Material Science Driven Water Technology Innovation

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1. Focal Area(s)

This white paper explores various Energy-Water Resilience (EWR) topics, including water for energy, energy for water, and intersections between energy and water. It proposes a suite of low-cost and scalable water-based material processes, each tailored for water-intensive industries, unified by the overarching goal of advancing water technologies through materials innovation.

2. Existing Challenge

Energy and water systems in the United States are deeply interconnected, imposing mutual constraints: water scarcity limits energy production, and energy-intensive water treatment burdens grid reliability and impacts affordability. Across the water-energy system, there are a number of technical challenges and opportunities for solutions at multiple scales.

2.1 Water for energy

- **Energy generation and conversion systems**: Thermoelectric, geothermal, and thermal energy storage systems heavily rely on water as a heat carrier fluid, necessitating a reduction in water usage for electricity generation and cooling[1,2].
- **Drilling and well completion**: Subsurface resource development (hydrocarbon, geothermal, and critical minerals) requires substantial volumes of water for drilling fluids, cooling, cuttings removal and reservoir stimulation[3,4]. Additionally, produced water must be treated to reduce environmental impacts and protect groundwater resources.
- **Corrosion and scaling**: These lead to significant infrastructure failure and major efficiency losses in power generation, desalination, and industrial cooling systems[1].

2.2 Energy for water

- **Membrane inefficiencies**: Effective pretreatment processes are essential to improve membrane efficiency for harsh water (high salinity, ionic strength, suspended solids, and organic contaminants) from brackish, municipal, industrial, and produced water.
- **Surface and groundwater remediation**: Due to complex pollutants, current remediation technologies are often energy-intensive, accounting for 30–60% of operational costs in water treatment facilities[5].

2.3 Intersections of water-energy

- **Mining and processing of critical minerals**: Extracting critical minerals from ores demands significant water for various processes, and mining produces large volumes of water that must be treated to manage contaminant loads[2].

3. Near-Term Opportunity

Breakthroughs in materials science, particularly low-cost, scalable technologies, are unlocking new potential to enhance EWR systems that can adapt to changing environmental and operational conditions. In the next 3–5 years, we have a key opportunity to integrate water-based material-centric innovations into energy-water infrastructure, significantly boosting efficiency, durability, and resilience across critical sectors.

3.1 Water for energy

3.1.1 Advanced heat-exchange materials

- Novel water-based materials (e.g., nanoengineered phase change composites) that can enhance thermal conductivity and heat storage density in heat carrier fluids[6].

- High-performance coating materials that improve heat exchanger efficiency, minimize cooling water volume, and lower operational energy costs.
- Materials for optimized thermal energy management have potential to increase heat utilization and distribution efficiency, enhance heat extraction from industrial, data center, sewage, and shallow geothermal sources, while facilitating heat distribution for space heating and low-temperature industries and enabling large-scale thermal energy storage.

3.1.2 Materials for mitigating corrosion and fouling of infrastructure

Corrosion and scaling hinder the efficiency and lifespan of power generation and industrial cooling systems. Advances in harsh-environment materials are enhancing protective interfaces, enabling geothermal wells, turbine blades, cooling towers, and condensers to endure extreme conditions, thus extending lifetimes, reducing maintenance, and minimizing water treatment needs[7]. Furthermore, new water-based materials offer innovative scaling mitigation solutions, boosting the efficiency and sustainability of clean energy-water infrastructure.

3.1.3 Materials for drilling, well completion and reservoir engineering

Materials innovations are improving efficiency, safety, and sustainability in subsurface energy production. Advanced drilling technologies enhance lubrication and cooling[8], reducing equipment wear. High-temperature responsive material is being developed for geothermal reservoir engineering[9,10]. High-strength, corrosion-resistant alloys and composites boost well casing durability[7], while innovative cement formulations strengthen well completions[11,12].

3.2 Energy for water

Innovative pretreatment process utilizing engineered materials (including nanomaterials) with unique physical, chemical and electrochemical properties that can efficiently aggregate and flocculate solid suspensions, microbial pathogen. Leveraging these materials, the pretreatment of harsh water sources becomes more efficient, leading to improved membrane separation performance, reduced operational costs, and enhanced sustainability in water treatment processes.

3.3 Intersection of water-energy in mining and processing of critical minerals

Material innovations in the mining and processing of critical minerals are vital for promoting sustainability in the industry. By focusing on advanced materials, the sector can significantly reduce water and chemical usage while enhancing operational efficiency and minimizing environmental impacts. Key near-term opportunities include:

- Targeted delivery of lixiviants for precision in-situ leaching, enhancing metal solubility and minimizing environmental impacts.
- Novel flocculants and coagulants that improve beneficiation efficiency, reducing environmental impact and water consumption.
- Incorporation of novel materials (including nanomaterials) in mineral separation to enhance recovery rates while using less water and fewer chemicals, enabling selective extraction of desired minerals[7].
- Advanced bioleaching agents with additives that maximize microorganism activity for metal extraction while minimizing toxic chemicals and water consumption.

