(05-003) - Can electric micro-mobility aged batteries be used on second-life applications?

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Electric mobility has finally entered the market with strength, and this time, it came to stay. Just like with all types of lithium batteries, the batteries used in mobility age over time and use. Additionally, it is asserted that batteries are no longer suitable for traction purposes when they have lost between 20% and 30% of their initial capacity, moment in which it is recommended to replace them with new ones.

In recent years, many studies and projects appeared for repurposing electric car batteries after their first life in the vehicle, but no one has yet investigated what happens with electric micro-mobility and whether this approach makes sense.

This study estimates, through cycling and testing in a climate chamber, the state of health of an electric bicycle battery that no longer meets the user's needs. Results show that the whole battery presents a state of health of 75% while, individually, each cell's state of health is above 90%. These high values of the health indicator of cells allow to think that they can be reused to build a new battery for the same or other applications.

Keywords: Second life; batteries; Micro-mobility; circular economy

¿Se puede contar con las baterías envejecidas de micro-movilidad eléctrica para almacenaje estacionario?

La movilidad eléctrica ha entrado con fuerza en la sociedad y, esta vez, ha venido para quedarse. Igual que ocurre con todo tipo de baterías de litio, las baterías utilizadas en movilidad envejecen con el paso del tiempo y su uso. Además, se afirma que las baterías ya no son apropiadas para tracción cuando éstas han perdido entre un 20 y un 30% de su capacidad, momento en el que se recomienda reemplazarla por otra nueva.

En los últimos años se ha estudiado la opción de reutilizar las baterías de coche eléctrico después de su primera vida en el vehículo, pero nadie ha investigado aún qué ocurre con la micro-movilidad eléctrica y si tiene sentido este planteamiento.

El presente estudio estima, mediante el ciclado y testeo en una cámara climática, el estado de salud de una batería de bicicleta eléctrica que ya no cumplía con las necesidades del usuario. Se observa que la batería, en conjunto, presenta un estado de salud del 75%, pero que cada una de sus celdas, individualmente, tienen un estado de salud superior al 90%. Esto permite considerar el desmontaje de la batería para remanufacturar otra para alargar la vida del producto.

Palabras clave: Segunda vida; baterías; micro movilidad; economía circular

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1. Introduction

Electric mobility has been growing tremendously in recent years. The trigger for this exponential growth was, initially, the electric vehicle, which ultimately opted for the implementation of lithium batteries as the energy storage system.

These batteries have certain characteristics that grant them a competitive advantage over other technologies: maximum efficiency (above 95%), no self-discharge, and power and energy densities acceptable for the automotive sector. Their main drawback was, and still is to some extent, their price (Benveniste et al. 2018).

However, the mass implementation of these technologies in the automotive sector, which has already had 14 years of global commercialization of electric models, led to increased industrialization and, consequently, a significant reduction in battery manufacturing costs (Nykvist et al. 2015). Moreover, this price decrease enabled a focus on electrifying last-mile mobility, which is very common in large cities like Barcelona today.

They are so common that, due to the inherent risk of fire they pose, the Metropolitan Area of Barcelona prohibited the use of scooters in its facilities a year ago (Autoritat Metropolitana de Transport 2023), challenging mixed mobility options where people from outside the city rely on public transportation to get close and then use their scooters or e-bikes for further movement. Nevertheless, this limitation only affects scooters, allowing other last-mile modes such as bicycles or folding bicycles to enter freely

In particular, the electrification of bicycles continues to increase (Hung et al. 2020), and both public shared bicycle services like "Bicing" in Barcelona (Bicing 2023), and private bicycles, which saw an increase in sales in Spain of almost 50% between 2022 and 2023, have a high percentage of electrification and are, in fact, the best-selling electric vehicle in Spain (Ortiz Ribera 2023).

Although bicycle batteries are lithium-based, it doesn't mean that they have the same characteristics as those used in automotive applications. In fact, the chemistries generally used are more economical and offer lower performance compared to the equivalents used in electric cars. This is because the criticality of replacement is lower, and the replacement cost is affordable. While the battery of an electric car can easily reach €15,000, a bicycle battery starts at around €200. (Mohammadi et al. 2023). This difference allows bicycle manufacturers not to feel the pressure to sell them with top-of-the-line batteries, and it may be necessary to replace them from the second year onwards due to operational inconsistencies (Zhao et al. 2014).

