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# A Techno-Economic Assessment of Sodium-ion Pouch and Coin Cells for Commercial Applications[#]

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**ABSTRACT**

Sodium-ion batteries are becoming prominent among next-generation energy storage technologies due to their abundant raw materials and seamless integration with existing lithium-ion battery manufacturing units. Sodium-ion batteries are anticipated to be deployed in microgrid applications and low-speed electric vehicles. A techno-economic analysis of these batteries is required to assess their potential from a cost and performance perspective. In this work, the modelling framework is developed to analyse the cost of the sodium-ion pouch and coin cell using the cell-level parameters. The numerical simulation is performed for the coin cell under various operating conditions to validate its performance with the experimental results. The electrode surface area is calculated using the electrochemical model and parameter estimation technique to design the pouch cell. The total cost of the cell is calculated by considering material, process, and overhead costs. The raw material cost for which the market price is unavailable is estimated using the cost estimation model. The study shows that the sodium-ion coin cell costs 209 $/kWh, and the pouch cell costs 240 $/kWh. The cost breakdown of various cell components is analysed. The study is further extended to account for full-fledged bulk production, discounting the process and overhead costs. It can be inferred from the study that the cost of the cathode is comparatively higher among cell materials, underscoring the necessity to develop cost-effective and high-capacity cathode material for sodium-ion batteries.

**Keywords:** Sodium-ion batteries, physics-based model, PyBaMM, cost analysis, BatPaC

**NOMENCLATURE**

| | |
|---|---|
| *Abbreviations* | |
| BatPaC | Battery Performance and Cost |
| HC | Hard carbon |
| LIB | Lithium-ion battery |
| NVPF | Sodium vanadium fluorophosphate |
| P2D | Pseudo-2-dimensional |
| PVDF | Polyvinylidene fluoride |
| PyBaMM | Python Battery Mathematical Modelling |
| SIB | Sodium-ion battery |
| *Symbols* | |
| A | Electrode surface area |
| L | Cell length |
| l | Electrode length |
| T | Cell thickness |
| W | Cell width |
| w | Electrode width |
| *Subscripts* | |
| c | Cell |
| n | Negative electrode |
| p | Positive electrode |
| s | Separator |

## 1. INTRODUCTION

The continuous growth in global energy demand has increased environmental concerns, necessitating a shift towards renewable energy resources [1]. These resources are clean and abundantly available but require efficient harvesting techniques due to their intermittent nature. Several energy storage technologies exist, among which battery storage stands out for its efficiency. Lithium-ion rechargeable batteries have gained significant attention because of their high energy and power density. However, these batteries are facing higher price fluctuations due to their scarcity of raw materials, leading to supply chain constraints [2]. There has been a 5.6 times increment in the cost of the battery grade $Li_2CO_3$ raw material from 2019 to 2022, marking significant price volatility [3]. Installing these batteries in large-scale applications such as microgrids would result in high initial investment and limitation in the supply of raw materials. Therefore, developing economical, sustainable novel energy storage technologies is required to meet future demands.

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Sodium-ion batteries (SIBs) share a similar architecture to LIBs and are paving their way into next-generation energy storage technology. The noteworthy advantage of these batteries comes from their abundant raw material and drop-in-replacement to the existing LIB manufacturing units [4]. Sodium-ion batteries are anticipated to have applications in the microgrids industry and low-speed electric vehicles [5]. The SIBs are being developed to enhance their performance, achieve economic viability and be free from toxic materials such as cobalt for commercialisation [6]. The practical deployment of SIBs can be directly linked to the chemical composition, cycle life, safety and cost. Various modelling approaches, such as the Battery Performance and Cost (BatPaC) model, TIAX model, and simplified energy-cost models, have been proposed in the literature [5]. Among these, the BatPaC model is frequently used to calculate the battery pack manufacturing for the grid and electric vehicles [7]. Several studies have been conducted on the cost, resource and environmental impact of the SIBs to analyse the competitiveness and future perspective [5]. These analyses concluded that optimising the electrochemical performance and developing higher specific capacity materials will make SIBs an attractive option and viable.

