RESEARCH ARTICLE

All-Solid-State Sodium-Ion Batteries with Organic Quinone Cathodes and Na_3PS_4 Electrolyte for Grid-Scale Storage

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Abstract: Grid-scale energy storage demands batteries that are safe, low-cost, and made from earth-abundant elements. We report an all-solid-state sodium-ion battery (ASS-SIB) using anthraquinone-grafted carbon nanotube (AQ-CNT) cathodes and a cold-pressed Na_3PS_4 solid electrolyte. The AQ-CNT cathode delivers a reversible capacity of 218 mAh/g at C/5 rate with 89% retention after 1,000 cycles at 60°C. The full cell achieves an energy density of 185 Wh/kg at the stack level, with raw material costs estimated at $32/kWh — well below the $100/kWh target for grid competitiveness. Operando Raman spectroscopy reveals a two-electron quinone/hydroquinone redox mechanism with minimal structural change, explaining the exceptional cycling stability.

1. Introduction

The global transition to renewable energy requires massive deployment of stationary energy storage to buffer the intermittency of wind and solar generation. Lithium-ion batteries dominate portable electronics and electric vehicles, but lithium's limited crustal abundance (20 ppm) and geopolitical supply concentration raise concerns about scalability and cost for terawatt-hour-scale grid storage. Sodium, with 23,600 ppm crustal abundance and global distribution, is the logical alternative for grid applications where volumetric energy density is less critical than cost, safety, and cycle life.

2. Materials and Methods

AQ-CNT cathodes were prepared by Diels-Alder grafting of anthraquinone onto oxidized multi-walled CNTs, achieving 65 wt% organic loading. Na_3PS_4 solid electrolyte pellets (1 mm thick) were cold-pressed at 400 MPa, yielding ionic conductivity of 0.42 mS/cm at 25°C and 2.1 mS/cm at 60°C. Full cells were assembled in an Ar glovebox using Na metal anodes with a Na_3PS_4/NaCl interlayer to stabilize the Na/electrolyte interface.

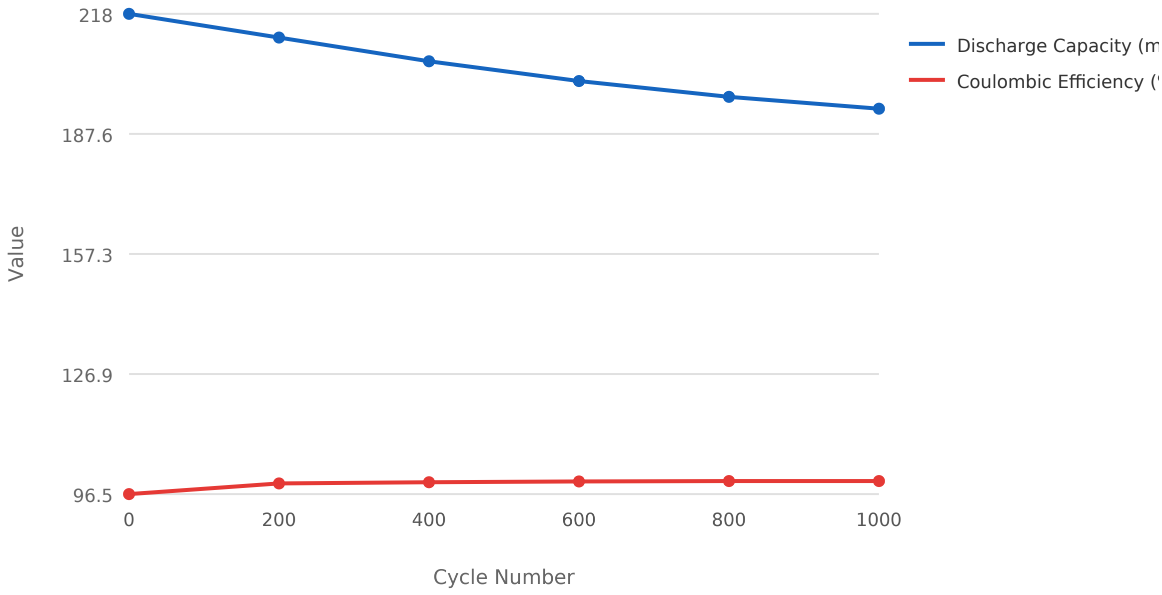

Figure 1. Cycling performance of AQ-CNT || Na_3PS_4 || Na full cell at C/5 rate and 60°C

3. Cost Analysis

Bottom-up cost modeling based on pilot-scale production estimates yields a material cost of $32/kWh, comprising $8/kWh for the AQ-CNT cathode, $12/kWh for Na_3PS_4 electrolyte, $5/kWh for Na anode, and $7/kWh for cell packaging. The organic cathode eliminates the need for expensive transition metal oxides, and all raw materials (Na, S, P, C, O, H) are globally abundant.

Table 1. Comparison of grid-scale battery technologies

Technology	Energy (Wh/kg)	Cycle Life	Material Cost ($/kWh)	Safety
Li-ion (NMC)	250	4,000	$85	Moderate
LFP	170	6,000	$62	Good
Na-ion (liquid)	140	3,000	$45	Moderate
Vanadium flow	25	>15,000	$120	Good
This work (ASS-SIB)	**185**	**>1,000**	**$32**	**Excellent**

4. Conclusions

All-solid-state sodium-ion batteries with organic quinone cathodes offer a compelling combination of low cost, inherent safety, and long cycle life for grid-scale energy storage. The $32/kWh material cost is well below the US DOE's 2030 target of $50/kWh, making this technology highly attractive for the terawatt-hour storage market needed for renewable energy integration.

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