity with safety tests.

In this paper, we would like to address the safety issues and concerns related to mandatory replaceability and removability of cells in LMT battery packs. RECHARGE calls for a correction so that only batteries as a whole and not individual battery cells shall be subject to Art. 11., and to delete the half-sentence "*as well as individual battery cells included in the battery pack*" from Article 11(5).

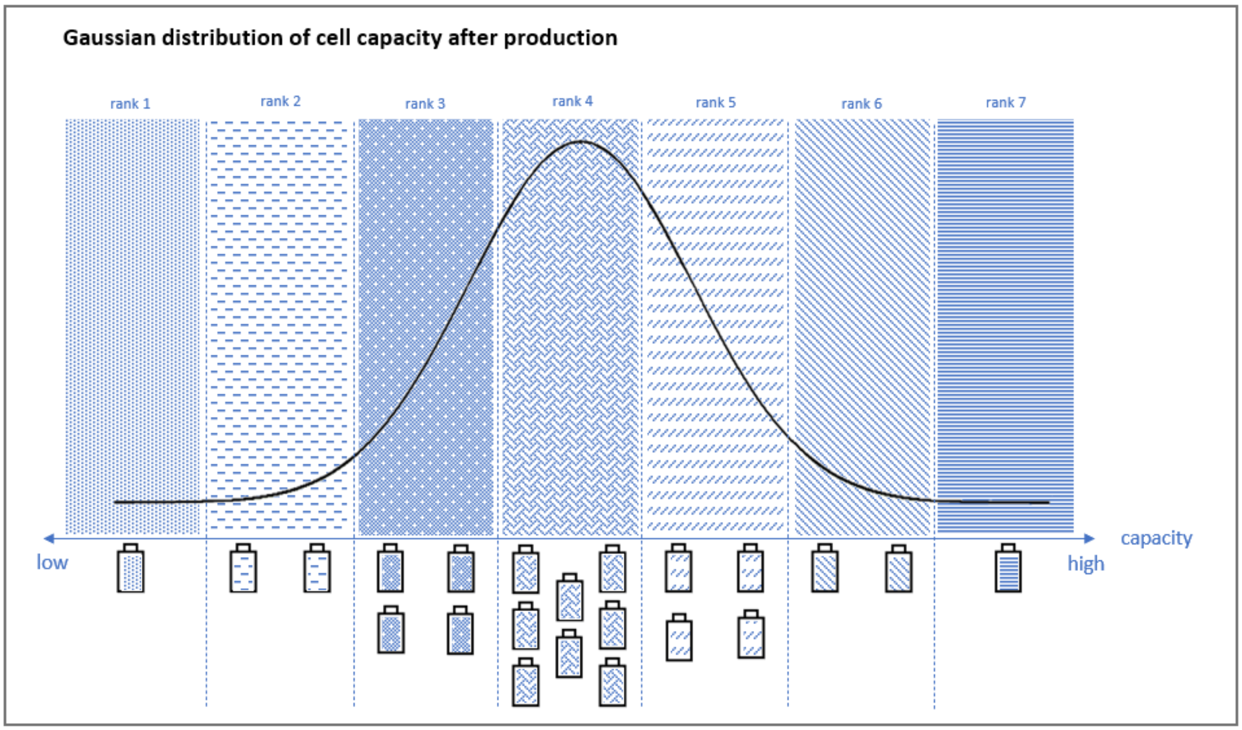
Due to the high level of expertise required for replacing cells inside a battery, this can only be applicable for specific battery designs and under the control of the original manufacturer. The suitability of such specific battery designs for the LMT application has not been proven.

The paper focuses on the following individual cell replacement issues:

1. Single-cell replacement exhibits only a marginally extended lifetime due to de-balancing effects
2. Repair exhibits insufficient sustainability gains in the case of cell replacement & single-cell failures are not a frequent enough error pattern
3. Replacing individual battery cells within a battery pack impacts safety as do actions related to the cell removal and replacement
4. A battery pack with a replaced cell would need to go through UN-T 38.3 testing again, but the requirements for compliance are out of reach of any individual repair-shop

1. Single-cell replacement exhibits only a marginally extended lifetime due to de-balancing effects

Battery packs are built with carefully selected battery cells from the same manufacturer, same production batch[1] and from the same rank[2] within that batch. Ranking cells within a batch is being done because even within one batch, battery cells have some dispersion in capacity and internal resistance. This is represented with a Gaussian distribution of the cell capacity of a production (see graphic). Matching cells from the same batch and from the same capacity rank within the batch are an important prerequisite to achieve product durability, as non-optimally ranked cells lead to so called de-balancing and thus a decreased performance.