Many of these models have wide applications and contributions in industry and academics. These models reveal the trade-offs between the battery chemistries and guide the development of novel materials. The ongoing research and development on the SIBs has minimised the cost gap between the LIBs and SIBs [8]. Baumann et al. [9] investigated and screened 42 different SIB cathode-active materials to benchmark them with the LIBs, which showed that SIBs have a promising future and energy density is a crucial factor in determining the potential impact of these batteries. The SIBs have become a complementary technology to the LIBs and are anticipated to have their deployment in large-scale applications. There are several studies performed on the state-of-the-art SIBs to analyse their reliability and economic viability using hypothetical parameters [5], publicly available parameters [10], stoichiometric calculations and laboratory data [9], exchanging the lithium with sodium along with current collector foil [2], assessment using the technical data sheets from the SIB manufacturer [11].

This study is the first attempt to conduct a techno-economic analysis of the SIB using cell-level parameters. The BatPaC model is used to design the 20 Ah sodium-ion pouch cell and the quantity of material required. The cost assessment is conducted for the battery materials and their impact on the total battery cost. The cost of the SIBs is discussed for the bulk manufacturing units, considering discounted process and overhead costs.

## 2. MODELLING AND CELL DESIGN

The early commercialisation stage of SIB packs necessitates an analysis of cost-effectiveness, market competitiveness, investment decisions, and sustainability. The SIB packs are complex systems with components such as cells, modules, bus bars, and thermal and battery management systems. The sodium-ion cells are the building blocks of these battery packs and have a significant role in determining the performance and cost of these battery packs. Therefore, this study focuses on the cell level, assuming all cells in the battery pack behave similarly.

### *2.1 Cell design*

The sodium-ion cell used in this study has a hard carbon (HC) anode and sodium vanadium fluorophosphate $Na_3V_2(PO_4)_2F_3$ (NVPF) cathode electrodes with the separator placed between them. The entire setup is soaked in the 1M sodium hexafluorophosphate ($NaPF_6$), ethylene carbonate and propylene carbonate ($EC_{0.5}$:$PC_{0.5}$) (w/w) electrolyte. The cell capacity depends on the active material quantity, specific capacity, mass loading and electrode surface area. Different cell designs, such as coin, pouch, and prismatic cells, are available in the market. The current economic analysis study is focused on sodium-ion coin and pouch cells. The battery modelling package Python Battery Mathematical Modelling (PyBaMM), which comprises various physics-based models, is used in this study [12]. The physics-based electrochemical pseudo-2-dimensional (P2D) model is used to analyse the concentration and potential variation in the cell under different operating conditions. The initial study is performed on the 2.9 mAh coin cell and later extended to the 20 Ah pouch cell for cost estimation. The numerical simulation results are validated with the experimental results of Chayambuka et al. [13].

A pouch cell comprises several bi-cell layers with sufficient material to make two unit cells, i.e., the current collectors coated with the electrode material on both sides with two separators. Fig. 1 shows the schematic representation of the pouch cell with stacked bi-cell layers, cell casing and terminal tabs. Getting the precise dimension of the sodium-ion pouch cell is not possible at this stage. Therefore, the sodium-ion pouch cell capacity is determined by varying the electrode surface area, and other properties of active material, coating thickness and porosity are similar to that of the coin cell. The estimated electrode surface area is later used as input for the BatPaC model to design the pouch cell.

The total number of the bi-cell layers and pouch cell thickness are calculated using the BatPaC model. The electrode length ($l_p$) is fixed to 225 mm, and the electrode length to width ($l_p/w_p$) ratio is fixed to 1.5 for the positive electrode, and subsequent cell dimensions are calculated.

