An improved relative integral capacity-K-means clustering method for capacity pre-sorting of decommissioned power batteries.

XU, X., WANG, S., LIU, D., FERNANDEZ, C. and BLAABJERG, F.

2024

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

An improved relative integral capacity-K-means clustering method for capacity pre-sorting of decommissioned power batteries

To cite this article: Xuntao Xu *et al* 2024 *J. Phys.: Conf. Ser.* **2853** 012057

An improved relative integral capacity-K-means clustering method for capacity pre-sorting of decommissioned power batteries

Xuntao Xu[1], Shunli Wang[1,2,3,6], Donglei Liu[1,2], Carlos Fernandez[4] and Frede Blaabjerg[5]

[1] School of Electronics and Information, MianYang Polytechnic, Mianyang 621000, China;
[2] School of Information Engineering, Southwest University of Science and Technology, Mianyang 621010, China;
[3] Electric Power College, Inner Mongolia University of Technology, Inner Mongolia 010000, China;
[4] Department of Energy Technology, Aalborg University, Pontoppidanstraede 111 9220 Aalborg East, Denmark;
[5] School of Pharmacy and Life Sciences, Robert Gordon University, Aberdeen AB10-7GJ, UK

[6] E-mail: 497420789@qq.com

Abstract. Capacity sorting is the primary prerequisite for the stepwise utilization of decommissioned power batteries. This study proposes an improved relative integral capacity- K-means clustering (RIC-KMC) method for preliminary sorting of decommissioned power battery capacity. Firstly, according to the electrochemical aging characteristics of decommissioned power batteries, combined with the ampere-time integration algorithm, a new lossless extraction method of the capacity characteristics of Lithium-ion batteries based on the segment voltage is proposed. Second, to minimize the interference of environmental factors and sampling errors on the charging capacity, the relative amount of charging capacity is introduced. Finally, to complete the capacity sorting before the ladder utilization, an improved RIC-KMC method is proposed, which combines the electrochemical aging feature values of decommissioned power batteries extracted from the segment voltage charging capacity with the K-means clustering algorithm. Using three sets of battery charging and discharging data to validate the sorting algorithm, the capacity sorting errors are reduced by 0.926%, 12.381%, and 10.185%, respectively, which verification the validity of the proposed RIC-KMC method. This study provides a new solution for capacity pre-sorting of decommissioned power batteries for stepwise utilization.

1. Introduction

With the increasing popularity and stock of new energy electric vehicles around the world, a negligible problem has gradually emerged, namely, the stepwise utilization of decommissioned power batteries[1-4]. The dynamic performance of power lithium-ion batteries will gradually degrade with use, characterized by capacity degradation as well as an increase in internal resistance[5, 6]. The occurrence of side reactions inside lithium-ion batteries leads to a decrease in active lithium content, resulting in capacity degradation, including changes in the positive and negative electrode structures, the formation of solid electrolyte interfaces, and the decomposition of electrolytes. After the capacity of a power lithium-ion battery has decayed to 80% of its rated capacity[7], the dynamic performance will not be sufficient for electric vehicle use. However, the usable battery life does not end at this point[8, 9]. Before the battery completely loses its electrochemical activity, decommissioned power batteries can be used in scenarios such as grid energy storage and home energy storage[10-12].

The sorting of decommissioned power batteries directly determines the length of the subsequent service life in a group. Reorganized battery packs with good consistency have a longer lifetime. The sorting of decommissioned power batteries has been focused on by researchers in various countries. Zhou Zihao, Ran Aihua et al. used the K-means method to form the clustering cluster family with the characteristic distance of electrical performance as the index, and then complete the battery collection screening[13]; Chen, Zuhang et al. proposed a classification reorganization method based on IC curves[14]; Wang Lujund et al. proposed an efficient and fast ladder battery equalization method based on a wide voltage range bi-directional converter for the equalization of stepped utilization battery packs[15]; To solve the consistency problem of decommissioned battery packs, Yin, Haojie et al. proposed a two-stage method for sorting decommissioned batteries by combining static and dynamic characteristics such as discharge capacity, temperature rise, and voltage profile[16].