3.4 System-Level Impacts

Collectively, Innovations in material science-driven water technology offer several benefits:

- For Energy Systems: Reduced water withdrawals, enhanced heat management, and extended lifetimes of critical infrastructure.
- For Water Systems: Lower energy requirements for treatment, improved water quality, and increased capacity for water reuse.

- For Intersectional Sectors: Enhanced reliability and operational efficiency to secure American critical minerals and materials supply chain.

3.5 Partnership

Achieving the above outcomes requires coordinated engagement among research, industry, and implementation partners. Key actors include:

- National Laboratories and DOE's advanced user facilities (e.g., LBNL's Molecular Foundry and ALS, METALLIC for critical minerals).
- Universities, academic and research institutions.
- Industry Partners: leverages shared expertise and resources to drive innovation, enhance efficiency, and accelerate the development of cutting-edge technologies.
- Cross-sector alliances: Forming alliances across different sectors—such as energy, water, and mining—enables the sharing of best practices and resources, synergizing between industries, and facilitating integrated solutions that enhance efficiency and sustainability.

4. Success Measures

4.1 Quantitative Measures

Water Usage Metrics:

- Reduction in freshwater withdrawal in industrial processes.
- Water use efficiency measured as liters per unit of energy or mineral produced.
- Volume of water recycled and reused.

Energy Production Metrics:

- Increased energy output and reduced levelized cost of energy (LCOE) attribute to material innovations.
- Reductions in energy input requirements for each unit of output.
- Grid congestion: Track levels of congestion across transmission networks, assessing the number of congestion events and their durations.
- Reduced power outages: Measure the frequency, duration, and impact of power outages across the grid.

Mining Metrics:

- Reduced water usage emphasizing the implementation of new materials.
- Improvements in recovery rates linked to enhanced processing technologies.

4.2 Qualitative Measures:

- Stakeholder feedback: Insights on improved water conservation and impacts on operations.
- Community perceptions: Evaluation of public opinion on long-term EWS changes.

4.3 Broader Societal Measures

- Economic Impact: Analyze benefits from reduced water usage, including cost savings.
- Job Creation: Track employment growth in water-saving technology sectors.
- Innovation and Entrepreneurship: Monitor the emergence of startups focused on material innovations.

4.4 Coordination Challenges and Policy Innovation

The interdependence of energy and water systems requires collaborative approaches that transcend traditional sector-specific policies. By developing integrated strategies to advance material-based water technologies across energy production, water management, and critical mineral processing, we can create synergies that enhance efficiency and sustainability within these interconnected systems.

References:

1. U.S. DOE, 2014. The Water-Energy Nexus: Challenges and Opportunities.
2. Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2018, Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, https://doi.org/10.3133/cir1441.
3. Valder, J.F., McShane, R.R., Thamke, J.N., McDowell, J.S., Ball, G.P., Houston, N.A., and Galanter, A.E., 2021. Estimates of water use associated with continuous oil and gas development in the Permian Basin, Texas and New Mexico, 2010–19: U.S. Geological Survey Scientific Investigations Report 2021–5090, https://doi.org/10.3133/sir20215090.
4. Fervo, 2025. Geothermal Mythbusting: Water Use and Impacts. https://fervoenergy.com/geothermal-mythbusting-water-use-and-impacts/.
5. Gude, V. G., 2016. Energy consumption and recovery in water desalination. Desalination Water Treat., 57(11), 233–269.
6. Chang, C., Kneafsey, T.J., Nakagawa, S., Rad, B., 2021. A Highly Stable nanoemulsion produced by low-pressure hydrodynamic cavitation: A step to underground thermal energy storage, presented at the 2021 AGU fall meeting.
7. Zhang, Q., Gallant, M.C., Chen, Y. et al., 2025. Isothermal solidification for high-entropy alloy synthesis. Nature, 646, 323–330.
8. Chang, C., Zheng, H. Gas nanobubble enabled fluids for wellbore drilling and method of use thereof. Pending patent to Berkeley Lab Intellectual Property Office.
9. Chang, C., Nakagawa, S., Sandoval, O. et al., 2024. Developing High-Temperature Functional Microcapsules for Delayed Flow Diverter Formation in EGS Reservoirs. PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, SGP-TR-227.
10. Chang, C., Nakagawa, S., Kneafsey, T, J., Patrick, D., 2025. Development of Chemical-Encapsulating Microparticles for Controlled Flow Diverter Formation in Geothermal Reservoirs. U.S. Patent Serial No. 19/331,024: 19/331,024.
11. Zheng, Q., Li, B., Liu, S., et al., 2025. Strain Release Through Hydrogen-Bond-Mediated Layer Twisting. Sci. Adv. 11, eady6869.
12. Liu, S., Devoe, M., Samuel, D. M. et al., 2025. Geo-responsive chemomechanics in aluminum oxyhydroxide via alkali-driven dehydroxylation for supercritical geothermal systems. ACS Mater. Lett. 7, 1869–187.