One of the critical factors in the electrification of mobility is the management of waste at the end of life. In this case, lithium batteries receive significant attention due to their abundant use of materials and their impact on vehicle prices. That's why since their inception, strategies of circular economy such as battery reuse, giving them a second life, have been studied and continue to be explored (Montes et al. 2022), (Etxandi-Santolaya et al. 2023). However, this analysis has primarily focused on relatively large batteries, such as those used in cars or other heavier means of mobility, overlooking micro-mobility or last-mile mobility.

For this reason, this study aims to analyze the battery of a commercial bicycle that has been in use for over three years and whose charger stopped charging it, necessitating replacement with a new one.

2. Objective

The objective of this study is to assess the suitability of using bicycle batteries (extrapolatable to other micro-mobility means) for stationary applications in a second life, similar to what is proposed with electric car batteries. This would provide greater options for reuse companies based in Spain, which are still waiting for the massive arrival of car batteries while bicycle batteries are being discarded without exploring the circular economy possibilities they offer.

3. Methodology

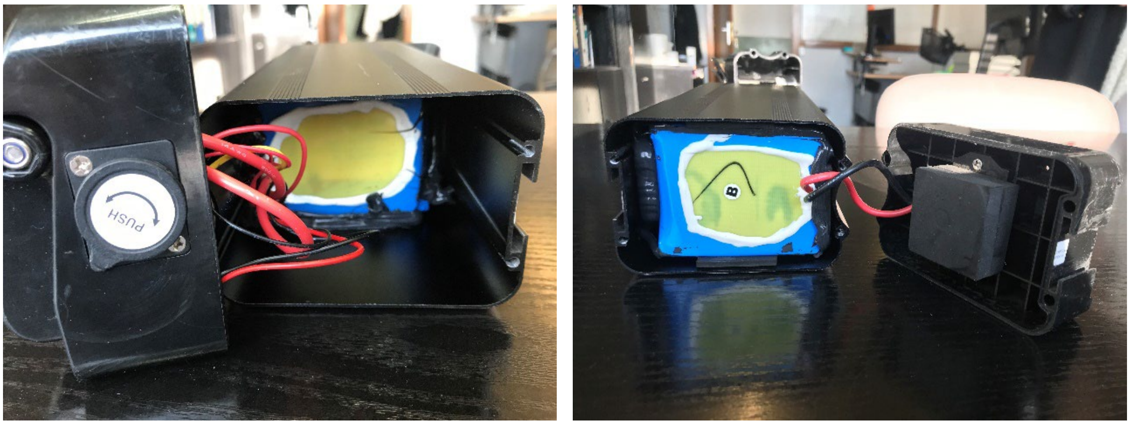
The study is based on the analysis of a battery from the commercial bicycle model "ebike 20" by the brand Mooma Bikes. As shown in Figure 1, it is a foldable urban electric bicycle. Like many other brands, this one has chosen to use a standardized and removable battery, which can be extracted by turning the key in the battery (which also allows it to be turned on).

Figure 1: Images of the ebike 20 (Mooma Bikes 2024)

According to the manufacturer's specifications, this is a lithium-ion battery with a nominal voltage of 36V and a capacity of 16 Ah (Mooma Bikes 2024).

The process of analysis involves removing the battery from the bicycle and, in turn, the cells and/or modules from within the enclosure or pack. This battery dismantling is needed to access and test the complete battery module and each of the cells for the analysis. The malfunction error, in these cases, is determined by the Battery Management System (BMS), and to inject or extract energy from the battery it is necessary to bypass it.

