Operational Flexibility for Integrated Energy-Water Resilience

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Focus Area(s)

The focal area of this white paper is the energy-water nexus by advancing grid-responsive operation of desalination and water treatment systems. It focuses on integrating operations between water and energy systems to improve resiliency through flexibility. This approach treats operational flexibility as a quantifiable mechanism for resilience, whereby system dynamics, control, and risk metrics are coupled to guide co-optimized investment and planning.

Existing Challenge

Across the US, energy and water systems are deeply interdependent yet operationally and functionally segregated. Thermoelectric generation accounts for roughly 40% of water withdrawals, while water systems can account for 30-40% of energy consumption in cities. Despite decades of recognition of this coupling, the two sectors continue to function with separate regulatory, operational, and investment frameworks (Conrad et al., 2010; Kenway et al., 2013; Conrad et al., 2017). This separation has led to different operational regimes, and this fragmentation undermines resilience.

There are four interrelated challenges that highlight the need for continued research to enable flexible, coordinated operation of energy and water infrastructure.

1) Transitioning from steady-state to dynamic operations. How can water operations and treatment, including energy intensive processes like desalination, be adapted to support flexible, grid-responsive operations without compromising water quality or system resiliency? This question centers on the core challenge of transitioning from traditional steady state system design and operations and the need to explore the technical and structural practicalities of dynamic operations.

2) Quantifying technoeconomic and resilience trade-offs. While the topic of flexibility has been studied in isolated contexts, it has been limited to cost avoidance analyses. A key need is to evaluate the technoeconomic tradeoffs and resilience co-benefits of integrating energy and water infrastructure. There is a gap in understanding and relating efficiency metrics like kWh per gallon treated and broader interdependence and adaptive measures related to real-time control, feedback, and learning capacity that extend the measure of resilience beyond reliability (Paglioni et al., 2025).

3) Identifying compatible technologies and operational strategies. Which water treatment technologies and operational strategies are most compatible with hybrid or distributed grid systems? A gap exists in understanding combinations of technologies, system configurations, and operational strategies that can be scaled or replicated across regions.

4) Overcoming institutional and data barriers to integration. What are the institutional, regulatory, and data-related barriers that need to be addressed to enable coordinated energy-water infrastructure planning and investment? Previous research on integrated and distributed

energy-water infrastructure highlighted that coordination, regulatory systems and governance, and data-integration gaps inhibit co-planning and shared investment (Conrad et al., 2017; Conrad et al., 2021).

These four challenges can be addressed by a generalizable decision-support framework for energy and water flexibility. Such a framework should address operational rigidity, data limitations in non-steady state operations in water treatment, the capital costs associated with retrofitting or operational wear and tear, and the holistic priorities of integrated water and power systems (O'Neil et al., 2024). It should also aggregate case specific insights into scalable scenarios, accounting for regional, social, and technical differences across utilities and communities.

Near-Term Opportunity

The next five years offer a unique opportunity to establish integrated water-energy flexible test beds that demonstrate the operational and resilience benefits of grid-responsive water systems. Building on existing systems analysis by the authors, several near-term opportunities can advance the integration of water infrastructure with a dynamic electric grid. These identified opportunities translate theoretical flexibility concepts into measurable, field-tested strategies that strengthen national energy-water resilience.

1) **Develop and experimentally validate flexible operational regimes for desalination and water treatment**: A key opportunity is to develop and test operational strategies for energy-intensive and advanced water treatment processes, particularly under variable load conditions driven by electric grid intermittency. This includes evaluating off-peak cycling, ramping rates, and partial-load operations to identify performance boundaries, reliability implications as well as design and control optimization.

2) **Deploy digital twin architectures for dynamic control and optimization**: Digital twins can provide real-time decision support for balancing energy consumption, treatment performance, and grid response. There are opportunities to tailor these tools for utility operators by incorporating site-specific constraints, probabilistic uncertainty, and multi-objective optimization to support operational decision-making and long-term planning. Digital twins should integrate feedback from both operational data and probabilistic scenario analysis to inform adaptive control boundaries.

3) **Advance technoeconomic and resilience assessment frameworks**: There is a near-term opportunity to support development of integrated frameworks that quantify the economic value, resilience, and environmental adaptive co-benefits of flexible operations. These tools could couple traditional cost and efficiency metrics (e.g., kWh per gallon treated) with resilience-oriented indicators such as load-shifting potential, response times, and avoided service disruptions. By embedding uncertainty quantification into these frameworks, utilities can evaluate flexibility not only as a cost-saving measure but as a quantifiable resilience investment.

4) **Synthesize insights across geographically and technologically diverse pilot studies**: DOE-supported pilot studies provide a critical opportunity to identify transferable design

principles from flexible water and energy operations. Coordinated synthesis of these efforts can encourage innovation, overcome siloed decision making, and accelerate technology transfer across utilities (Conrad et al., 2024). Comparative analysis across pilot sites will help capture regional differences, highlight effective operational practices, and inform scalable strategies for coordinated investment and implementation.

5) **Evaluate institutional, regulatory, and market-based mechanisms to enable flexibility**: Coordinated planning and investment across the energy and water sectors require new incentive and governance structures. There are near-term opportunities to evaluate the potential of dynamic pricing, demand response programs, and performance-based incentives in unlocking the latent flexibility of water infrastructure.

Collectively, this combination of near-term opportunities informs a systems-level framework for resilient and economically viable energy-water infrastructures that are rooted in operational validation, technoeconomic assessment, and institutional coordination.

Success Measure

Quantitative and qualitative success metrics can evaluate the effectiveness, scalability, and resilience benefits of coordinated energy–water flexible operations. While conventional metrics such as cost per million gallons of water treated or carbon intensity per unit of water can be used, true success will be technology transfer to operators who can make decisions to optimize both economic and resilience performance.

Additional technoeconomic metrics could be used to assess the value proposition of flexible operations under various electrification scenarios. Operational success will be measured by the extent of load shifting achieved, response time and ramping capability of treatment processes, and the integration efficiency with variable energy and storage systems. From a systems perspective, the framework will also evaluate scalability and transferability across different utility contexts.

Qualitative success could be gauged through stakeholder engagement outcomes, including feedback from utility managers and operators to ensure that the framework is actionable, relevant, and aligned with real-world operational constraints and decision-making needs. Overall success will be defined by how well resilience metrics translate into quantifiable decision mechanisms that enable utilities to anticipate and adapt to disruptions through data-informed flexibility. These measures demonstrate how flexibility transitions from a design attribute to a measurable system capability.

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