Transport-Controlled Sodium–Polysulfide Flow Batteries for Reliable, Low-Cost Long-Duration Grid Storage

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U.S. Department of Energy

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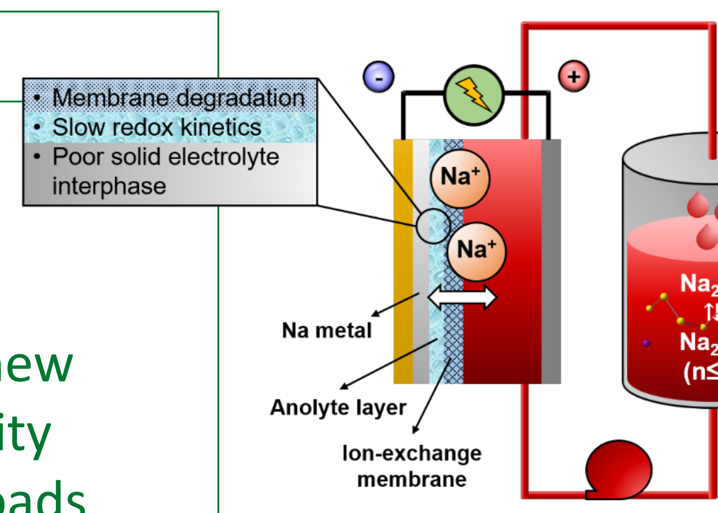
PROJECT PROFILE

Topic: Long-duration energy storage – Flow batteries| Vertical: Materials and Systems Innovation

Strategic Pathway: Grow the grid through new storage technologies; Optimize grid reliability through durable storage; Stabilize critical loads through dispatchable backup storage

Project start and finish: FY25-FY26



Anode half reaction:

$$Na^+ + e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} Na$$

Cathode half reaction:

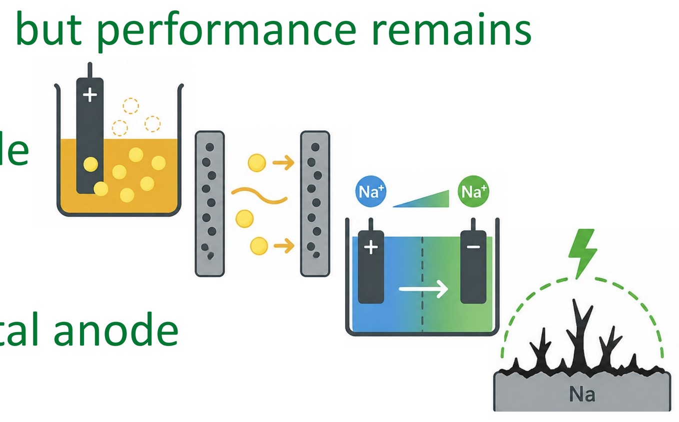
$$(x+1)Na_2S_x - 2e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} xNa_2S_{(x+1)} + 2Na^+$$

PROBLEM

Background: Grid-scale storage needs technologies that are affordable, reliable, safe, and scalable. Vanadium flow batteries depend on >$300 /m² Nafion, exceeding 40 % of system cost. Vanadium availability is restricted domestically. This keeps LCOS well above the 5 ¢/kWh-cycle target.

Sodium-polysulfide flow batteries are attractive because they use earth-abundant active materials and decouple energy from power, but performance remains constrained by four coupled losses:

- incomplete polysulfide utilization at the cathode
- species crossover through the separator
- transport imbalance between two tanks
- sluggish/unstable Na^0/Na^+ exchange at the metal anode



Solving only one of these bottlenecks is not enough; the full stack must be engineered as an ion-transport problem.