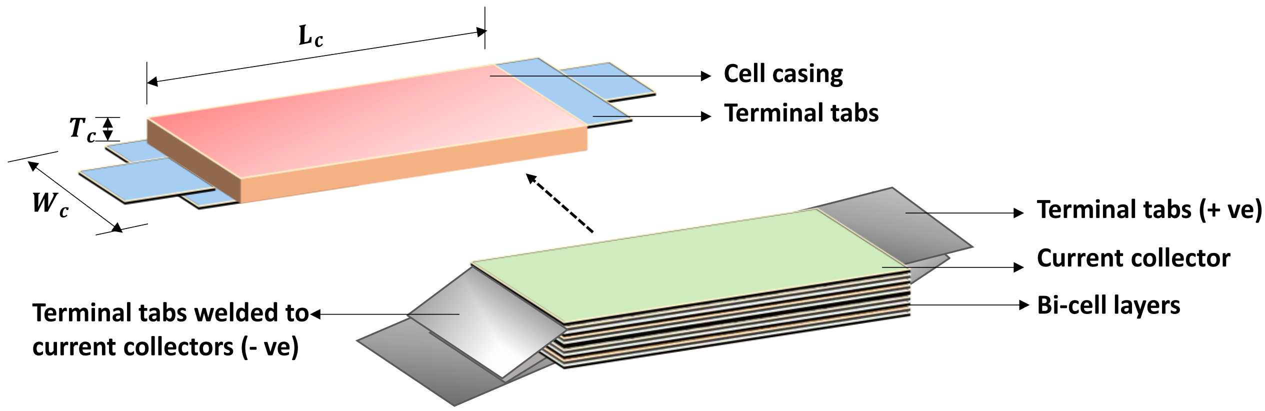


*Fig. 1 Schematic representation of sodium-ion pouch cell and bi-cell layers*

*2.2 Cost analysis*

The cell cost is calculated from the numerical simulation and BatPaC model design inputs. The costs associated with installation, operation, and manufacturing are unavailable as SIBs do not have a fully-fledged manufacturing industry, for which the values are referred from the literature [14]. The cost estimation model calculates the price of the cathode material and the electrolyte [9,15].

The raw material and fabrication costs significantly affect the electrode price. The electrode mass fraction of the active material generally varies between 60% and 90%, along with a proportionate mixture of the conductive additives and binders [16]. The NVPF is a polyanionic compound notable for its structural stability, higher operating potential and specific capacity [17]. The carbon-based conductive additive is used to enhance electrode conductivity, and the polyvinylidene fluoride (PVDF) binder is used to improve the mechanical stability of both electrodes [18]. The cathode with 80 wt.% NVPF, 10 wt.% PVDF binder, and 10 wt.% conductive additive is used in this study [19]. The HC is a non-graphitisable amorphous carbon consisting of pores and crosslinked turbostratic nanodomains manufactured with carbon-rich precursor materials. The anode used in this study contains 85 wt.% HC, 8 wt.% PVDF binder, and 7 wt.% carbon conductive additive [20]. The HC cost is assumed to be 6.81 $/kg obtained from the coconut shell as a raw material [11].

In addition to the electrodes and electrolytes, the cell has various components, such as current collectors, separators, and cell casing. The aluminium is used as the current collector, terminal tabs, and cell casing as it does not alloy with sodium at the lower voltage, unlike lithium in LIBs, and it is less dense and economical, reducing the weight and cost of the battery offering a significant advantage for SIBs. The cost associated with precursor materials for the cost estimation model is obtained from the chemical suppliers [21]. The total cost of the cell in this study is calculated as the summation of the material cost, process cost and overhead cost as proposed by Patry et al. [14]. The process cost is associated with electrode manufacturing, cell stacking and assembly. The overhead cost is associated with the licenses, warranty, financial charges, research, and development. However, SIBs are currently in the early stages of commercialisation and still need to establish manufacturing units. The discount rate is considered for the process and overhead cost to account for the average annual growth of manufacturing plant units [5]. The analysis is performed with and without discount rates to assess the cost variation in bulk manufacturing over the period. The process cost is 69 $/kWh and 44 $/kWh for 50 µm and 100 µm anode thickness, respectively, for LIBs [5]. The anode used in this study is 64 µm, for which the process cost is assumed as 58 $/kWh accordingly.

## 3. RESULTS AND DISCUSSIONS

This section consists of numerical simulation validation with experimental results using the PyBaMM package. The cost of the materials considered for this study is based on the bulk manufacturing units rather than the lab scale, as later would result in higher costs [10]. The cost distribution of the cell materials and the process and overhead expenses for SIBs are analysed. The scope of improvement to reduce the total cost of the cell is discussed for the future perspective.

The numerical simulation and validation with experimental results of the coin cell are performed using the P2D model [13]. The accuracy of the results is assessed with terminal voltage vs cell capacity at different C-rates of 0.1 C, 1 C and 1.4 C, as shown in Fig. 2. The model's performance at different C-rates is quantified with root mean square error at 0.1 C, 1 C, and 1.4 C are 0.039 V, 0.035 V, and 0.090 V, respectively.