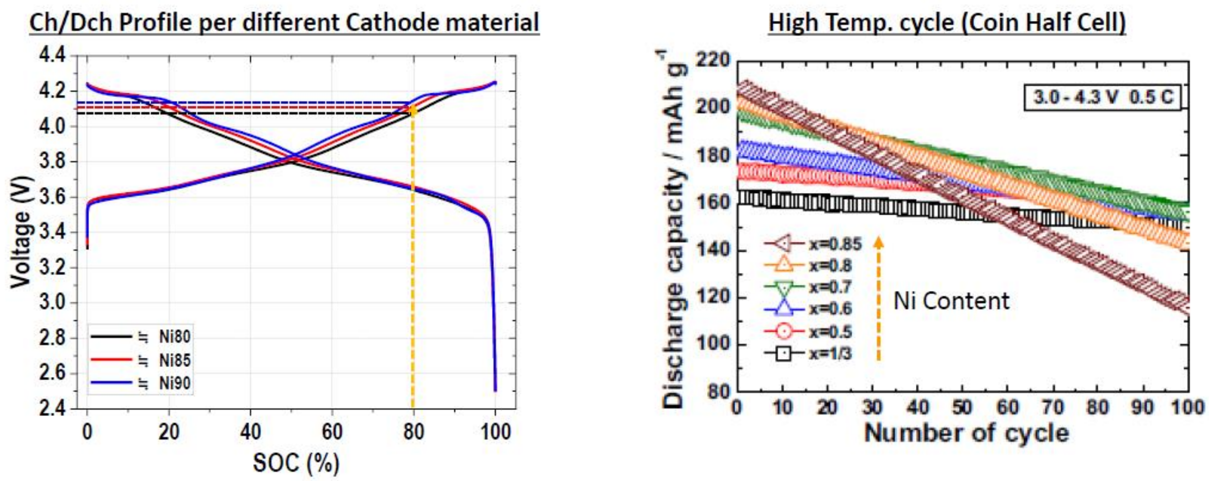


In the case of replacement, the replacement cells would likely need to be from the same manufacturer, batch, and rank as the original cells to ensure optimal matching, otherwise the battery will be underperforming. This may be simply impossible because a batch is available only once. Cells from a different supplier may be used within the same pack, but only if they have been tested and demonstrated having an equivalent performance to the original cells in the pack, as an approved OEM repair method. Using cells based on a similar size and capacity is not possible, because they may have different performances: the main reasons for this are differences in (mainly cathode) material and manufacturing processes, leading to characteristic calendric and cyclic aging behaviour as well as specific voltage curves during discharge. Particularly, even different models from the same supplier cannot be compared based

[1] Another synonymously used term for production batch is production lot.
[2] Another synonymously used term for rank is grade.

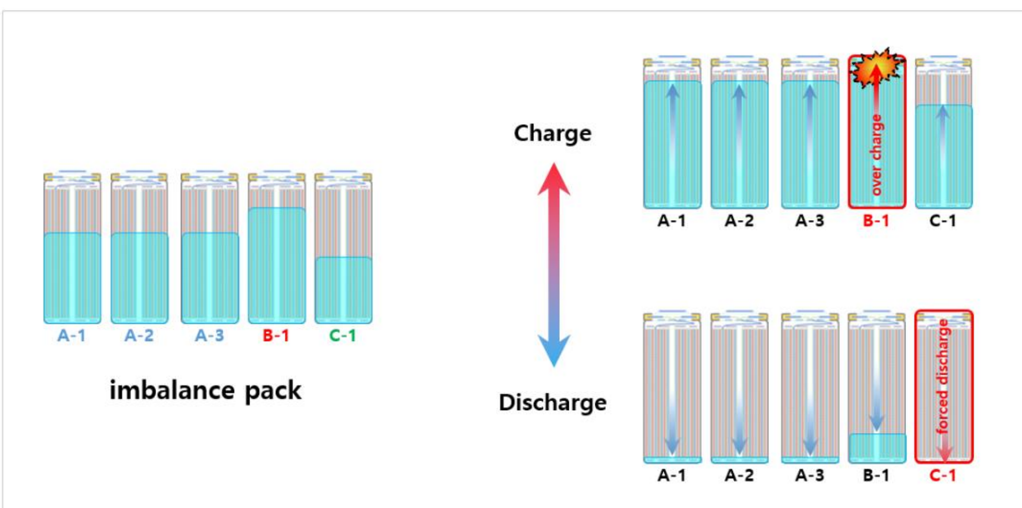
on the measure of an open circuit voltage (OCV) and a State-of-Charge (SOC) level (see graphic). An additional State-of-Health (SOH) estimation is needed and requires specific measurement equipment with reproducible and reliable processing. If a cell with a different SOH is replaced, it causes inter-cell imbalance.