APPROACH

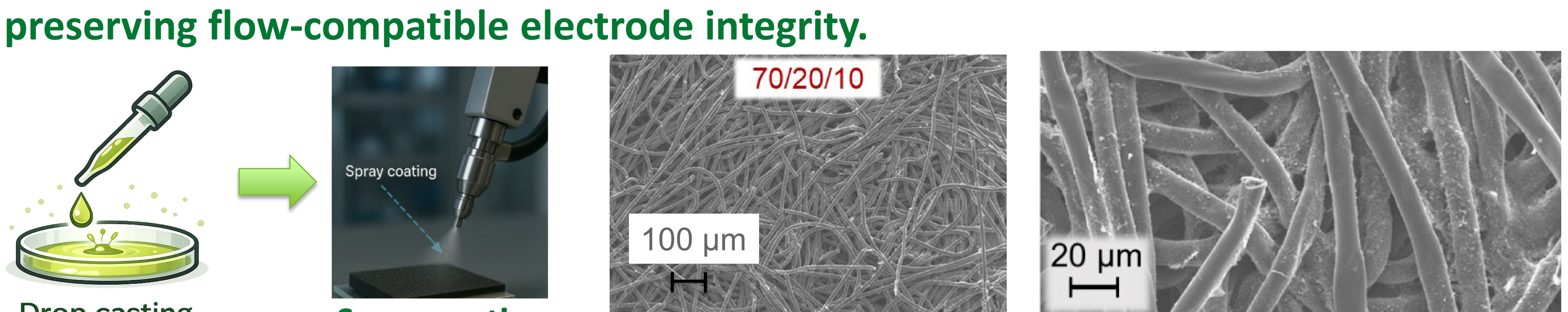
Hypothesis: Na–S flow batteries can be improved by controlling transport at each interface, not by optimizing a single component in isolation.

Solution: Develop **membrane-electrode assemblies (MEAs)** that enables controlled transport with cost-effective solutions

Approach: Address coupled bottlenecks through four coordinated strategies: (I) binder-stabilized carbon cathode hosts, (II) ionic-strength-balanced electrolytes, (III) PFAS-free membrane functionalization, and (IV) cation-diffusive carbon interlayers at the Na anode.

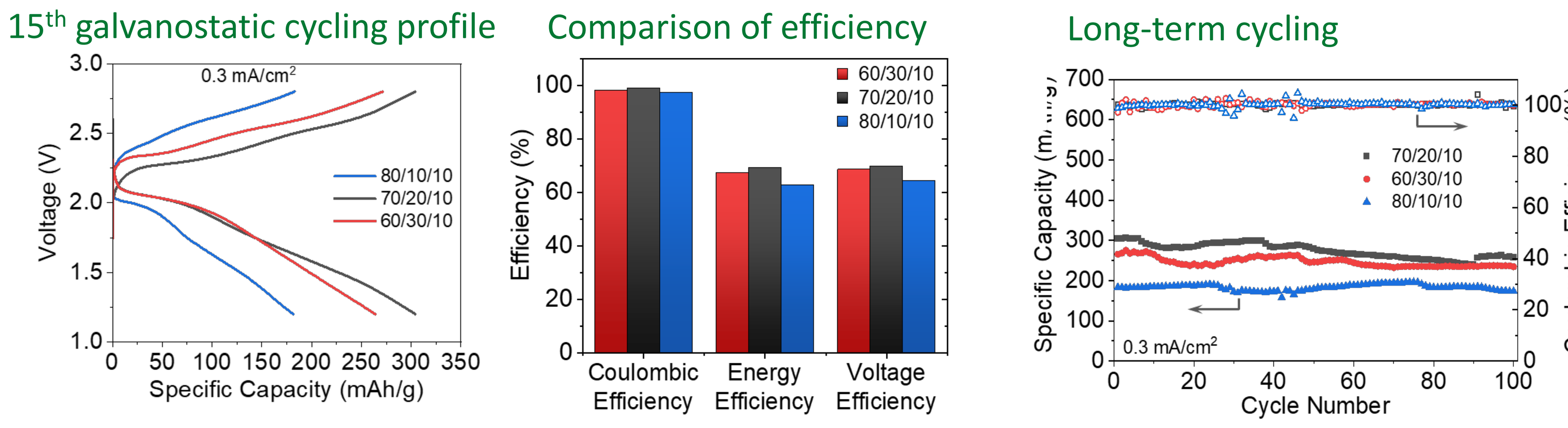
Results Card 1 - Catholyte utilization

Design rule 1: Optimized CNF/CB/binder architecture increases sulfur utilization while preserving flow-compatible electrode integrity.