All the existing research on decommissioned power batteries has realized the capacity sorting of decommissioned batteries by extracting the characteristics through charging and discharging experiments of lithium-ion batteries. Nevertheless, a complete charging and discharging process will accelerate the aging of decommissioned power batteries. Ion buildup and side reactions inside the lithium-ion battery will be enhanced in the low and high charge intervals. When the energy range is between 0.4 and 0.8, lithium-ion batteries age so slowly that the aging between two adjacent cycles can be ignored. Lithium-ion batteries do not have memory at this point. This study applies this characteristic of lithium-ion batteries to achieve the minimization of damage sorting of decommissioned power batteries. Based on fully analyzing the electrochemical aging characteristics of lithium-ion batteries, the internal aging mechanism and external stress aging model are constructed. The RIC-KMC method is formed to realize the capacity sorting of decommissioned power batteries by using the ampere-time integral capacity extraction method, combined with the relative amount of charging capacity.

2. Mathematical analysis

2.1. Relative integral capacity-K-means clustering method analysis

The same brand and the same type of battery packs have high similarity in aging characteristics during use, which can be utilized to screen out batteries of the same aging state. The batteries with the same aging state with the same dynamic characteristics during charging have similar stresses, which means that the charging voltage curves of different aging batteries are not the same under the same excitation conditions. Experiments show that compared to the aging battery new battery constant current charging time is longer, which means that the process of voltage from the discharge cut-off voltage to the maximum voltage takes longer, such a phenomenon suggests that in the case of charging the same amount of electricity, the voltage lift of the aging battery will be higher. Since decommissioned batteries do not have the same initial charge state, the number of charging and discharging times during sorting should be minimized to avoid further aging of the batteries. Before re-assembling and utilizing, the decommissioned batteries need to be fully charged, using the same segment voltage in the charging process to differentiate the battery's degree of aging, which can minimize the aging process of the battery. Based on such a thought of lossless sorting of batteries, an improved RIC-KMC method is proposed, as shown in Figure 1.

Firstly, according to the charging electrochemical characteristics of the decommissioned power battery combined with the ampere-time integral algorithm, the segment voltage method is applied to extract the aging characteristics of the decommissioned power battery, which means that the charging charge is different under the same segment voltage as shown in Equation (1). In Equation (1) Q_{LV} means the charging charge of the limited segment voltage, Q_i means the charging capacity of the ith battery, I mean the charging current, t_{V1} means the integration start time, and t_{V2} means the integration end time.

Secondly, the relative charge electrical capacity is introduced to minimize the interference of environmental factors and sampling errors on the charging capacity, as shown in Equation (2). The traversal method is used to compare the segment voltage charging capacity of all batteries to obtain the minimum and maximum segment voltage charging capacity of the batteries. Q_{min} is the minimum value of the battery's single charging capacity; Q_{max} is the maximum value of the battery's single charging capacity; δ_i represents the characteristic value of the relative segment voltage charging electric charge of the ith battery.