Graph below: Profile per different Cathode material

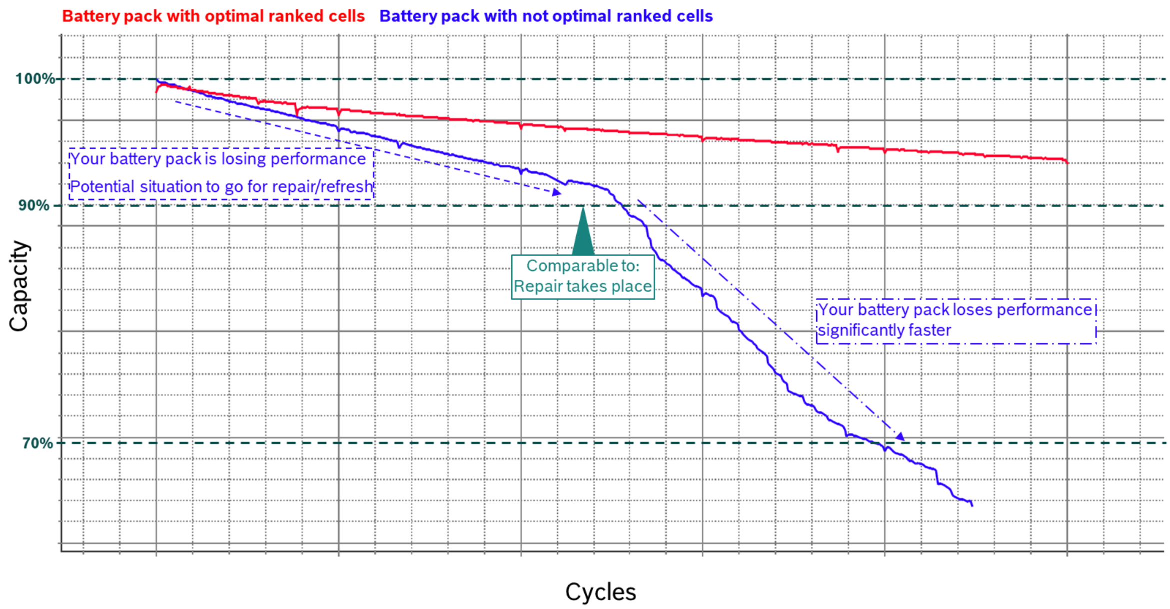


That means that optimally matched cells are highly important, as otherwise imbalance is accelerated.

Graph below: Image in case of imbalance situation



An acceleration of imbalance (known as de-balancing) leads to accelerated ageing and thus decreases the life duration and performance of the battery. Evidence for de-balancing effects can be found even with battery cells from the same batch that have not been optimally ranked (see graphic). Replaced battery cells will lead to fast de-balancing (within several cycles). In conclusion, the pack will end up ageing faster, having less capacity and lower performance level (peak power).