CNF/Carbon black/Na-CMC (Sodium carboxymethylcellulose)

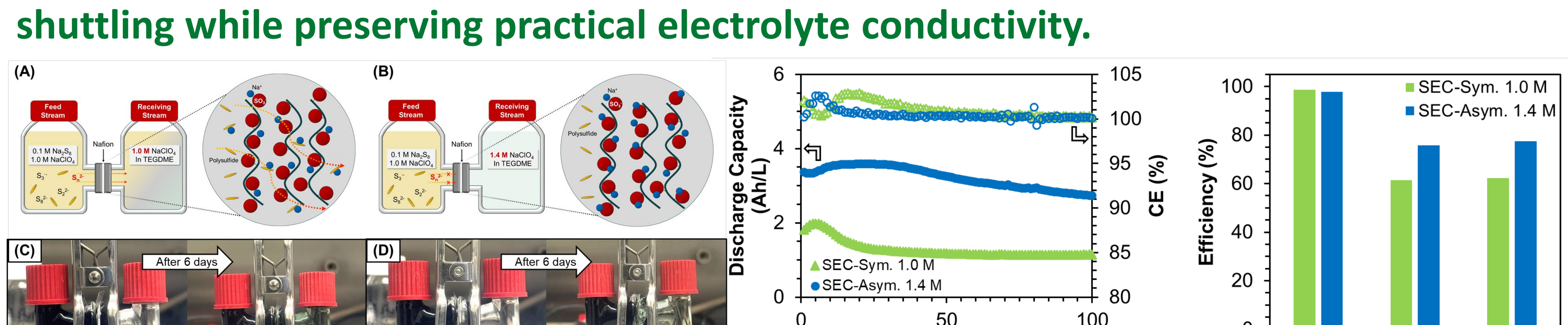
15th galvanostatic cycling profile | Comparison of efficiency | Long-term cycling



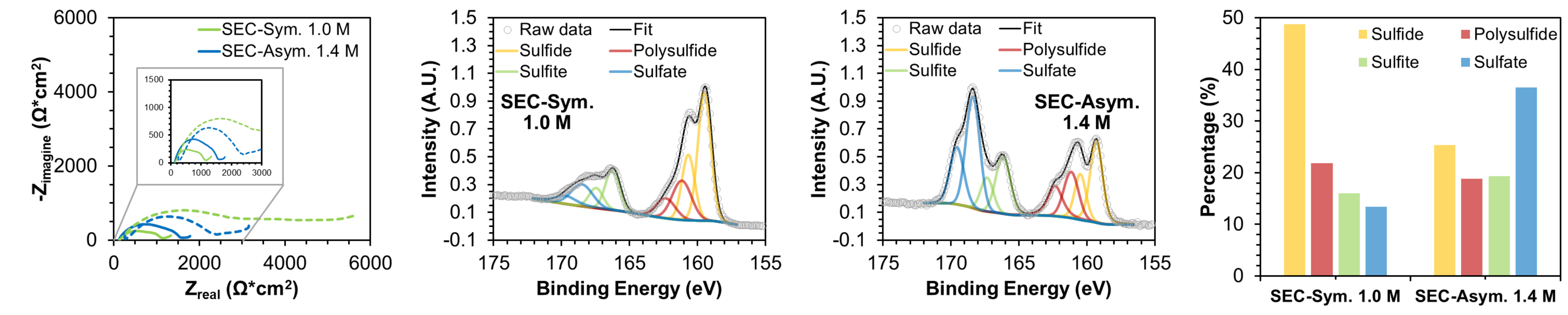
- Optimized 70/20/10 CNF/CB/Na-CMC composite on carbon paper gave the best balance of conductivity, binder distribution, porosity, and stability.
- **Mechanism:** CB improves redox kinetics; CNFs provide conductive pathways; Na-CMC helps stabilize the composite and improve cycling.

Results Card 2 - Electrolyte ionic-strength control

Design rule 2: Balancing anolyte/catholyte ionic strength suppresses polysulfide shuttling while preserving practical electrolyte conductivity.