Figure 2: Pictures of the casing and cells inside the battery pack



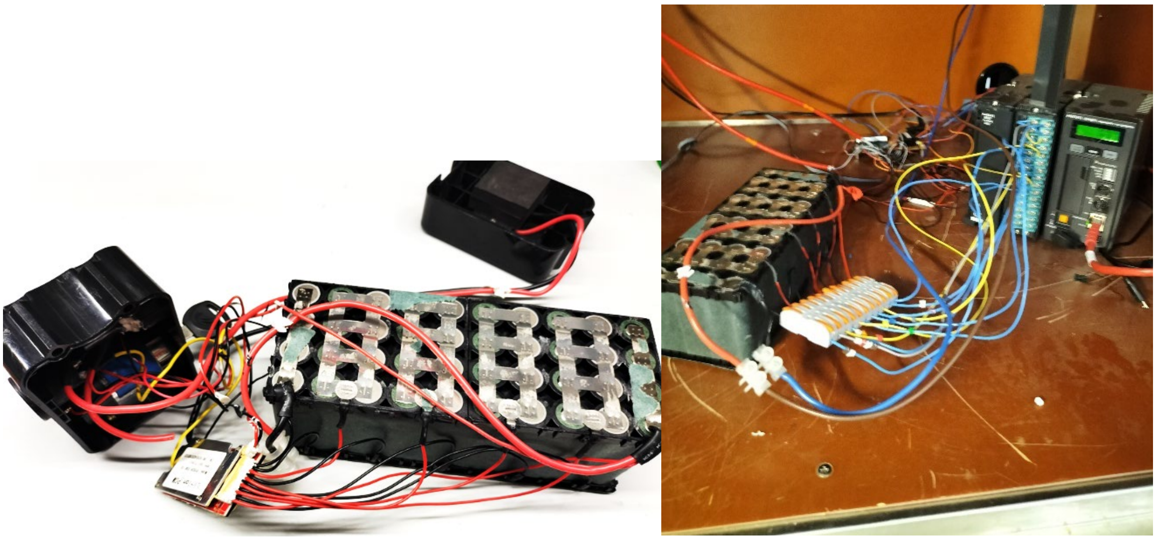
The battery cells are housed within a blackened aluminum casing and fixed to it employing some sort of viscous adhesive resembling silicone (Figure 2). There is a sizable space between the cells and the top of the battery, likely because the same casing is used for different models that may have higher voltage or capacity. At the top, the BMS is located along with all the wiring connections, while only the two copper cables (through which the current runs) and associated sensing goes toward the cells

The only way to extract the cells is by cutting the aluminum casing. This process is carried out with extreme care using a Dremel circular saw, ensuring not to touch, and consequently damage, the cells inside.

Once extracted, both the power cables and those connected to the BMS are utilized to extract all the information regarding the battery's operation towards the cyclers during testing (Figure 3).

As shown in Figure 3, the battery consists of a single module with 10 cells connected in series and 4 parallels. The cells used are 18650P cells with a nominal voltage of 3.6V and a capacity of 2.2Ah, which, with the 10s4p configuration, achieve battery pack nominal values of 36V and 16Ah. The module is equipped with voltage and temperature sensors.

Figure 3: Ebike battery configuration counting on a unique module of 10 cells in series and 4 in parallel (left) and how all the wiring has been re-used to monitor the battery and cells during the testing inside the climatic chamber.



Initially, the complete module is tested to analyze the imbalance and effective capacity of all cells operating simultaneously as it occurs in its normal operation. The testing is conducted within a climatic chamber (Figure 3) to ensure controlled working temperature and protection against electrical failures. The cyclers utilized are the Basytec Battery Test System located at the facilities of the Catalonia Institute for Energy Research (IREC).

Subsequently, the data is analyzed, and the most imbalanced cells are selected to attempt to identify behavioral differences.

The tests conducted in both cases correspond to a capacity test and a pulse test. These typical and standardized tests for battery characterization and their processes are described in Tables 1 and 2, corresponding to the capacity test and pulse test, respectively.

Table 1: Capacity test program

Comand	Parameter	Termination	Action	Registration
Start		U>1UBatMax&t>1s U<1UBatMin&t>1s I>1IBatMax&t>1s I>1IBatMin&t>1s T1>40ºC		
Cycle-start				
Charge	U=UbatCh I=0,5A	I<0,05CA		T=1s U=10mV
Pause		T>600s	Next	T=1s
Discharge	I=0,5ª	U<3V	Next	T=1s
CalcOnce	SoH			
Cycle-end	Count=2			
Stop				

It is worth noting that the (simple) program for measuring the battery capacity is established with a low current intensity (a ratio less than C/4) for two reasons: i) for safety after having been handling the battery, ii) and to ensure identification of the maximum capacity that could be extracted from the battery.

Furthermore, note that the process is repeated twice. Firstly, it is charged at a fixed intensity until the maximum voltage is reached, at which point it continues at constant voltage (commonly referred to as CCCV process). At this moment, a pause of about 600s is made to stabilize the cells, and then the discharge is initiated. Once the discharge is completed, the State of Health (SoH) parameter is calculated using Equation (1).

$$Batpar_{soh} = \frac{Ah\ discharge}{Nominal\ capacity} \quad (1)$$

where the nominal capacity is 2,2Ah for the cells and 16Ah for the whole battery pack.

