Decommissioned batteries and their usage in multilevel inverters as an addition to the circular economy

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Abstract
Research on decommissioned batteries emphasizes the value of lost energy in batteries. This article analyzes the leftover battery capacity after its decommissioning from electric vehicles. This analysis includes the discreteness of the battery capacity, sorting based on a QC/T-standard and alteration among the battery capacities. The potential of decommissioned batteries in other applications is presented, and a roadmap for the circular economy is suggested. Based on the data collected in China, significant faults occurring inside electric vehicles' battery packs are reviewed. An alternative inverter is tested to solve the significant challenges in using decommissioned batteries. Advancements are made toward a new intuitive cell balancing technique to utilize maximum capacity in each cell.

KEYWORDS
battery capacity, battery mutation, circular economy, decommissioned (retired) batteries, multilevel inverter (MLI), rotational balancing

1 | INTRODUCTION

Electric vehicles (EVs) and climate goals push for sustainable energy storage and conversion. Batteries are the go-to solution for this rapid energy demand, and recently, batteries have been used in cascaded H-bridge multilevel inverters (MLI) as an alternative in medium and high-voltage applications.\(^1\) Lithium (Li) polymer batteries have established themselves as the ideal energy storage material due to their high energy density and a developed market supply chain. Commercially, two types of Li-polymer batteries are widely in use: (a) lithium nickel manganese cobalt oxide (NMC) due to its high specific energy and (b) lithium iron phosphate (LFP), due to its long life cycle and capability to operate between wide temperature range.\(^1\)

The research was carried out on the LFP batteries as a result of the Chinese Government’s decision to implement LFP batteries as the energy source in public transport. In China’s city, Shenzhen, public transportation has been powered by batteries for more than 5 years. After decommissioning these batteries, experiments were conducted on them to gather their data.

EVs require high-performance batteries to ensure power performance, driving range, and safety. As an EV battery’s State of Health (SOH) reaches 80%, car manufacturers do not consider it useful for traction purposes and decommission it. The remaining lifespan after their decommissioning is estimated at 40%.\(^2,3\) However, most of the estimations are based on designed experiments in the laboratory. For improved estimation, real-life data are required.
The Li-polymer battery will be used for many years to come, and hence there will be a tremendous amount of discarded batteries. Currently, most of the focus is on the recycling of materials; the remaining energy in discarded batteries is not utilized in the circular economy (CE).

Decommissioned batteries are also referred to as “retired batteries.” Some critical factors should be considered for the use of decommissioned batteries in a circular economy. The decommissioned batteries can be used for less sensitive applications (lower charging and discharging conditions) after screening and re-grouping. Examples of secondary applications include energy storage in a DC power supply, microgrids, and low-speed electric vehicles (mopeds). If the filtering is done rigorously, it can also be used in large-scale energy storage applications. One such example is demonstrated in Amsterdam’s “Johan Cruyff Arena.”

The state of art in research indicating necessary steps for recycling is summarized as following. A method for selecting the retired NiMH and Li-Ion batteries has already been investigated by Schneider et al. A grading method for utilizing EV batteries in other applications using SOH and usage conditions was invented by Guo et al. The non-destructive method for sorting out the retired batteries with higher capacity has also been invented by Wenlong et al.

The core steps to utilize decommissioned batteries include battery evaluation, group balancing, operation and maintenance, and economic evaluation. Diao et al. analyzed the internal resistance \( (R_i) \) and battery capacity to combine the two independent factors, leading to a more accurate estimation of SOH and hence the aging of the battery pack. Zhao and Wu developed a parameters-based method for evaluating the usability of decommissioned battery cells and established a battery health assessment system. The evaluation method screens for capacity, internal resistance, cycle performance, and membrane degradation. The economic analysis of battery reusability has already been done by Bai et al.

