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Title: From Modeling to Testbeds: Taking an Expanded Look at Wastewater Reuse

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Focal Area(s): The primary focus is on energy for water, considering the myriad tradeoffs influencing the adoption of wastewater reuse, particularly considering its energy intensity.

Existing Challenge: Freshwater is a critical resource, vital for human, agricultural, and industrial activities. However, across the United States, pressures such as increasing demand, drought, water pollution, and land use change have reduced the availability and quality of surface and groundwater resources historically relied upon.[1] At the same time, emerging sectors such as data centers and advanced manufacturing, with their high electricity demand and associated cooling requirements, are placing new stresses on local energy and water systems.[2] These challenges are particularly relevant to utilities and municipal water providers, who operate at the nexus of these complex energy and water issues.

Wastewater reuse offers a compelling opportunity to concurrently tackle water scarcity and enhance energy efficiency. The economics of water reuse have quickly improved as new treatment technologies have driven the cost of treatment down while the availability of cheap freshwater resources have diminished. The economics are further improved with fit-for-purpose water reuse that benefits from the reduced economic and energy burden of treating all water to potable standards, which is not necessary for many agricultural, industrial and mining applications. Potentially game changing opportunities could be realized through novel integration of wastewater reuse with resilient power infrastructures (i.e., microgrids and battery energy storage), economically promising activities like aquaculture for commercial products and critical mineral extraction, electrochemical commodity production, geothermal energy generation and others.

While water reuse shows promise, the application space is complex, making it difficult to identify economically viable solutions. A range of modeling tools are available to assist with such analyses; however, rapid changes in the opportunity space (i.e., emerging technology, new fit-for-purpose applications, secondary value streams, and multi-sector tradeoffs) require enhanced and new approaches. Such tools need to combine understanding of regulatory viability, economic feasibility, water quality requirements (e.g., salinity, nutrient loading, microbial content), cross-sectoral opportunities, and infrastructure capacity. Given the growing complexity, models also need to be grounded with experimental data from testbeds that can explore this range of tradeoffs. While individual sector testbeds do exist, few demonstrations have been constructed for a multi-component future economy.

Near-Term Opportunity: The feasibility of wastewater reuse could expand with the exploration of new application spaces. To fully capitalize on the potential of water reuse, there is the need to create a holistic approach for evaluating the feasibility of water reuse across a myriad of scenarios, as well as the establishment of testbeds to ground truth their efficacy.

High Resolution Modeling: Spatially and temporally resolved modeling is needed for exploring the disparate quantitative relationships between municipal and industrial wastewater sources and potential end-users.[3] Such analyses could consider local nuances in the chemistry of both the waste- and product-water streams, system capacity, concentrate disposal constraints, as well as how all of these factors dictate viable treatment options and their energy intensities[4]. Analyses could also consider potential value streams, such as thermal energy, nutrients, critical minerals, and fresh water, that could be harvested from the wastewater, as well as the ecological benefits realized by no longer needing to discharge the wastewater to the open environment. The real value of reuse can best be evaluated when weighed against the cost (e.g., economics, environmental impact, water produced) of alternative water sources (e.g., fresh groundwater, desalination, brackish water).[5] Such an innovative approach not only addresses immediate water and energy resource challenges but also fosters long-term economic resilience by creating new markets and business opportunities within the wastewater sector.

Regional to Global Scale Modeling: Regional to global scale modeling provides a valuable complement to high resolution modeling by contextualizing these localized studies within a broader, collective setting. Straight forward application could be made by leveraging integrated multisector models capable of a basin, national and global perspective.[6-7] Consideration of wastewater reuse technologies within multisector models simply requires integration of relevant process models into their market equilibrium framework. The addition of a wastewater reuse module within these larger models could provide a means to quantify the energy-water tradeoffs associated with direct and indirect water use across various sectors. This approach enables the evaluation of wastewater reuse feasibility, potential spatial-temporal impacts, infrastructure constraints and the economic barriers and benefits involved. It could also allow for an unprecedented view of water reuse from the local to global scale.

Testbeds: Scalable real-world testbeds are valuable for bounding forecast and model conditions, providing model inputs (validating modeling efforts), as well as de-risking component technologies and their myriad arrangements. Existing research facilities have energy-water components and are positioned for taking on research across potentially beneficial sectors, while evolving plans to site data centers on national laboratory properties could offer exciting new possibilities. Ideally, candidate testbeds could provide localized capabilities to analyze production streams' chemical, biochemical, and physical properties, as well as accurately track key system budgets including water, energy, waste, and economic. Many existing testbeds are configured to admit a range of waste stream compositions and treatment train configurations to achieve fit-for-purpose product water. Added value could be realized by pairing such capability with symbiotic industrial processes (e.g., mineral extraction feedstocks, algal fuel and commodity production feedstocks,[9-11] grid-scale battery cooling,[8] marine and geothermal energy generation, electrolysis,[12] on-demand chemical production, and pumped storage hydropower). Such campus-scale testbeds could provide a physical basis for how a variety of flow arrangements could extract maximum value from a water stream by pairing appropriate changes in temperature, salinity, alkalinity, chemical composition, and biological composition with production centers that either see minimal efficiency reductions from such changes or actively benefit from them. Future iterations might demonstrate direct feedback loops between energy/resource efficiency models and automated control of production centers, possibly including Artificial Intelligence (AI) and Machine Learning (ML) forecasting.

Success Measures: In this context, success might best be measured in terms of expanded water supply realized with improved energy efficiency and cost. Equally important is the identification of new opportunities for coordination and synergies across the energy, water, and waste management sectors.

These successes could be realized in part through the analysis of tradeoffs associated with water reuse in a variety of settings. Key performance indicators could include quantitative metrics such as potable water saved, energy reductions, economic impacts and avoided freshwater withdrawals assessed alongside qualitative measures of cross-sector coordination and regulatory applicability. Developing a comprehensive analysis framework could aid in identifying when and where wastewater reuse could serve as a viable solution within the energy-water nexus, ultimately paving the way for new markets and enhancing economic, water, and energy resilience.

Success measures related to establishing water reuse testbeds include generation of datasets cataloging chemical / biochemical / physical alterations of water streams, efficiency alterations of various sector technologies under various flow arrangements, and correlations thereof. Additional value would be realized by the automation of data gathering and processing for modeling efforts, as well as demonstration of feedback-loop style control of these sector technologies, possibly including AI/ML-based forecasting.

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