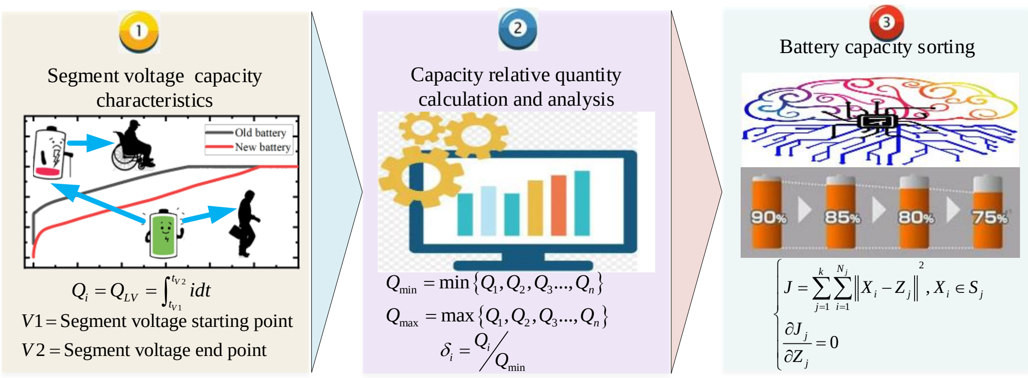


Figure 1. RIC-KMC method flowchart.

$$Q_i = Q_{LV} = \int_{t_{V1}}^{t_{V2}} Idt \tag{1}$$

$$\begin{cases} \delta_i = Q_i / Q_{\min} \\ Q_{\min} = \min\{Q_1, Q_2, Q_3..., Q_n\} \\ Q_{\max} = \max\{Q_1, Q_2, Q_3..., Q_n\} \end{cases} \tag{2}$$

$$\begin{cases} CCS_j = \sum_{i=1}^{N_j} \|X_i - Z_j\|^2, X_i \in S_j \\ J = \sum_{j=1}^{k} CCS_j \end{cases} \tag{3}$$

Finally, to realize the research on reuse sorting of decommissioned power batteries, the RIC-KMC method is formed by applying the relative segment voltage charging capacity eigenvalue combined with the K-means algorithm, as shown in Equation (3). In Equation (3), CCS_j is the intra-cluster sum of squares of the jth cluster, j represents the jth cluster, X_i represents the ith element of the jth cluster, Z_j is the mean vector representing the jth cluster, N_j represents the number of elements in the jth cluster, S_j denotes the clustering interval, J is the overall clustering sum of squares, and k denotes the number of clusters that are eventually clustered. Cluster analysis is to find the k cluster center points that minimize the overall cluster sum of squares. In this research, relative segment voltage integral capacity is used for cluster analysis, and decommissioned power batteries with similar aging characteristics are clustered into the same group to achieve sorting.

3. Experiments and discussions

3.1. Experimental platform and experiment

The validation experiment uses the commercial 18650 power cell for electric vehicles, the rated capacity of the battery is 3200 mAh, the rated voltage is 3.6 V, the charging cut-off voltage is 4.2 V, the discharging cut-off voltage is 2.75 V, the maximal discharging multiplication rate is 3 C, and the normal working temperature is 0~40 ℃. The experimental data acquisition equipment is a high-power charge/discharge tester for power lithium-ion batteries (CT-4016-5V100A-TFA), which can charge/discharge 16 batteries at the same time. The built experimental platform is shown in Figure 2.