Many early stage decommissioned batteries were returned from a demonstration energy storage project due to their abrupt and accelerated degradation. This abrupt degradation is quite common; however, the technology to analyze the degradation and assess the batteries’ State of Power (SOP), is still in a developing stage. Therefore, the use of retired batteries for large-scale energy storage, which predominantly relies on them for electricity supply, is not advised with the current technological advancement. It is suggested that such batteries can be directly used with some improvements. Previous research work lacked decommissioned batteries’ cycle performance data. The decommissioned batteries from electric vehicles have not been analyzed for their usage applications in the commercial or private sector. No standards were considered while sorting the batteries. Similarly, there has been no road map for utilizing leftover energy storage as a part of the circular economy on a global scale.

The objectives of this article were to (a) bring to light the characteristics of decommissioned batteries from EVs; (b) streamline their usage in the future through a roadmap; and (c) make this a part of CE to show the batteries’ ideal usage in current technologies for secondary applications. The focus of the work lies on the effects on batteries after commercial use, since recycling the lithium-polymer batteries will be more challenging in the future, and a method is suggested to extract the full energy potential of batteries before discarding them.

This article analyzes decommissioned battery modules from two applications after their service in public transport: (a) buses and (b) taxis. Both applications represent different usage behavior, such as discharging, load profile (the number of passengers), the power requirement, and the driving pattern. The rest of this article is organized as follows: Section 2 discusses the methodology and the standards used for the experiment on the battery. Section 3 depicts the results along with their assessment under the following order: (a) capacity distribution; (b) module sorting; and (c) battery characteristics. Section 4 discusses the challenges and their solution, which gives an overview of different factors that contribute to the failure of battery packs in EV. Cascaded MLI is suggested for the implementation of retired batteries in the secondary applications. It can use any combination of batteries with different rated capacities and still use the maximum potential of each battery without any losses. This technology is named as an alternative inverter as it does not require an inverter to convert DC into AC. The concept is introduced for using decommissioned cells in secondary applications. Some steps required for CE are suggested, and Section 5 gives the conclusion of this article.

2 | METHOD

Data of decommissioned LFP batteries were collected from buses and taxis. The batteries were tested to analyze (a) their potential for use in secondary applications and (b) to observe the leftover capacity’s characteristics. The application of such batteries was presented in CMC with its advantages.

The first decommissioned battery sample was deployed in public buses for 5 years. A new battery cell
in buses had a rated voltage of 6.4 V and a capacity of 22 Ah. Twelve of these cells were connected in parallel to create a module. This module had a rated voltage of 6.4 V and a capacity of 264 Ah (initial capacity). The second decommissioned battery sample was deployed in taxis for 4 years. The cells used in taxis had different voltage and capacity ratings. Each cell had a nominal voltage of 25.6 V and a capacity of 25 Ah. Eight cells were connected in parallel to create a battery module with a rated voltage of 25.6 V and 200 Ah capacity. The battery modules can be combined in series to generate any required voltage.

Further information on batteries is deemed unnecessary to avoid complexity in the research. The total samples obtained from buses were 56 modules, whereas 132 modules were gathered from taxis. In the first phase, the capacity of all the modules was measured through discharging capacity tests and plotted to give an overview of the leftover capacity.

One cycle of the discharge capacity test is based on the standard GB/T 743-2016 and can be summarized as follows: temperature was maintained at 20°C with a tolerance of ±5°C. The battery was completely discharged and was left to stabilize for 15 min. In the next step, the battery was charged with “Constant Current” (CC) of 0.3 C (according to C-rate) until the maximum cut-off voltage. Then the battery was charged with “Constant Voltage” (CV) until the C-rate was reduced to 0.05 C. After 30 min of relaxation time for voltage stabilization, the battery was discharged at 0.5 C until the voltage dropped to the cut-off voltage, the amount of current discharged is considered as capacity of a battery in Ah.15

Based on the results from phase one, the modules from both sources were assessed for their future potential. The aim was to bundle as many modules together as possible for a secondary application. The main criteria for sorting the modules are based on the 3% rule of maximum capacity. This rule dictates that the batteries can be paired according to the matching standard of ±3% of the total leftover capacity. The value of ±3% originates from QC/T: “Technical specification of Battery Management System for Electric vehicles.”16 This standard requires the State of Charge (SOC) to be determined with ±3% accuracy. SOC is considered a crucial factor of a battery, as maximum capacity also represents 100% SOC. If cells are not kept within a ±3% capacity range, it can lead to inaccurate SOC estimation for the collection of modules in any application. This standard also ensures that batteries with similar conditions can be sorted together in one module.