Cell-matching for repair is a basic requirement to ensure at least the originally expected lifetime of the battery pack is met. Based on the former explanations a cell-matching for repair is a basic requirement to ensure at least the originally expected lifetime of the battery pack is met. Introducing a new cell into the already aged battery pack (from same supplier) necessarily requires information about:

- capacity levels
  - measurement feasible, but time consuming
- self-discharge
  - measurement feasible, but controlled environmental conditions needed and extremely time consuming (weeks)
- resistance
  - fast measurement, but comparison only if cells exhibit same and homogenous temperature and SOC
- SOH
  - requires consideration of many impact factors like temperature, resistance of contacting system, preparing charge process, discharge current level etc. and is a multidimensional characterisation far beyond simple Ah-capacity according to standard determination (IEC 61960-3)

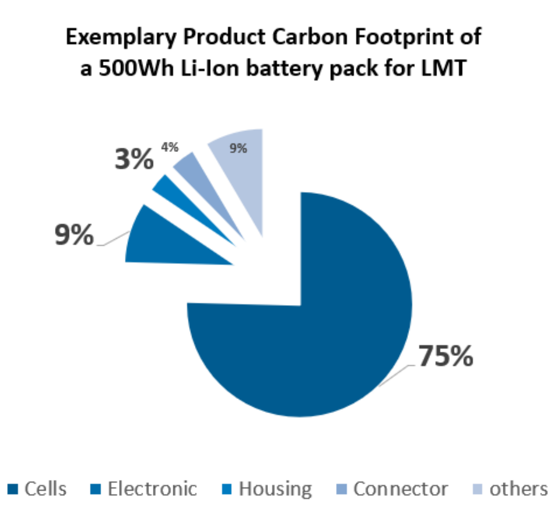
In addition, it should also be noted, that it is both impractical and very difficult for a repair shop to have access to the exact matching cells with the same state of health (SOH) as the original cells within the pack, and the same ageing behaviour. To summarise, there is a risk for accelerated ageing and imbalance when exchanging cells that are from a different rank, batch and supplier.

2. **Repair exhibits insufficient sustainability gains in the case of cell replacement & single-cell failures are not a frequent enough error pattern**

As shown above, the replacement of an individual cell may not lead to a longer lifespan but poses a significant risk of a rather rapid ageing process of the battery pack. Therefore, no significant if any sustainability gains are achieved. Taking into account the environmental impact to be considered for repair (logistic, testing, energy etc..) the marginal footprint gains can be assessed as insignificant.

75% of product carbon footprint of a battery pack is driven by cells, 25% by electronic, housing, connector and other components. Therefore, replacing the most valuable and environmentally impactful part of the battery by new cells (and the old recycled by the repairers) at the expense of the product life duration, is in the majority of cases not providing any environmental benefit, when a global LCA is realised.

Only in the case where a prolongation of the lifespan of the battery is actually achieved with single-cell replacement and proven, might this action represent an environmental benefit. However, single-cell failure is not observed on the market in high numbers with quality batteries. Data of warranty claims by battery pack manufacturers suggests that single-cell failures only account for <5% of root-causes for battery failure. It is also important to keep in mind that de-balancing is a part of the ageing process. A single cell failure could therefore also simply indicate the first failing cell in an aged pack, where the remaining cells are also close to their end-of-life. Therefore, the amount of true single-cell failures in the field overall is negligible.

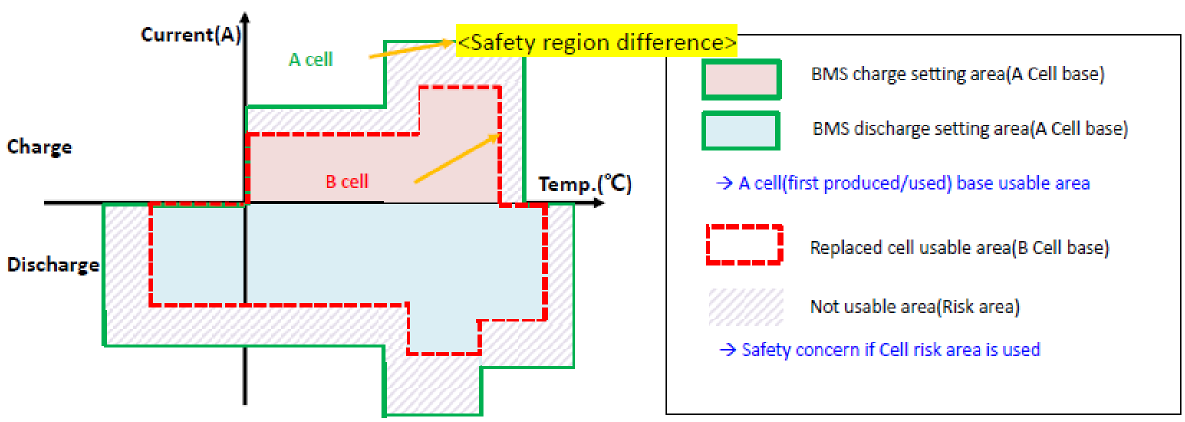


Thus, the cells' replacement operation cannot be justified as a clear environmental benefit cannot be demonstrated, while at the same time compromising the performance and safety of the product.