Each stage ends when the conditions in the "termination" column are met, which refer to maximum and minimum voltages, but also to maximum and minimum currents (which are important for determining the end of the constant voltage charging process), or if, for some reason, the battery reaches a temperature higher than 40ºC, which would be dangerous. Note that, in no case, this temperature value was reached and all the tests were stopped following the termination condition.

The pulse test, on the other hand (Table 2), is performed to identify the internal resistance of the battery at different states of charge. The internal resistance is also used, in some cases, for the identification of the State of Health (SoH) or functionality (SoF) (Etxandi-santolaya et.al, 2024).

Table 2: Pulse test program

Comand	Parameter	Termination	Action	Registration
Start		U>1UBatMax&t>1s U<1UBatMin&t>1s I>1IBatMax&t>1s I>1IBatMin&t>1s T1>40ºC		
CalcOnce	As10SoC			
CalcOnce	As10SoCch			
Cycle-start				
Pause		T>30min	Next	T=1s U=10mV
Charge	U=4.1V I=0,5A	U>1UbatCh Ah>As10SoC	Goto Pulse Next	T=1s U=10mV
	Cicle-end	Count 10		
Pause		T>30min	Next	T=1s U=10mV
Discharge	I=0,5ª	U<3V Ah<As10SoC	Goto End Next	T=1s U=10mV
Cycle-end	Count=10			
Stop				

In this case, a pulse is performed every 10% of State of Charge (SoC), which is calculated during the *CalcOnce* step at the beginning of the cycle, both during charging and discharging. This test is quite lengthy because, as it can be observed, a stabilization time of 30 minutes is required before each pulse. On this occasion, the priority is to observe the behavior of the cells when stressed at current peak changes. In all cases, the test is conducted at relatively low currents, specifically at 0.5A (less than C/4) for the same aforementioned reasons.

4. Results

The test with the complete battery module shows how the nominal capacity of 16Ah could not be achieved. In fact, the SoH value obtained through the division of the current available capacity between the initial capacity of the whole battery pack (equation 1) is 75%, which is aligned with what literature states as the end-of-life of batteries for traction purposes (Thompson 2018). After observing Figure 4, it is concluded that the reason for not reaching the nominal 16Ah, is mainly due to cell imbalance, which is another common indication of battery degradation (Naguib et al. 2021).

As shown in Figure 4, there is a block of cells in parallel (4p) that exhibits a notably different behavior compared to the rest, with a voltage significantly lower than the others. These differences are particularly noticeable when looking at the voltage at the end of the charge and discharge (maximum and minimum). It is precisely this block of cells that marks the end of the discharge while, during the charge, almost all the other cells reach the maximum voltage well before this block does so. Consequently, with each cycle, they become increasingly imbalanced.

In cases like this, with an exaggerated imbalance of more than 0.3V, the BMS identifies this behavior as defective and does not allow further battery use. However, to reduce costs, bicycle batteries often feature very basic BMS without the capability to balance the cells in series and parallel in the battery pack, a feature present in higher-performance applications (Ziegler et al. 2021).

Notice that, due to one of the parallels of the module, the effective capacity of the rest of the module is underutilized, stopping at a voltage of 3.38V when it could still descend to 3V. Although this might seem like a significant difference, it's important to highlight that at the voltage values close to the end of the discharge, the voltage-discharging curve undergoes a sharp change, and the voltage descends rapidly, as seen in the case of the problematic cell.