Since the battery modules of the buses were decommissioned after 5 years, these modules also depicted more discreteness in comparison to a taxi. Therefore, it made sense to observe the behavior of cells inside the buses’ modules. The aim was then to stimulate the cell’s characteristics in the future. For this purpose, 56 modules from buses were dismantled, and 12 cells were randomly selected for 2000 discharge capacity tests. The cell capacity was measured after each cycle. These measured values were used to generate the capacity reduction of a cell over 2000 cycles. The capacity reduction is presented as the “decay rate” of capacity in percentage.

The battery’s decay rate can be defined as the rate at which the capacity of a battery is decreasing. It can be interpreted as the leftover SOC compared to the initial values. In mathematical terms, it is the difference of “capacity after decommissioning” ($C_n$) with the “capacity for the nth cycle” ($C_0$). The difference is divided by the $C_0$ to convert it into a percentage. Equation (1) shows the capacity decay rate

$$R_n = \frac{(C_0 - C_n)}{C_0}.$$  

$R_n$ is the capacity decay rate for the “nth” cycle; $C_0$ is the initial discharge capacity after decommissioning, and $C_n$ is the discharge capacity of the “nth” cycle for the decommissioned battery.

In the last section, a prototype of CMC is shown. A different set of batteries are combined and successfully tested in a prototype at the University of Ulm. For demonstration, 100 cells are used in a prototype and tested with the Keysight InfiniiVision DSOX2014A Digital Storage Oscilloscope and an internally developed software (Grid Control) on Microsoft Visual Studio 2017 with C++ for controlling the output during charging and discharging. The verification is presented in the discussion.

3 | RESULTS AND ASSESSMENT

3.1 | Capacity distribution of modules

3.1.1 | Buses

Figure 1 shows the 56 decommissioned battery modules gathered from buses. Buses’ battery modules had an initial capacity of 264 Ah. The remaining capacity of the 56 modules is between 45% (118.8 Ah for Module 1) and 80% (211 Ah for Module 56) of the initial capacity. It can be seen that the residual capacity is not evenly distributed.

As the minimum capacity of the battery module is observed at 45%, if there is any second module in series with a higher capacity, for example, 80%, the energy of

![Image of battery modules](image-url)
the second module will not be fully utilized since the energy of battery with higher capacity would be wasted in balancing. This issue is further explained in Section 4.1.

### 3.1.2 | Taxis

Figure 2 shows the 132 decommissioned battery modules gathered from taxis. Taxis’ battery modules had an initial capacity of 200 Ah. The remaining capacity of the 132 modules is between 75% (150.14 Ah for Module 1) and 91.5%(183 Ah for Module 132) of the initial capacity.

In the first sample (buses), the mean capacity of modules is approximately 189 Ah with an SD of 20.65 Ah; in percentage, the SD of modules has increased from nearly zero to 10.9% after decommissioning. Whereas in the second sample (taxis), the mean capacity is 166 Ah with an SD of 6.3 Ah; in percentage, the SD has increased from 0% to 3.8% after decommissioning. Thus, it is clear that in buses, the capacity difference of battery modules is relatively vast and non-uniform compared to taxis. Further analysis between the two samples suggests that the number of cycles and other factors (such as temperature, discharge rate, and the chemical reactions inside the battery) significantly impact the battery life.

### 3.2 | Module sorting for secondary applications

The aim during sorting was to gather the maximum number of modules that can be used in a single secondary application, for example, energy storage in a grid. The modules are sorted as per the 3% rule. If this standard is implemented for the first research sample (buses), most of the batteries cannot be matched and reused due to the significant disparity between the battery cells. However, in the second research sample (taxis), this method resulted in groups of six different capacity intervals. It is shown in Figure 3.