3. Replacing individual battery cells within a battery pack impacts safety as do actions related to the cell removal and replacement

Battery cell manufacturers provide very strict voltage and temperature operating windows. The Battery Management System (BMS) is parameterised to monitor the safe operating window of the cell type in use (minimum and maximum voltage, maximum current, minimum and maximum temperature). Should a cell be replaced within a pack, that safe operating window would be affected if the replacement cell does not have the same exact characteristics. Therefore, a mixed usage with cells from a different manufacturer or different cells from same supplier can be dangerous due to the change/shift of the safe operating window.

Graph below: Image change/shift of safety region

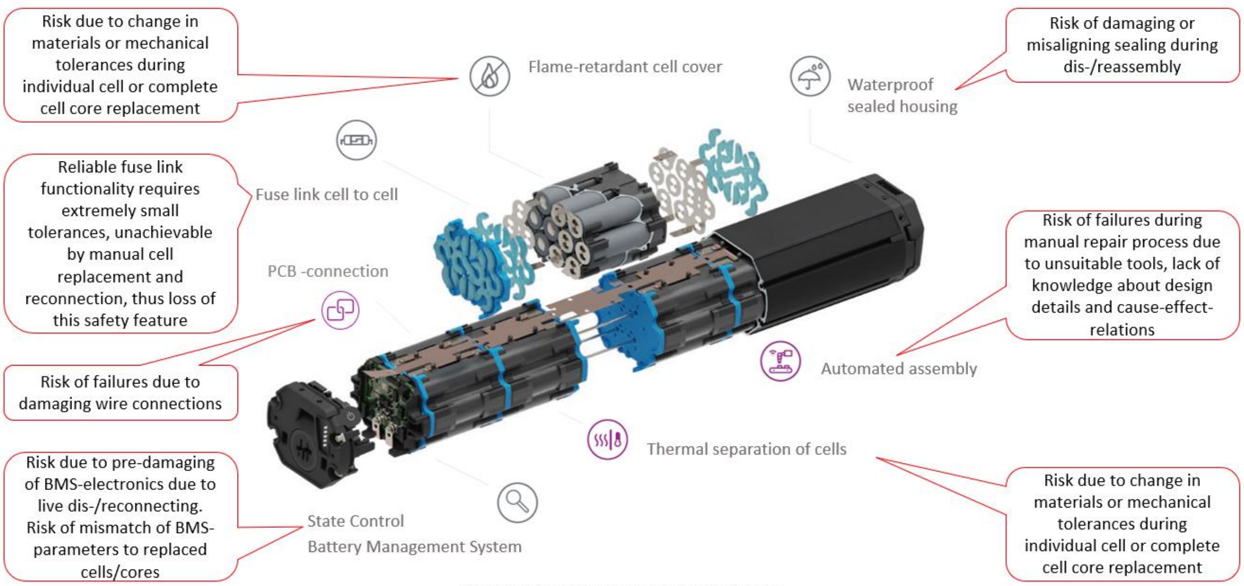


Different cells that are not from the same batch and from the same capacity rank within a batch exhibit different states regarding voltage, internal resistance and ageing condition. This leads to de-balancing (as is explained in the first part of the paper) but also to potentially generating a default of control by the BMS as the BMS is not calibrated for controlling mixed cells. This is an effect that even occurs when not only a single cell is being replaced but also a group of cells.

Cell replacement also means dis- and reassembly of the case sealing, reconnecting wires, replacing materials, parts and joints etc. All of these elements play a part in making lithium-ion battery packs as safe to use as possible.

State-of-the-art knowledge prerequisites a certain sealing concept, preventing water ingress and thus water contact with BMS/electronics, causing additionally corrosion within the battery pack potentially leading to a thermal incident. Therefore, major efforts were spent by battery manufacturers to ensure a robust tightness concept accompanied by state-of-the-art tightness class (IP class) and testing methodology for the use case of light means of transport.