- Polysulfide crossover reduced with anolyte contains higher salt concentrations;
- Full-cell demonstration showed better discharge capacity, energy/voltage efficiency, and improved capacity retention using the SEC-Asym. design.



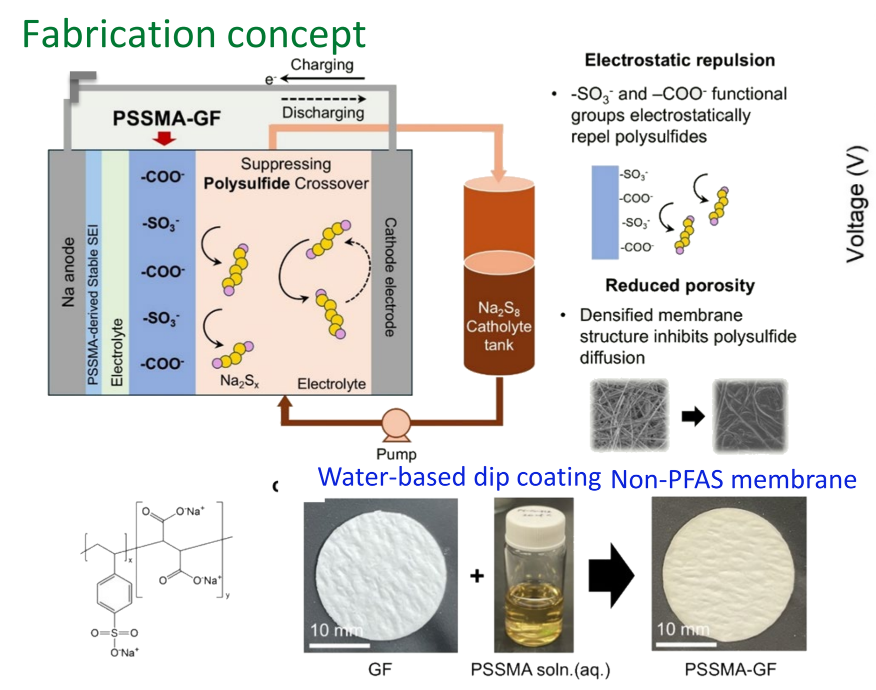
- Post-cell EIS and XPS confirm that the 1.4 M SEC-Asym electrolyte suppresses resistance growth and reduces polysulfide shuttling products from 70.61% to 44.19%.

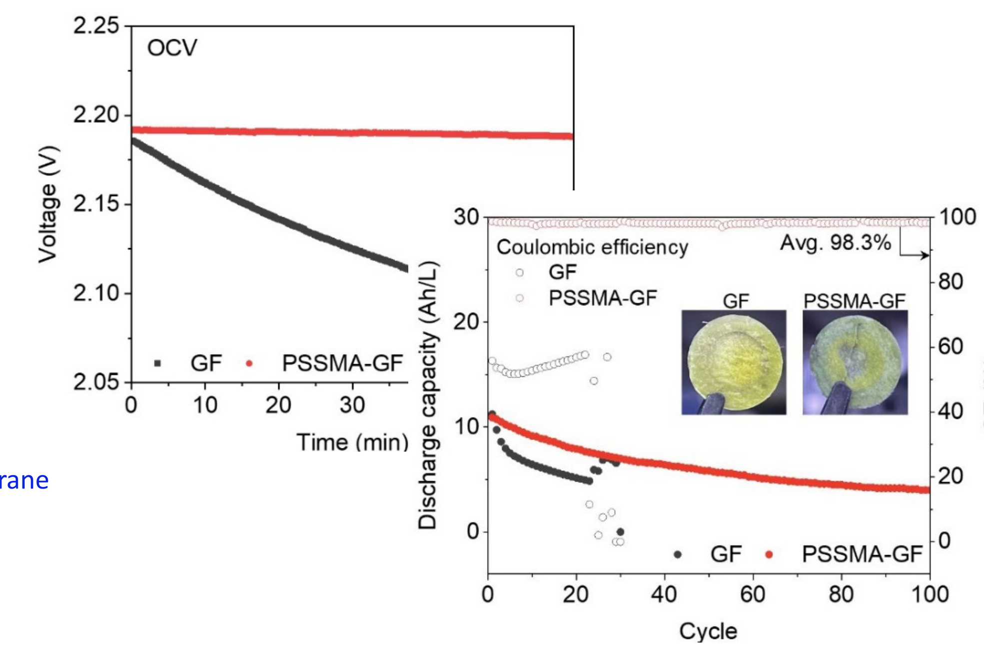
Mechanism: Raise salt concentration in anolyte (governed by ionic-strength) reduces polysulfide shuttling, limits Na parasitic reactions, and preserves interfacial kinetics.