The capacity intervals for sorting the battery modules is determined as follows, the taxi module with the highest leftover capacity(183 Ah) is used as a base point, and 3% of 183 Ah translates to an interval of 5.5 Ah. Thus, the first interval is 177.5-183 Ah. The module with a capacity lower than 177.5 Ah is used as a base point for the second interval. This is continued until the last module (150 Ah) is sorted. Figure 3 shows that at most, 61 battery modules
are in the same capacity interval. These 61 modules can be combined and used for secondary applications like energy storage in grids for peak demand matching, street lights or communication towers. The remaining 71 cells constitute five different capacity intervals and hence have to be implemented in another project depending upon the load requirements.

Modules from buses could not be combined into a group because of higher disparity. Hence, they cannot be used to make a large pool of energy storage units. At this point, it was clear that the cells in buses had gone through severe changes. It was necessary to understand the characteristics of the cells in the modules. Therefore, the assessment is refined to single cells of a module in the next section.

3.3 | Battery characteristics

3.3.1 | Decay rate of the cell

Twelve cells are randomly selected from the buses. From the results, there were two conclusions. First, the average leftover capacity after using a new cell in EV for 5 years is around 80% of the initial capacity, that is, a bus cell with a capacity of 22 Ah had around 17.6-17.9 Ah left overcapacity. Thus, it can be said that 5 years seem to be the limit of batteries in bus applications. Second, after 2000 capacity discharge tests of 12 randomly selected decommissioned cells from the buses, if the average decay rate is calculated as a linear function, it can be concluded that every 1000 cycles decrease the capacity of an LFP cell by approximately 3.518%. In terms of Ah of the cell, after testing, the average leftover capacity of a cell is around 16.5 Ah. The result is presented in terms of percentage decay rate in Figure 4.

3.3.2 | Battery mutation

Out of the 12 cells, one of the cells showed an anomaly and gave a crucial result. This result is shown in Figure 5. It shows the decay rate gradually increasing with the number of cycles. However, at the 1250th cycle, the cell exhibited abrupt mutation and suddenly expired.

The first implication of this result is that it can be seen that the sudden expiry of the battery is an unpredictable phenomenon, which should be expected during the secondary application. Meaning, the phenomena should not be neglected and requires attention while reusing the decommissioned batteries. It also implies that the cells need to be constantly monitored for sudden death, and such cells should be somehow bypassed to avoid the impact on other cells in series. The second implication is that since one out of the 12 cells showed this mutation, the probability of sudden death in this study is 8.3%, that is, every 12th cell could show such mutation. However, the actual number could be lower or higher depending on battery conditions.

Wang and Zhao’s experiments support the idea of sudden death. In their research, while measuring the number of cycles against battery capacity, the experiments proved that the decay rate of the battery exponentially increased before its expiry. This experiment can be summarized as follows: a capacity discharge test was carried out on a decommissioned battery with 1 C-rate, that is, it was charged and discharged continuously.

![Figure 4](attachment:image1.png)  Average battery’s capacity decay rate as a linear function of number of cycles

![Figure 5](attachment:image2.png)  “Sudden Death” of a battery. Based on Wu et al
with 1C. After 700 cycles of charging and discharging, the battery undergoes mutation and expires between cycle number 760-790, that is, and the battery decay rate grows exponentially to 100%.

This result can be correlated to the findings in Section 3.1. To understand the capacity distribution difference between the first research sample (buses) and the second research sample (taxis), we can consider the number of cycles as the crucial factor, as the 1 year of difference between their operational time can increase the chances of sudden death.

4 | DISCUSSION

Considering the results of modules and cells, we need to address two significant issues. First is the challenge regarding the battery failure in EV, and second is the CE of batteries after decommissioning. Based on the summary from these two points, a solution is proposed to address the given issues.

4.1 | Challenges

Further challenges in EV batteries are presented through an analysis of “monthly accumulative breakdowns of EV powered by Li – battery.” This analysis is based on the “Annual Report on the Big Data of New Energy Vehicle in China (2018).” The report gives us the factors causing battery failure in EVs. It states that 52% of battery modules are discarded due to problems such as (a) loss of consistency of power (20%); (b) overvoltage of single-cell (18%); and (c) undervoltage of a single cell (14%). These problems arise due to battery cells on an individual level (as assessed in Section 3.3.2) and are directly related to the number of cycles, that is, excessive charging and discharging. The excessive charging and discharging from an engineering perspective could be directly related to battery management system (BMS).