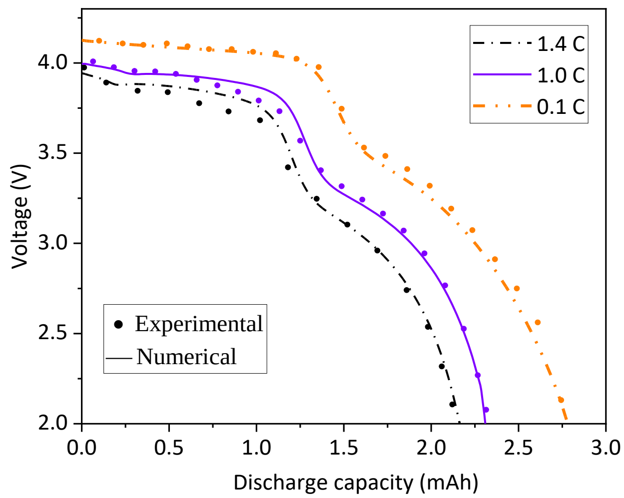


*Fig. 2 Numerical simulation results validation with experimental results*

A comprehensive mass balance is required to ascertain the quantities of materials used in cell production. The electrode surface area for the 20 Ah pouch cell is 2.18 m$^2$, calculated from the parameter estimation technique. The pouch cell has 28 bi-cell layers enclosed in an aluminium casing of thickness 100 µm and has terminal tabs for charge transfer. The negative electrode is designed with an excess length and width of 2 mm to ensure the complete overlap between the electrodes, and the separator is provided with an excess length of 4 mm and 2 mm to prevent the electrodes from short-circuiting. The pouch cell dimensions are calculated using the BatPaC model, as in Table 1. The dimensions of the coin cell are referred from the experimental study conducted by Chayambuka et al. [22].

*Table 1 Sodium-ion pouch cell dimensions*

| **Parameter** | **Value** |
|---|---|
| Cell length $(L_c)$ | 230 mm |
| Cell width $(W_c)$ | 152 mm |
| Cell thickness $(T_c)$ | 10 mm |
| Positive electrode surface area $(A_p)$ | 2.18 m$^2$ |
| Negative electrode surface area $(A_n)$ | 2.20 m$^2$ |
| Separator surface area $(A_s)$ | 2.24 m$^2$ |

The mass loadings on the electrodes are 12 mg/cm$^2$ for the cathode and 6 mg/cm$^2$ for the anode [22]. The total amount of active material required is calculated from the electrode surface area and respective mass loadings. The electrolyte cost is calculated based on the stochiometric ratios of the solvent and salt required per

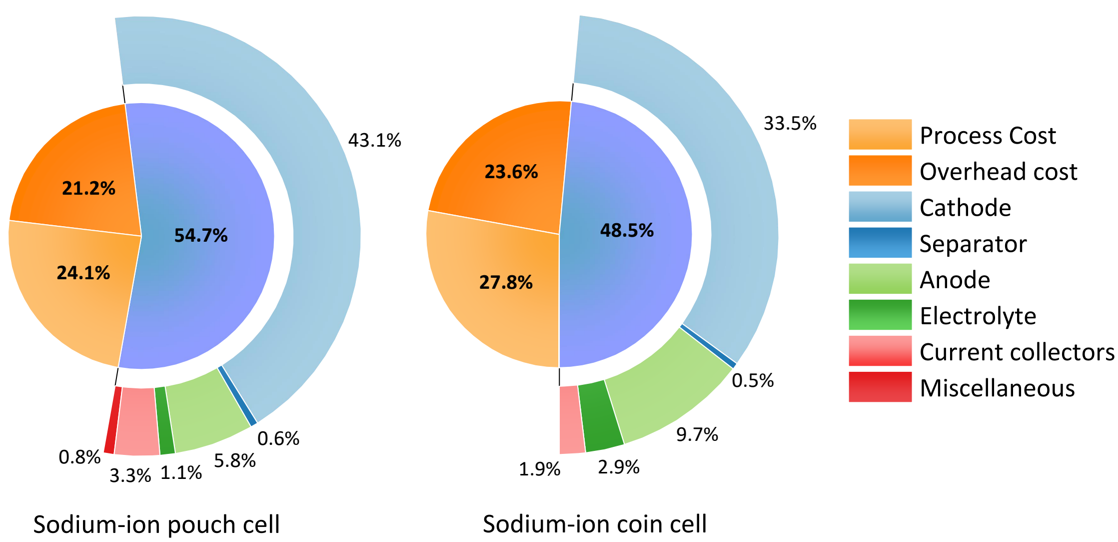


*Fig. 3 Cost distribution of materials, process and overhead costs for the sodium-ion pouch and coin cell*