Figure 4: Voltage of the blocks of cells in series and parallel

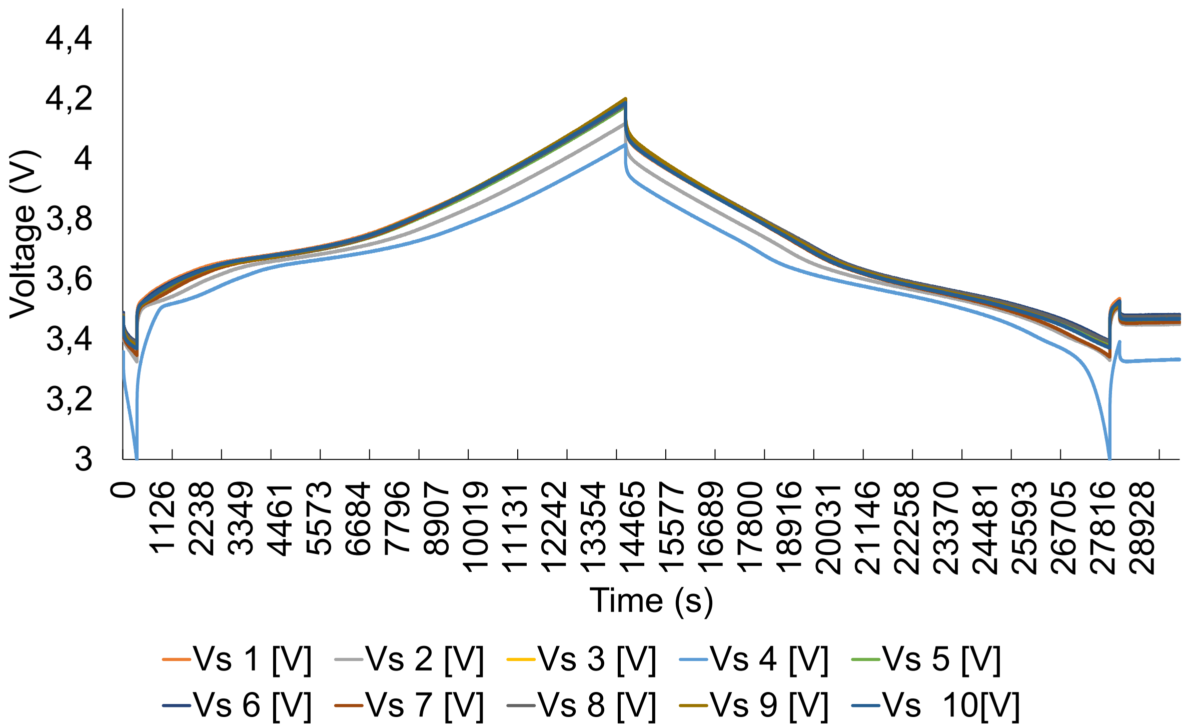
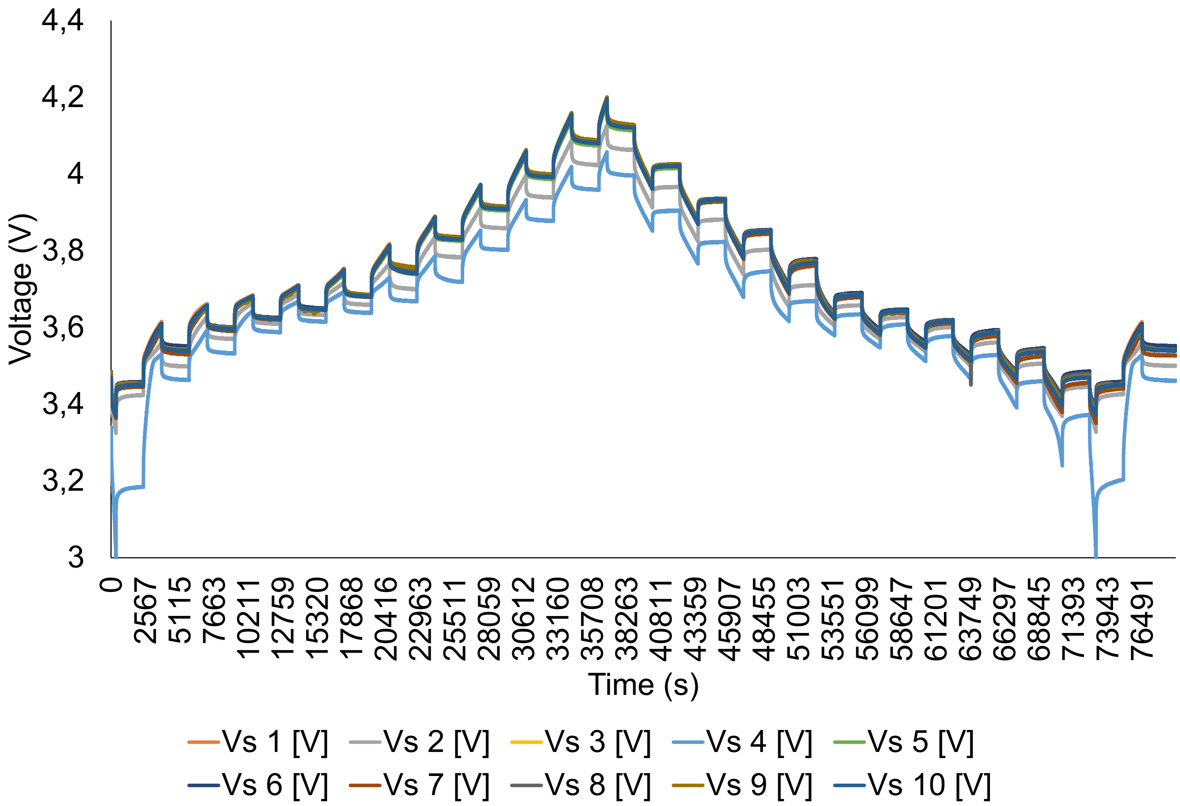