Active and passive balancing methodologies are the two most common BMSs. The energy that can be utilized is limited to the weakest cell (lowest capacity). “During discharging, the cell with the lowest capacity will reach its lower limit of safe operation voltage first; at this time the BMS has to turn off the discharging and switch to charging. A similar situation happens during charging: the cell with the lowest capacity will reach its upper limit of safe operating voltage first; thus, BMS has to stop the charging process.”

For active balancing, the batteries with excess energy are used to charge the batteries with less energy and balance the capacity of batteries, whereas, in passive balancing, a resistor is used to balance the battery cells until all of them reach the same capacity. The primary drawbacks in both methods are that (a) battery life and efficiency depend on the number of cycles (n), and “n” increases with each balancing cycle; (b) the maximum output of the battery is reduced due to the weakest cell in the battery pack; and (c) if there is a dead battery cell, excess energy is wasted on charging that cell.

To summarize, a battery pack may suffer from different capacities of individual cells, rendering the efficiency of the whole battery pack equivalent to that of the weakest cell. This effect is observed prominently in old cells, as a higher discrepancy exists between cell’s capacities. For example, the balancing of the modules in Figure 1 would limit the maximum deliverable capacity of the module to 45%, and any active or passive balancing would waste energy and have an impact on the life of the battery. Similarly, the battery pack also becomes useless if one of the cells in the series expires (0% capacity). Another challenging part is that this retired cell cannot be easily identified in conventional BMS technologies, and as the cells are always connected in series, there is always a voltage and current flow, making it dangerous to replace the damaged cell.

4.2 | Potential use of decommissioned batteries

CE would utilize the battery’s full potential from an energy perspective before recycling the materials. However, at the moment, Li-ion batteries do not have standards or best practices for CE. Therefore, excerpts from battery specialists were analyzed for secondary applications. Based on the opinions, we would like to suggest the following concept.

Different applications have different battery requirements. According to Zhang and Liu, a decommissioned battery can be used for the following purposes: power storage in microgrids, low-speed electric vehicles, renewable energy storage for peak demand and communication base station’s backup power. However, each one of them has different requirements. For example, the requirements are not high for a backup battery for the communication base station. These requirements include the battery’s performance, energy density, size, large current and voltage, but a quick response time and large capacity is essential. Usually, the capacity required by a single communication base station is approximately 30 kWh. On the other hand, energy storage for power generation and distribution has high requirements, for example, high frequency of use and high cycle life (number of cycles of batteries). If the requirements are simplified, it
can be said that they are based on battery specifications and technology. These requirements are shown in Figure 6A.

The batteries could be used after defining the requirements for the application based on a pyramid scheme, where strict requirements would be at the top of the pyramid and batteries with the best qualities would be used for it. On the other hand, applications with lower requirements would use batteries of lower quality. This method is named as battery power ladder, which describes the technique of reusing decommissioned batteries for the secondary applications as per their power, capacity, and design elements, that is, module specification and rated voltage. The concept is shown in Figure 6B. The ladder process can make use of the remaining power of the battery until it is entirely exhausted. However, in order to utilize the ladder, batteries would require multiple inspections.

According to Figure 6A, to sort the batteries based on their chemical composition, we can use battery comparisons from “Advanced Energy Materials.” For example, LFP is used for high cycle life and temperature resistance, whereas NMC is used for high energy density. On the other hand, the technology side is solved by using CMC to fulfill all the requirements.

Since the value and industrial chain have not been set up yet, another step to consider in CE is setting up a chain of responsible bodies that will sell the decommissioned batteries to interested parties, that is, who will sell the product to whom. The duty of the recycling body is also not established at the moment. Therefore, there is not enough lucrative interest for the CE market to develop itself. For now, saving the environment is the only benefit of CE.