Exemplary State-of-the-Art Safety Features and Risks associated with Repair Actions



Picture adapted; original image source: Robert Bosch GmbH (2023)

A note on the connection mode: Currently it is state-of-the-art to weld lithium-ion cells to ensure metallic continuity with stable contact resistance over lifetime of the battery. Other non-welded modes of connection (like a pressure loaded contact for cylindrical cells) have been explored, but do not provide the same level of reliability for the usage conditions applicable to the LMT batteries. Particularly,

- when cells are not welded, contact resistance between cells and connectors cannot be controlled evenly,
- if physical shock or vibration occurs, the non-welded area / battery cell can move leading to drastic increase in contact resistance leading to hot spots, thus safety and performance risks arise.

The repair operation should ensure a similar quality and performance as the original product. Unfortunately, it cannot be expected from non-specialised companies, such as the usual repair shops, to provide the required expertise and manufacturing and control equipment for replacing cells inside a battery with the original level of safety.

4. **A battery pack with replaced a cell would need to go through UN-T 38.3 testing again, but the requirements for compliance are out of reach of any individual repair-shop**

The lithium batteries are classified as dangerous goods for transport. Based on the UN regulation, their transport is only authorised when they have successfully passed a test described in the UN Manual of Test & Criteria, chapter 38.3 (UN-T 38.3).

Changing battery cells, BMS or other safety relevant components of the battery with non-original components lead to voiding the UN-T 38.3 type test. Therefore, batteries where cells are replaced would generally need to go through the UN-T 38.3 test cycles again. The repair-shops are not in the position to comply with this regulation, as they do not have access to original cells with an SOH equivalent to the cells in the pack for repair. The repair of a few batteries does not enable the production of "identical batteries", (batteries described as being "batteries of the same type" according to the definition as described in UN-T 38.3) that are required to qualify a product.

Table 1: adapted table based on UN Manual of tests and criteria 7th edition, valid as of 01.01.2021, Table 38.3.3

<table>
<tr><th colspan="11">Required tests for rechargeable cells and batteries</th></tr>
<tr><td>Test series</td><td></td><td>T.1 Altitude simulation</td><td>T.2 Thermal test</td><td>T.3 vibration</td><td>T.4 shock</td><td>T.5 External short circuit</td><td>T.6 Impact/ crush test</td><td>T.7 overcharge</td><td>T.8 Forced discharge</td><td>Sum</td></tr>
<tr><td rowspan="2">Small batteries (gross mass of less than 12kg)</td><td>First cycle, fully charged state</td><td colspan="5">4</td><td></td><td>4</td><td></td><td>16</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">4</td><td></td><td>4</td><td></td><td></td></tr>
<tr><td rowspan="2">Large batteries (gross mass of >12kg)</td><td>First cycle, fully charged state</td><td colspan="5">2</td><td></td><td>2</td><td></td><td>8</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">2</td><td></td><td>2</td><td></td><td></td></tr>
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Therefore, enabling the cell replacement without very specific requirements is simply opening the door to the placing on the market of repaired products that do not comply with the UN requirement for the safety of batteries.

Conclusions

In conclusion, the replacement of individual cells will in most cases fail to deliver the benefit being sought of extended useful life of the product and lower carbon footprint, due to the risk of de-balancing caused by poorly matched cells. The design requirement for individual cell replacement rather creates the potential for safety risks that have already been overcome by developing the current state-of-the-art high-quality production of batteries.

Without specific precautions, it will be unsafe to allow the cells replacement. The know-how required to do cell replacement safely is beyond the knowledge of most of the actors expected to propose such a cell replacement ("*independent professional*").

Making the batteries less safe than today by legitimising repair will eventually lead to more thermal incidents. Apart from the negative effect on consumer health and reputation of the LMT mobility industry as a whole, this will create a reversal of burden of proof, where original battery manufacturers/OEM will have to prove that a battery was no longer in the original state and had been repaired. It is also important to keep in mind, that LMT batteries are stored and charged in houses/apartments of the end consumers. Any incident is thus coupled with risk of severe harm.

Source/reference of graphs:

All graphs have been provided by RECHARGE members.

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