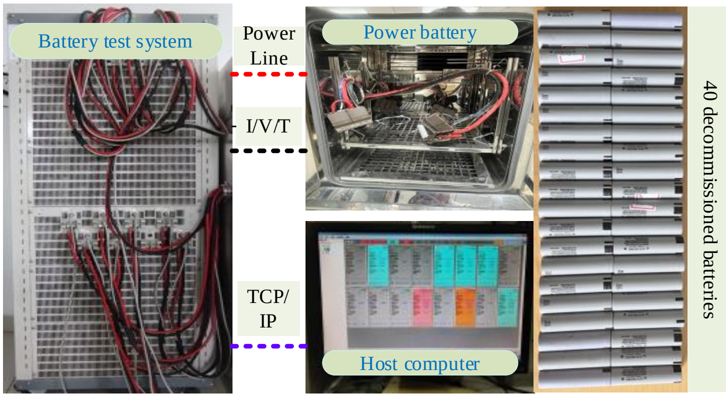
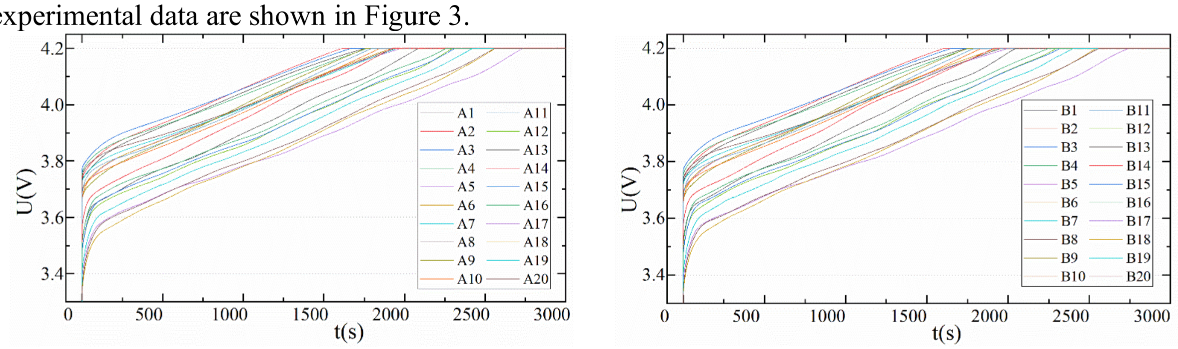


Figure 2. Multi-battery parallel charge/discharge test platform.

To verify the proposed sorting method, decommissioned battery segment voltage charging experiments are designed using the constructed multi-battery parallel charge/discharge test platform. In which, the charging experiments are directly charged on the basis of the existing power, instead of being fully discharged. The two groups of 20 decommissioned power batteries, group A and group B, are designed with the same constant-current and constant-voltage charging experiments, and the experimental data are shown in Figure 3.



(a) Charging voltage curve of group A battery (b) Charging voltage curve of group B battery

Figure 3. Decommissioned power battery charging voltage diagram.

3.2. The analysis results of the relative integral capacity-K-means clustering method sorting

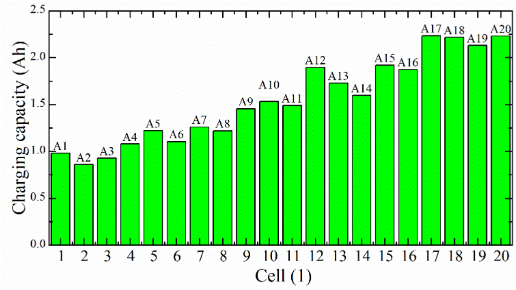
In this research, the starting voltage of the relative segment voltage is 3.5 V, and the termination voltage is 4.2 V. In order to verify the effectiveness of the proposed sorting strategy, the RIC-KMC method and the relative integral capacity classification (RICC) method are applied to sort the 40 retired power batteries, and the sorting results are shown in Figure 4. Figure 4 (a) shows the relative segment voltage charging capacity of 20 decommissioned power batteries in group A. Where the horizontal coordinate represents the battery number and the vertical coordinate represents the segment voltage charging capacity. Figure 4 (b) shows the sorting results of 20 decommissioned power batteries in group A using the RICC method. Figure 4 (c) shows the sorting results of 20 decommissioned power batteries in group A using the RIC-KMC method. Where the horizontal coordinate represents the group number and the vertical coordinate represents the true discharge capacity of the battery. Figure 4 (d) shows the results of the segment voltage charging capacity of 20 decommissioned power batteries in group B. Where the horizontal coordinate indicates the battery number and the vertical coordinate indicates the segment voltage charging capacity. Figure 4 (e) shows the sorting results of 20 decommissioned power batteries in group B using the RICC method. Figure 4 (f) shows the sorting results of 20 decommissioned power batteries in group B using the RIC-KMC method. Where the horizontal coordinate indicates the group number and the vertical coordinate indicates the real discharge capacity of the battery. To provide further verification of the robustness of the algorithm, a group C containing 40 decommissioned power batteries is constructed utilizing a mixture of groups A and B. Figure 4 (g) shows the results of segment voltage charging capacity of 40 decommissioned power batteries in group C. Where the horizontal coordinate indicates the battery number and the vertical coordinate indicates the segment voltage charging capacity. Figure 4 (h) shows the sorting results of 40 decommissioned power batteries in group C using the RICC method. Figure 4 (i) shows the sorting results of 40 decommissioned power batteries in group C using the RIC-KMC method. Where the horizontal coordinate indicates the group number and the vertical coordinate indicates the real discharge capacity of the battery. Figure 4 (j) shows the sorting error of three groups for decommissioned power batteries using two sorting methods. Where the error value is the maximum difference between the capacity of the group contents.