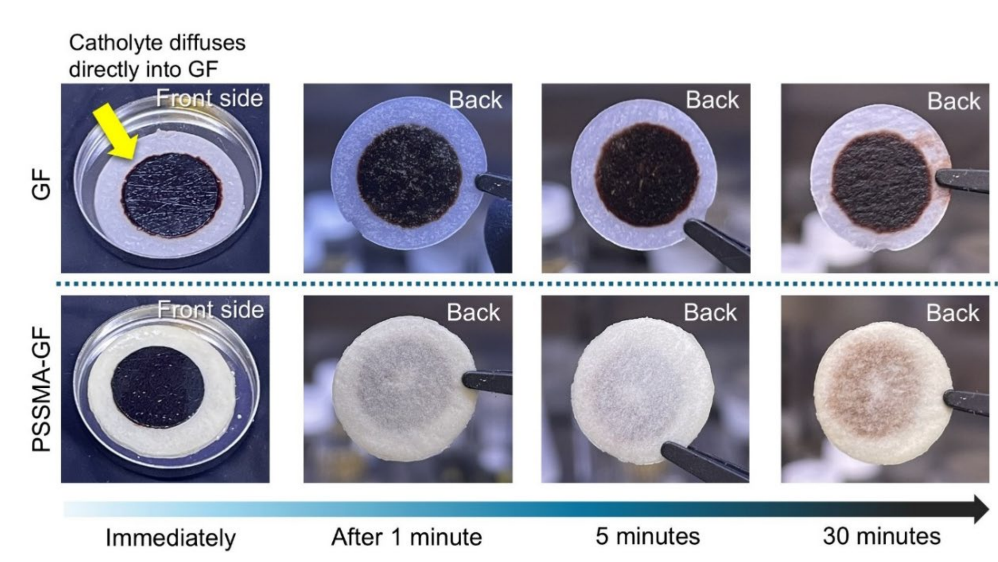
Results Card 3 - PFAS-free separator selectivity

Design rule 3: Oxyanion-functionalized porous separators electrostatically repel polysulfides while maintaining flow-compatible ion transport.

Fabrication concept







PSSMA-GF converts low-cost glass fiber into a selective, PFAS-free separator, raising Coulombic efficiency to 98.3% and suppressing self-discharge.

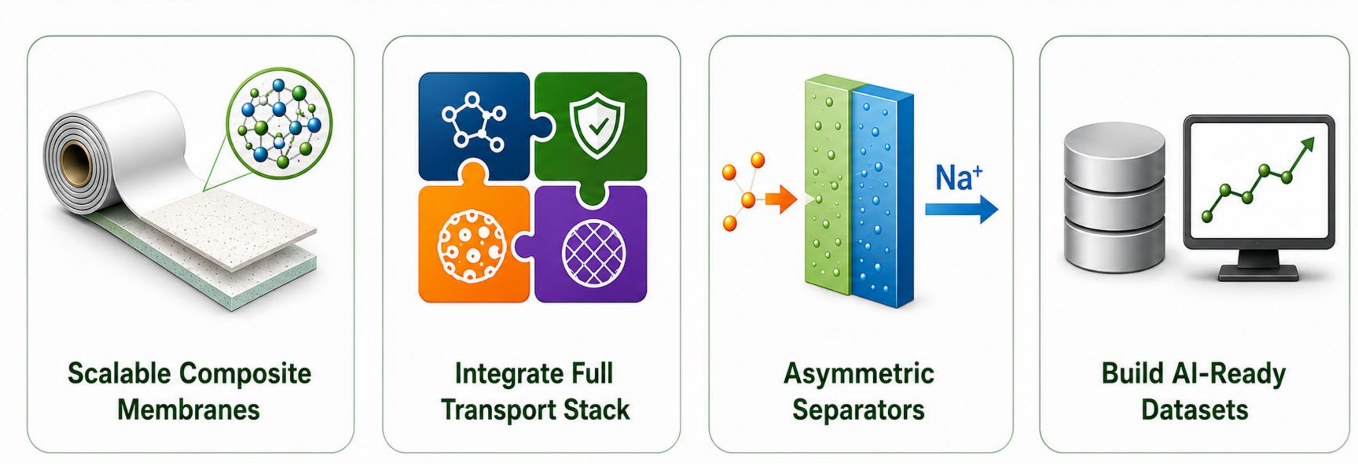
Mechanism: fixed $-SO_3^-$/$-COO^-$ groups repel polysulfide anions, densify the porous GF network, increase Na^+-favored transport, and promote a more stable Na interface.