Figure 5: Voltage of the cells in the pulse test



Due to the 10s4p configuration, the voltage of the 4-block of cells in parallel is measured without being able to identify which series contains the problematic cell. As observed, apart from the Vs4 block, followed by Vs2, the rest of the blocks exhibit fairly similar behavior with slight voltage deviations. This same behavior, but even more pronounced, can be seen in Figure 5 with the pulse test.

It's worth noting that, due to the very low current cycling, no significant overheating occurred during testing.

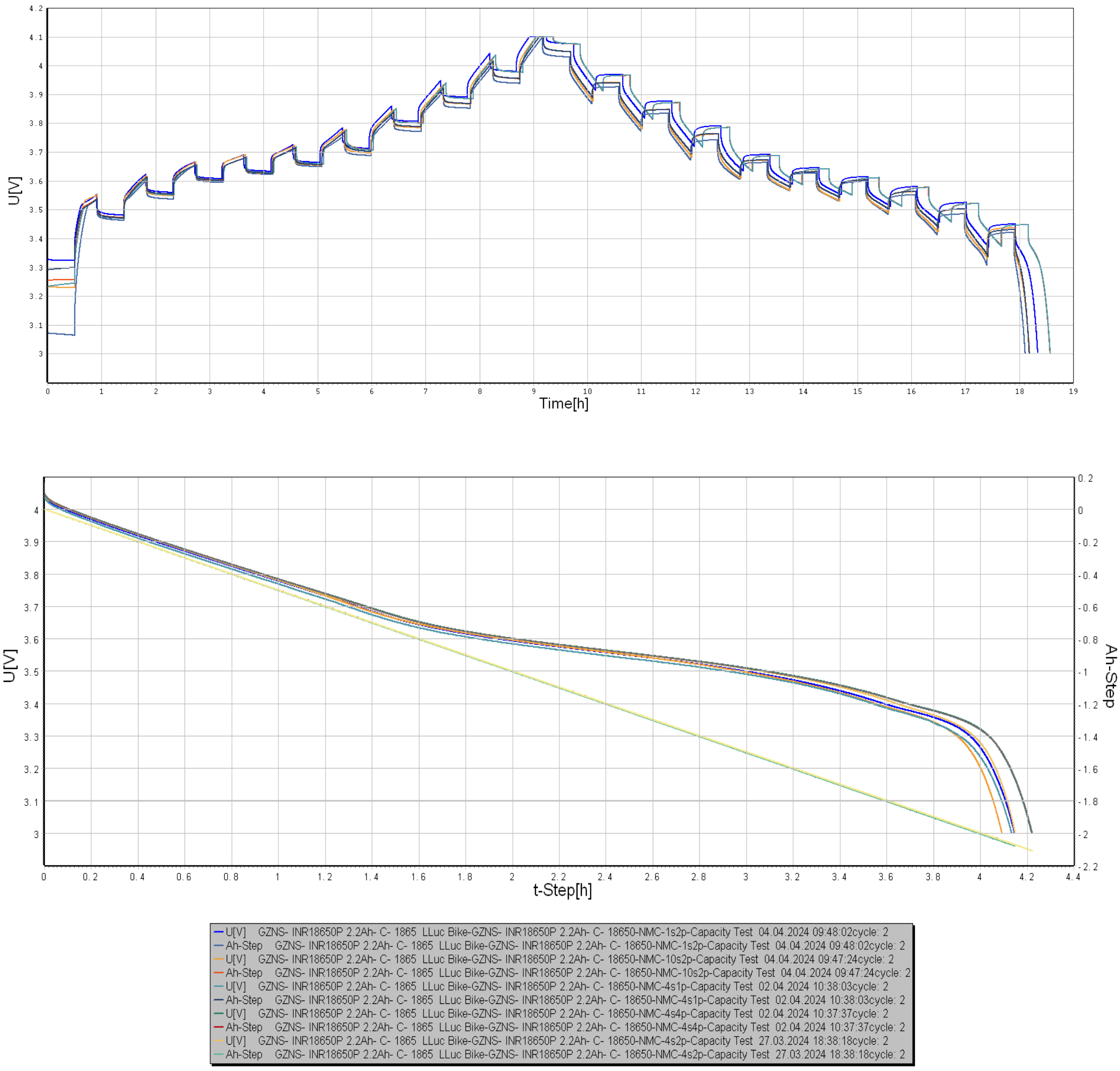
Seeing these results, the battery pack was disassembled, and 6 cells were specifically tested (Figure 6): the 4 cells from the 4th parallel showing lower voltage behavior along with one from the beginning of a series (1s2p) and another from the end (10s2p).