litre. The total amount of the electrolyte in the cell is calculated from each electrode's total electrolyte volume fraction. The sodium-ion pouch and coin cells cost 240 $/kWh and 209 $/kWh, respectively. The pouch cell is 13.3% more expensive than the coin cell. The cost distribution of the sodium-ion pouch and coin cell is shown in Fig. 3. The total material cost accounts for 54.7% and 48.5%, having a maximum contribution from the cathode with 43.1% and 33.5% for the pouch and coin cell, respectively. From the cost distribution, it can be inferred that developing a higher-capacity cathode could potentially reduce the cost of the SIBs.

The cell level cost of the LIBs in the market is less than 150 $/kWh [23]. The cost calculated in this study for the SIBs is substantially higher than that of the LIBs, as they have yet to have a full-fledged market. The cost associated with the process, overhead, and cathode materials has resulted in higher costs, likely to be reduced when these materials are bulk manufactured on an industry scale. The analysis is further extended to assess the cost for the coming years to account for the discount rates of 0.396 and 0.629 for the process and overhead expenses, respectively [5]. After the discount rate, the sodium-ion pouch and coin cell costs are 187 $/kWh and 155 $/kWh, a 22% and 25.8% drop in the total cost, respectively. Commercialising these materials on a large scale could reduce the overall cost of SIBs. The larger ionic radii, higher atomic mass, and redox potential are concerns with SIBs, underscoring their shortcomings compared to LIBs. Nevertheless, with recent advancements and ongoing research, these batteries can be anticipated to have utility in large-scale applications. Various companies such as HiNa, Altris, CATL, and Faradion are actively involved in commercialising SIBs for the future [8].

## 4. CONCLUSIONS

Techno-economic analysis was conducted on the sodium-ion pouch and coin cell. The PyBaMM package is employed to validate the numerical simulation with the experimental results for the coin cell. The parameter estimation is performed to calculate the electrode surface area for the 20 Ah pouch cell. The BatPaC model is used to design the pouch cell using the cell level parameters that consist of 28 bi-cell layers with 230 x 152 x 10 mm dimensions. The cost analysis is performed for pouch and coin cells considering material, process, and overhead costs. The cost of the pouch cell is 13% higher than that of the coin cell. The cathode cost is comparatively higher than other materials. The battery cost may be reduced for bulk industrial production, which could be inferred from the study, considering the discounted process and overhead cost. Although the current analysis shows that the overall cost of SIB is higher than that of LIB, it is imperative to consider that LIBs have matured technology and wide applications.

In contrast, SIBs are still in the early stages and have the notable advantage of seamless integration compatibility with LIB manufacturing units, which minimises the initial investment and reconfiguration of new machinery, facilitates production's easy adoption, and reduces cell costs. The development of higher specific capacity electrodes at low cost may reduce the cost of these batteries, making them an attractive alternative option to the existing LIBs.

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## REFERENCE

[1] Hannah Ritchie PR and MR. Energy Production and Consumption 2020. https://ourworldindata.org/energy-production-consumption (accessed March 25, 2024).

[2] Vaalma C, Buchholz D, Weil M, Passerini S. A cost and resource analysis of sodium-ion batteries. Nat Rev Mater 2018;3:18013.

[3] Survey USG. Mineral commodity summaries 2024. 2024. https://doi.org/10.3133/mcs2024.

[4] Chayambuka K, Mulder G, Danilov DL, Notten PHL. From Li-Ion Batteries toward Na-Ion Chemistries: Challenges and Opportunities. Adv Energy Mater 2020;10:1–11.

[5] Schneider SF, Bauer C, Novák P, Berg EJ. A modeling framework to assess specific energy, costs and environmental impacts of Li-ion and Na-ion batteries. Sustain Energy Fuels 2019;3:3061–70.