CONCLUSIONS & IMPACT

- **Initiating an integrated transport-control strategy for Na–S flow batteries across multi-components;**
- **Improved material utilization, suppressed polysulfide crossover, reduced self-discharge, stabilized Na metal;**
- **Demonstrated scalable design routes using optimized carbon electrodes, electrolyte ionic-strength balancing, PFAS-free separator functionalization.**

Impact: advances low-cost, earth-abundant Na–S redox-flow batteries toward durable long-duration energy storage for grid reliability and critical-load backup

FUTURE DIRECTIONS: Advancing Na–S Flow Batteries



GOAL: Deliver integrated, manufacturable Na–polysulfide flow cells for higher-current, longer-life, safer, and lower-cost energy storage.

FY26 ACHIEVEMENTS

Journal Publications (X5) [New since last OE review meeting]

Lead:

1. Wenda Wu, Monojoy Goswami, Cheng-Tien Hsieh, Chanho Kim, Yuanshun Li, Nian Liu, and Guang Yang. "Cation-Diffusive Carbon Interlayers Stabilize Na Metal and Double the Current in Na-S Redox-Flow Batteries for Grid-Scale Energy Storage." *Adv. Funct. Mater.* **2026,** 36, e31310.
2. Jieun Kang, Cheng-Tien Hsieh, Wenda Wu, Guang Yang, and Nian Liu. "Suppressing Polysulfide Crossover in Sodium-Polysulfide Redox Flow Batteries with an Oxyanion-Functionalized Glass Fiber Separator." *ACS Nano* **2026,** 20, 19401.
3. Michelle L. Lehmann, Wenda Wu, Yuanshun Li, Chanho Kim, and Guang Yang. "Binder-Stabilized Carbon Fiber Hosts for High-Utilization Sodium–Polysulfide Flow Catholytes." *J. Electrochem. Soc.* **2026,** 173 110512.
4. Wenda Wu, Fuead Hasan, Yawei Gao, Chanho Kim, Inyoung Jang, Harry M. Meyer, Cheng Lei, Michelle Lehmann, Christopher M. Bejger, Xiaolin Li, and Guang Yang. "Suppressing Polysulfide Shuttling via a Supporting Electrolyte Concentration-Asymmetric (SEC-Asym) Design Based on Electrolyte Ionic Strength for Stable Promoted Na–Polysulfide Redox-Flow Batteries." *Energy Storage Mater.* **2026,** 90, 105275.

Collaborated:

5. Yutong Wu, Maxim Zhelyabovskiy, Zhitao Chen, Karam Eeso, Alexandros Filippas, Haochen Yang, Guang Yang, and Nian Liu. "Complexing Agent-Assisted Membraneless Zinc–Iodine Aqueous Batteries." *J. Phys. Chem. Lett.* **2025,** 16, 8024.

Inventions (X1)

- Dry Processing of Ceramic–Polymer Hybrid Membranes Invention Disclosure ID# : 202506130, DOE S# (Inventors: Yang and Kim) [https://www.ornl.gov/technology/202506130]

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.