Another problem is when a decommissioned battery pack needs to be dismantled, and each cell needs to be tested individually and repacked into a module for utilization in the battery power ladder. This process is made complex by the fact that there is no standard for batteries shape and construction. The dismantling and recycling processes are complicated and bring high costs.

In summary, there is a need for government initiatives to standardize the size and shape of the battery through the world’s leading automotive manufacturers. This would ensure that decommissioned batteries can be used universally in secondary applications without any barriers. We would also need to consider all available criteria for a battery module to be used efficiently, that is, capacity, cycle life, response time, design elements, and energy density. A CE roadmap based on an engineering perspective is presented in Figure 7.

### 4.3 | Solution

A conventional inverter can be used for uninterrupted power supply (UPS), control of electrical machines, and active power filtering. However, it lacks control over multiple batteries. All of the problems mentioned above can be solved by using an alternative inverter, that is, CMC, and a new intuitive system of balancing designed by the institute, named as “Rotational balancing.” CMC can produce sinusoidal output through steps generated by different batteries connected in series with negligible harmonics.

The sorting mechanism can be described as following: rotational balancing would always ensure that while

![Figure 6](image-url)
discharging the batteries with the highest capacity are used the most and hence make the base of the sinusoid, whereas the battery with the least capacity makes the peak of the sinusoid and vice versa for the charging. In CMC, a simple algorithm in the house-internal software lets us monitor the operating voltage of each cell and bypass any dead battery through the help of an H-Bridge made of MOSFETs. Since the cells and battery holders are numbered, we can constantly monitor every cell’s status. Moreover, due to H-bridge technology, the electronic circuit can be completely turned off (no current flow), thus offering ease of maintenance. The concept is explained in the following sections.

4.3.1 Cascaded multilevel converter

The schematics of CMC are shown in Figure 8.
This circuit diagram helps understand the charging and discharging process of the battery modules (presented as “bat1”-“batn”). An H-Bridge consisting of four MOSFETS is used to control the charging and discharging process. A hardware prototype with 100 slaves and one master board are developed at the institute. The prototype is shown in Figure 9.

In this prototype, 100 slave boards with a double battery holder are used. One slave board monitors one battery module. A master board controls the slaves mounted in front (blue plate). The master board decides whether the battery should be charged or discharged with priority or bypassed to deliver the required power with maximum efficiency while keeping the number of cycles minimum.

As per the application, the design of CMC can be adjusted to integrate one or multiple cells in a single module. The number of battery cells used depends on the application and nominal voltage of each cell for example, if we use a single cell in a module for home application, and the cell has a cut off voltage of 2 V, we would need to use 120 slaves. In this way, the device could consistently deliver 220 V with a redundancy of 10 cells. However, to ensure higher redundancy, a module should have at least two cells in series.

4.3.2 | Rotational balancing

The method of balancing used in the institute is called rotational balancing. This method ensures that the batteries with the most capacity are discharged first during the...
discharging phase, and while charging, the batteries with the least capacity are charged first. Best understood from a screenshot of a house internal software in Figure 10. This sorting and balancing continue until all the batteries reach the same capacity.

Figure 10 is used as an example and uses six cells with approximately four volts to generate a sinusoidal wave. Battery 6 is at the base, representing that it was used to discharge the most. It was selected by the master board for the longest time (as base supply) because it was recognized as the one with the highest capacity in comparison to the other batteries. Whereas battery one was selected to engage for the shortest time (used at the peak), it presented the least amount of capacity. The capacity is estimated directly from the voltage and current flow.

To present the same phenomena in our prototype, a screenshot from Oscilloscope DSO-X 2014A is shown in Figure 11. It shows the upper part of the sinusoidal wave with 20 cells.

The design for the prototype is configurable and can be used to generate any required voltage. We can continue this pattern to generate 100 steps with any step size. In this demonstration, 100 news cells with an average voltage of 3.6 V were used. Each step is so tiny that their combination produces a smooth sinusoidal wave. Sample output with a peak voltage of 360 V at the frequency of 50.218 Hz is shown in Figure 12. After reaching the configured voltage, the batteries with the least capacity are redundant and bypassed.