From Figure 4 (a), Figure 4 (d), and Figure 4 (g), the fragment voltage charging capacity is different for different batteries, which shows the difference in the charging acceptance capacity of different batteries in the same fragment voltage interval, which is caused by the internal electrochemical aging of the batteries. From the final sorting results of group A, group B, and group C, both sorting methods can realize the capacity sorting of decommissioned power batteries using the aging characteristics extracted by relative integral capacity. Among them, the maximum capacity difference of the RICC method is 0.108Ah, 0.105Ah, and 0.108Ah for group A, group B, and group C. The maximum capacity difference of the RIC-KMC method for group A, group B, and group C is 0.107Ah, 0.092Ah, and 0.097Ah. RIC-KMC method compared to the RICC method capacity sorting error is reduced by 0.926%, 12.381%, and 10.185% respectively. The accuracy improvement in group A is relatively small, due to significant differences in segment voltage charging capacity in group A, which RICC can capture well. However, the limitations of the RICC method will be manifested when dealing with battery groups with smaller differences in segment voltage charging capacity. In the meanwhile, from the sorting results of mixed group C, with the increase in the number of batteries that are to be sorted, the maximum capacity sorting error does not increase, showing that the method has a certain degree of robustness.

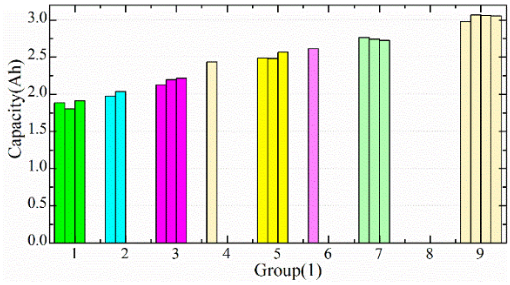
4. Conclusions

To solve the problem of capacity sorting of decommissioned power batteries, this research proposes a relative segment voltage aging characteristic analysis method based on the analysis of the electrochemical aging mechanism of lithium-ion batteries and forms an RIC-KMC capacity sorting method for decommissioned power batteries by combining with the K-means clustering algorithm. The electrochemical aging characteristics of the decommissioned power battery are extracted by means of relative segment voltage. This kind of extraction for aging characteristics extraction method can extract the characteristic parameters that respond to the aging state of lithium-ion batteries at the current stage through the existing charge/discharge data. An improved RIC-KMC method is proposed, based on the constructed dynamic stress aging model, combined with the K-means clustering algorithm. The effectiveness of the proposed RIC-KMC method is verified by using charge and discharge data of three groups of batteries, and the capacity sorting errors are reduced by 0.926%, 12.381%, and 10.185%, respectively. This study provides an effective solution strategy for the capacity sorting problem of the decommissioned power battery for secondary utilization.