[6] Tarascon JM. Na-ion versus Li-ion Batteries: Complementarity Rather than Competitiveness. Joule 2020;4:1616–20.

[7] Knehr K, Kubal J, Nelson P, Ahmed S. Battery Performance and Cost Modeling for Electric-Drive Vehicles (A Manual for BatPaC v5.0). Argonne, IL (United States): 2022.

[8] Zuo W, Innocenti A, Zarrabeitia M, Bresser D, Yang Y, Passerini S. Layered Oxide Cathodes for Sodium-Ion Batteries: Storage Mechanism, Electrochemistry, and Techno-economics. Acc Chem Res 2023;56:284–96.

[9] Baumann M, Häringer M, Schmidt M, Schneider L, Peters JF, Bauer W, et al. Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials. Adv

Energy Mater 2022;12.
[10] Innocenti A, Beringer S, Passerini S. Cost and performance analysis as a valuable tool for battery material research. Nat Rev Mater 2024;9:347–57.
[11] Peters J, Peña Cruz A, Weil M. Exploring the Economic Potential of Sodium-Ion Batteries. Batteries 2019;5:10.
[12] Sulzer V, Marquis SG, Timms R, Robinson M, Chapman SJ. Python Battery Mathematical Modelling (PyBaMM). J Open Res Softw 2021;9:14.
[13] Chayambuka K, Mulder G, Danilov DL, Notten PHL. Physics-based modeling of sodium-ion batteries part II. Model and validation. Electrochim Acta 2022;404:139764.
[14] Patry G, Romagny A, Martinet S, Froelich D. Cost modeling of lithium-ion battery cells for automotive applications. Energy Sci Eng 2015;3:71–82.
[15] Nelson PA, Bloom KG, I Dees DW. P.A. Nelson, K.G. Gallagher, I. Bloom, D.W. Dees, Modeling the performance and cost of lithium-ion batteries for electric-drive vehicles, Electrochemical Energy Storage Theme, Chemical Sciences and Engineering division, Argonne National Laboratory, Septem. Argonne Natl Lab 2011:121.
[16] Broux T, Bamine T, Simonelli L, Stievano L, Fauth F, Ménétrier M, et al. V IV Disproportionation Upon Sodium Extraction From Na 3 V 2 (PO 4 ) 2 F 3 Observed by Operando X-ray Absorption Spectroscopy and Solid-State NMR. J Phys Chem C 2017;121:4103–11.
[17] Xiong H, Liu Y, Shao H, Yang Y. Understanding the electrochemical mechanism of high sodium selective material Na3V2(PO4)2F3 in Li+/Na+ dual-ion batteries. Electrochim Acta 2018;292:234–46.
[18] Hein S, Danner T, Westhoff D, Prifling B, Scurtu R, Kremer L, et al. Influence of Conductive Additives and Binder on the Impedance of Lithium-Ion Battery Electrodes: Effect of Morphology. J Electrochem Soc 2020;167:013546.
[19] Broux T, Bamine T, Fauth F, Simonelli L, Olszewski W, Marini C, et al. Strong Impact of the Oxygen Content in Na 3 V 2 (PO 4 ) 2 F 3– y O y (0 ≤ y ≤ 0.5) on Its Structural and Electrochemical Properties. Chem Mater 2016;28:7683–92/
[20] Irisarri E, Amini N, Tennison S, Ghimbeu CM, Gorka J, Vix-Guterl C, et al. Optimisation of Large Scale Produced Hard Carbon Performance in Na-Ion Batteries: Effect of Precursor, Temperature and Processing Conditions. J Electrochem Soc 2018;165:A4058–66.
[21] Shanghai Metals Market,. SMM Spot Met Prices 2024. https://www.metal.com (accessed May 29, 2024).
[22] Chayambuka K, Jiang M, Mulder G, Danilov DL, Notten PHL. Physics-based modeling of sodium-ion batteries part I: Experimental parameter determination. Electrochim Acta 2022;404:139726.
[23] Liu J, Xiao J, Yang J, Wang W, Shao Y, Liu P, et al. The TWh challenge: Next generation batteries for energy storage and electric vehicles. Next Energy 2023;1:100015.