4.3.3 | Harmonics

The harmonics generated in this process are well below the current standards of IEEE519 or EN50160. For example, fundamental voltage of 211.59 V at 50.25 Hz generated total harmonics distortion of 0.175% and all the other harmonics are well below 0.1%. Therefore, the results of harmonics comply with the industrial standards for direct usage in any application. Additionally, the device has been tested and also qualifies for VDE-AR-N 4105.

4.4 | Advantages of CMC with rotational balancing

The complete system allows multiple benefits. (a) The battery with different capacities, compositions and manufacturers can be used together. This advantage is significantly relevant in the case of decommissioned batteries. (b) Every cell’s total capacity is utilized, thus delivering an average total capacity of all the cells in a battery without losses. (c) The output voltage is configurable. (d) Since each cell’s current and voltage are constantly measured, it can also estimate the battery’s SOC and bypass all the redundant cells after reaching the output voltage. Furthermore, since CMC offers modular construction, the number of redundant cells can be defined by the user for each application. (e) Any dead cells can be replaced individually without much effort. (f) Batteries
with different “parameters” (manufacturer, efficiency, capacity, life state, and size) can be used without any need for sorting. (g) This method also has the advantage of replacing the inverter and is cheaper than conventional batteries with an inverter. (h) The DC to AC conversion efficiency is 99%, with a response time of 1 ms in UPS applications. (i) The modular design of CMC allows the energy capacity (kWh) to be set as per requirements. 21

The benefits of CMC with decommissioned cells are explained through a theoretical example. The values of 56 decommissioned modules from buses (Sample 1) are used. Regardless of voltage requirements in the end application, the total percentual cell capacity values can be used in this prototype, that is, 45% is now considered as the weakest cell capacity and 91% as the highest cell capacity. The rotational balancing in CMC would ensure that there are no energy losses in balancing. CMC would extract the maximum energy from each battery, and total capacity output after calculation equaled 71% (average of maximum available capacity in each cell), thus increasing the efficiency of total available capacity by more than 50%. The effect is summarized in Figure 13.

5 | CONCLUSION

This paper presented a new and simple grouping method of batteries based on previously available standards as well as a new balancing method in batteries. The rest of the findings are summarized as following.

The battery modules from buses and taxis suggest that the residual capacity and characteristics of the decommissioned batteries from vehicles meet the requirements for secondary applications. However, the capacity inconsistency and probability of sudden death of a battery posed challenges in secondary applications. In some cases, after 5 years, a module had only 45% of its original rating. It was found that the number of cycles can be used as a vital factor for understanding the battery mutation and the capacity distribution difference between the research samples.

The analysis of significant faults in EV shows that the active and passive balancing can be directly related to the fault in individual cells. The rotational balancing developed at the institute method is proposed as an alternative to other balancing methods. This method is only applicable in MLI. This technology offers an optimal solution for inconsistent battery capacity and monitoring of individual cells in the battery pack. It can also use the full potential of any old cells and maximize energy conversion efficiency, thereby also improving recycling from an energy perspective.

The roadmap presented in this paper needs to be implemented as soon as possible to achieve a true CE, otherwise it will take a long time before the lithium-polymer batteries circular economy is completed.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

Research data are not shared.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| Ah     | ampere-hour |
| C      | charging/discharging rate |
| $C_0$ | initial discharge capacity of the decommissioned battery |
| CMC    | cascaded multilevel converter |
| $C_n$  | discharge capacity of the nth cycle of the decommissioned battery |
| EN     | European Standards |
| EV     | electric vehicle |
| I      | current |
| IEEE   | Institute of Electrical and Electronics Engineers |
| Li     | lithium |
| LFP    | lithium iron phosphate |
| $n$    | number of cycles |
| NMC    | lithium nickel manganese cobalt oxide |
| $R_i$  | internal resistance |
| $R_n$  | capacity decay rate of the nth cycle |
| SOC    | State of Charge |
| SOH    | State of Health |
| V      | volts |

FIGURE 13 Available capacity in CMC (right) compared to the conventional method (left) for a battery module
CC constant current
CV constant volume
UPS uninterrupted power supply
CE circular economy