Note that the process for dismantling, once the casing and glue is extracted, is notably simple, as the cells' positive and negative electrodes are welded to a grid forming the different series and parallel strings. This welding is not complicated to break and thus, to remove the grid and rapidly separate each cell.

Once separated, these cells are just like any other cylindrical cell in the market and, therefore, can be regrouped using available manufacturing lines to build new battery modules to be used back into an ebike as a replacement or for other stationary applications, as cylindrical cells are commonly used to build battery packs in many applications not related to mobility purposes (Maiser 2014).

The individual testing of cells in the pulse and capacity test showed (Figure 6), as expected, differences between cells.

Figure 6: Voltage of the cells in the pulse test (top) and capacity test (down)



However, these differences are not as significant as one would expect from a BMS-triggered failure mode. In fact, the recorded capacity for each of the cells is:

- 1s2p: 2,078 Ah, corresponding to SoH=94,45%.
- 4s1p: 2.073 Ah, corresponding to SoH=94,5%.
- 4s2p: 2,078 Ah, corresponding to SoH=94,45%.
- 4s3p: 2,11 Ah, corresponding to SoH=95,91%.
- 4s4p: 2,11 Ah, corresponding to SoH=95,91%.
- 10s2p: 2,04 Ah, corresponding to SoH=92,86%.

Surprisingly, none of the cells from parallel nº4 showed a particularly poor performance. In fact, the one showing the lowest discharge capacity is the 10s2p cell. What ultimately caused the battery to fail was its configuration and progressive imbalance due to prolonged use without any means of adjustment, leading to rendering the battery unusable when it could still have been functional.

Putting this into numbers, the cell imbalance presented a battery with a SoH of 75% when, looking individually at each cell, the SoH could still be higher than 90%. Consequently, considerable underuse of the battery is observed for not incorporating any cell balancing method to enlarge the battery lifespan in the ebike.

This study needs some future work to reach completely reliable conclusions. For instance, higher-intensity discharges should be conducted where other functional issues will emerge, such as the impact on the temperature and the operative capacity caused by the voltage drop at high-power demand conditions.

5. Conclusions

This study has cycled a used bicycle battery whose BMS triggered a failure stop that prevented its charging and, consequently, its regular use. The objective is to identify the overall state of the battery and the reasons behind its condition to assess the suitability of these types of batteries for participation in circular economy initiatives.

It is concluded that the battery cells are not in such a bad condition as one would expect from a BMS-triggered shutdown. The reason that marked the end-of-life of this battery pack is the imbalance between cells due to factory configuration and years of use. The overall SoH at reception is around 75%, while the individual SoH of cells is always above 90%, having still plenty of margin to be used again in a similar or any other application.

Thus, it appears that, once the module is disassembled and the cells separated, which do not have any particularly complicated anchoring and assembly systems, they could be regrouped to form semi-new but functional modules for second-life applications.

Under such circumstances, it is consistent to assess that the second life of batteries from small electric mobility devices makes sense to extend their lifespan and avoid recycling resources prematurely when they still have useful potential. Thus, it is worthwhile to continue investigating in this research line.

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