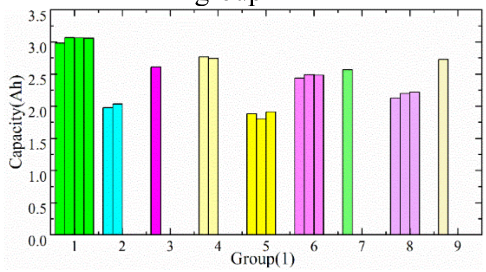
Journal of Physics: Conference Series **2853** (2024) 012057
doi:10.1088/1742-6596/2853/1/012057



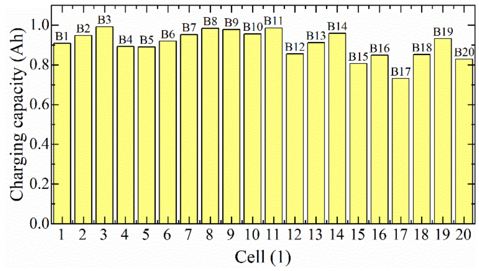
(a) The segment voltage charging capacity of group A



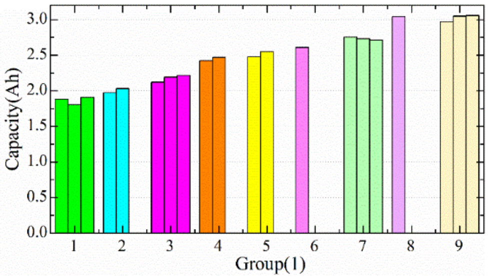
(b) RICC method sorting results for group A



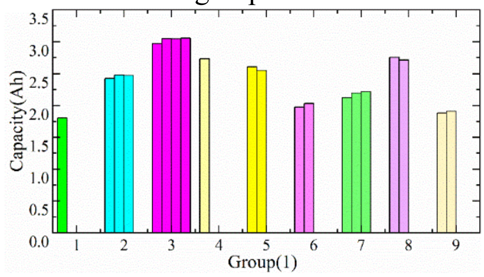
(c) RIC-KMC method sorting results for group A



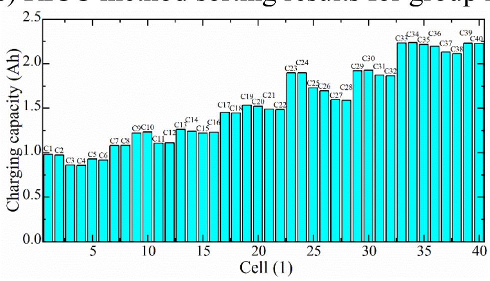
(d) The segment voltage charging capacity of group B



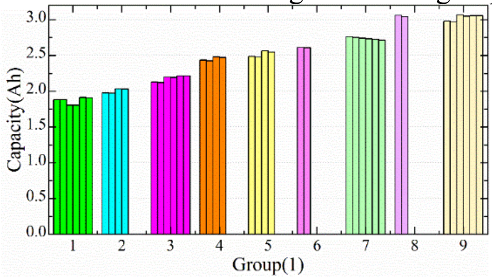
(e) RICC method sorting results for group B



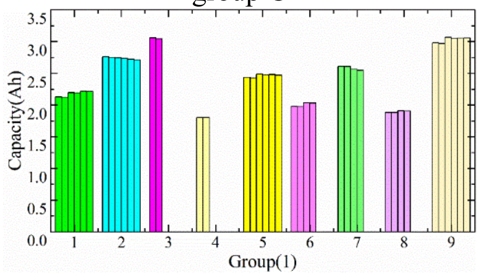
(f) RIC-KMC method sorting results for group B



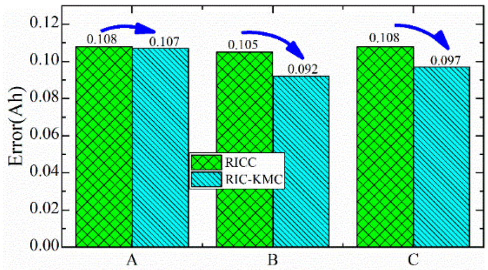
(g) The segment voltage charging capacity of group C



(h) RICC method sorting results for group C



(i) RIC-KMC method sorting results for group C



(j) The maximum capacity error for sorting results

Figure 4. The sorting results of decommissioned power battery capacity.