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REFERENCES
1. Choudhury S, Bajaj M, Dash T, Kamel S, Jurado F. Multilevel inverter: a survey on classical and advanced topologies control schemes, applications to power system and future prospects. Energies. 2021;14:5773. doi: 10.3390/en14185773
2. A. Routray, R.K. Singh, R. Mahanty, Capacitor voltage balancing in hybrid cascaded multilevel inverter using modified model predictive control, International Conference on Emerging Trends in Communication, Control and Computing, 2020, pp. 1–5.
3. Miao Y, Hynan P, von Jouanne A, Yokochi A. Current li-ion battery technologies in electric vehicles and opportunities for advancements. Energies. 2019;12:1074. doi: 10.3390/en12061074
4. Canals Casals L, Barbero M, Corchero C. Reused second life batteries for aggregated demand response services. J Clean Prod. 2019;212:99-108. doi: 10.1016/j.jclepro.2018.12.005
5. W. Z. Po, W. Cheng & Li Yang et al., Annual report on the big data of new energy vehicle in China, Beijing, 2018.
6. Durmus YE, Zhang H, Baakes F, et al. Side by side battery technologies with lithium-ion based batteries. Adv Energy Mater. 2020;10:2000089. doi: 10.1002/aenm.202000089
7. Chen Y, Dou A, Zhang Y. A review of recycling status of decommissioned lithium batteries. Front Mater. 2021;8:634667. doi: 10.3389/fmats.2021.634667
8. Pagliaro M, Meneguzzo F. Lithium battery reusing and recycling: a circular economy insight. Helion. 2019;5:e01866. doi: 10.1016/j.helion.2019.e01866
9. Schneider EL, Oliveira CT, Brito RM, Malfatti CF. Classification of discarded NiMH and li-ion batteries and reuse of the cells still in operational conditions in prototypes. J Power Sources. 2014;262:1-9. doi: 10.1016/j.jpowsour.2014.03.095
10. Guo J, Daotan L, Wang S, et al. A classification method for reuse of EV’s power batteries (in chinese). ZL. 2014;2011(1):0410608.
11. Wenlong W, Guangjin Z, Jingjuan G, et al. Sorting and Assessing Method for Retired Power Batteries Reuse (in Chinese). ZL. 2014;2012(1):0267131.
12. Diao W, Jiang J, Zhang C, Liang H, Pecht M. Energy state of health estimation for battery packs based on the degradation and inconsistency. Energy Procedia. 2017;142:3578-3583. doi: 10.1016/j.egypro.2017.12.248
13. Guangjin Z, Wenlong W. A usability evaluation method for retired power lithium-ion batteries (in Chinese). ZL. 2017; 2014(1):0433190.
14. Bai B, Xiong S, Song B, Xiaoming M. Economic analysis of distributed solar photovoltaics with reused electric vehicle batteries as energy storage systems in China. Renew Sustain Energy Rev. 2019;109:213-229. doi: 10.1016/j.rser.2019.03.048
15. Jin G, Wubin Q. Study on capacity consistency and decay characteristics of retired lithium iron phosphate batteries (in Chinese). CBEA, 2018.
16. Standardisation Administration of China (SAC), the Chinese National Committee of the ISO and IEC, GBT 31486–2015, Electrical performance requirements and test methods for power batteries for electric vehicles_National Standard Committee(in Chinese). 20150515.
17. Wang G, Zhao G. Reuse and Recycling of Lithium-Ion Power Batteries (First Press) (in Chinese). Beijing, China: China Electric Power Press; 2015.
18. Zhao G, Wenlong W. Active and passive combined equalization circuit and method of series battery packs (in Chinese). ZL. 2016;2014(1):0338200.
19. J. Qi, D. Dah-Chuan Lu, Review of battery cell balancing techniques, Australasian Universities Power Engineering Conference (AUPEC), Perth, WA, Australia, 2014, pp. 1–6.
20. Ying Z. New energy power battery ladders take long roads and obstacles, 2019.
21. Based on the testing of SAX Power GmbH, Erbach, Germany: SAX-Power GmbH.

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