Acknowledgments
The work is supported by the National Natural Science Foundation of China (No. 62173281, 52377217, U23A20651), Sichuan Science and Technology Program (No. 24NSFSC0024, 23ZDYF0734, 23NSFSC1436), Dazhou City School Cooperation Project (No. DZXQHZ006), Technopole Talent Summit Project (No. KJCRCFH08), and Robert Gordon University.

References

[1] Zhang, C., Y.-X. Tian, and M.H. Han 2022 Recycling mode selection and carbon emission reduction decisions for a multi-channel closed-loop supply chain of electric vehicle power battery under cap-and-trade policy. Journal of Cleaner Production **375** p. 1-16

[2] Zhang, C., H. Li, and Y.X. Tian, 2023 Manufacturer's carbon abatement strategy and selection of spent power battery collecting mode based on echelon utilization and cap-and-trade policy. Computers & Industrial Engineering **177** p. 1-14

[3] Wei, Q., et al. 2023 Spent lithium ion battery (LIB) recycle from electric vehicles: A mini-review. Science of the Total Environment **866** p. 1-15

[4] Khowaja, A., M.D. Dean, and K.M. Kockelman, 2022 Quantifying the emissions impact of repurposed electric vehicle battery packs in residential settings. Journal of Energy Storage **47** p. 1125-1137

[5] Wu, Y.F., et al. 2020 Temporal and spatial analysis for end-of-life power batteries from electric vehicles in China. Resources Conservation and Recycling **155** p. 1-13.

[6] Zhang, L.S., et al. 2022 Revealing the lithium dendrite deposition/dissolution progression based on Monte Carlo method. Journal of Energy Storage **55** p. 1-21

[7] Chen, H.P., et al. 2022 Assessment and management of health status in full life cycle of echelon utilization for retired power lithium batteries. Journal of Cleaner Production **379** p. 1-11

[8] Zhao, S.L. and C.H. 2022 Ma, Research on the coordination of the power battery echelon utilization supply chain considering recycling outsourcing. Journal of Cleaner Production **358** p. 1-21

[9] Yu, H., et al. 2020 Big-Data-Based Power Battery Recycling for New Energy Vehicles: Information Sharing Platform and Intelligent Transportation Optimization. Ieee Access **8** p. 99605-99623

[10] Rufino Junior, C.A., et al. 2023 Towards a business model for second-life batteries-barriers, opportunities, uncertainties, and technologies. Journal of Energy Chemistry **78**: p. 507-525.

[11] Sharma, P. and R.C. Naidu 2023 Optimization techniques for grid-connected PV with retired EV batteries in centralized charging station with challenges and future possibilities: A review. Ain Shams Engineering Journal **14**(7) p. 1132-1146

[12] Azad, A. and H. Shateri 2023 Design and optimization of an entirely hybrid renewable energy system (WT/PV/BW/HS/TES/EVPL) to supply electrical and thermal loads with considering uncertainties in generation and consumption. Applied Energy **336** p. 1-15

[13] Zhou, Z., et al. 2020 A fast screening framework for second-life batteries based on an improved bisecting K-means algorithm combined with fast pulse test. Journal of Energy Storage **31** p. 1-13

[14] Chen, Z.H., et al. 2022 An efficient regrouping method of retired lithium-ion iron phosphate batteries based on incremental capacity curve feature extraction for echelon utilization. Journal of Energy Storage **56** p. 1-21

[15] Wang, L.J., et al. 2022 Efficient and Fast Active Equalization Method for Retired Battery Pack Using Wide Voltage Range Bidirectional Converter and DBSCAN Clustering Algorithm. Ieee Transactions on Power Electronics **37(11)** p. 13824-13833

[16] Yin, H.J., et al. 2023 A two-stage sorting method combining static and dynamic characteristics for retired lithium-ion battery echelon utilization. Journal of Energy Storage **64** p. 1234-1246