Title: Energy-Enabled Decentralized Treatment of Brackish Water Sources for Agricultural Irrigation

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Focal Areas: Energy for water is the focal area. This white paper addresses the potential of decentralized brackish water treatment for agricultural irrigation and the energy systems needed for optimal performance.

Existing Challenge: Agricultural irrigation in many regions of the United States and globally increasingly relies on freshwater supplies that are stressed, fully allocated, or declining in quality. Non-conventional water sources including brackish groundwater are concurrently under-utilized[1]. Leveraging these alternative sources for irrigation presents a dual challenge at the energy-water nexus. The treatment and distribution of such waters often involve elevated energy burdens and operational complexity, and many users (i.e. growers) in the agricultural sector are spatially disconnected from energy-water integrated systems.

Water scarcity in arid and semi-arid regions has led to the depletion of conventional freshwater sources and is a threat to agricultural food production; therefore, new water supplies must be developed. To use brackish groundwater for agricultural irrigation, treatment is required to reduce electrical conductivity [< 0.7 decisiemens per meter (dS/m)] and total dissolved solids [(TDS), < 700 mg/L] to maintain of soil structure and crop health[2]. However, salt removal is both energy and cost intensive. Seawater desalination has been implemented in over 100 countries globally; nevertheless, associated energy requirements remain high at a thermodynamic minimum of ~1.06 kWh/m^3[3]. In comparison, state-of-the-art membranes can achieve less than 2 kWh/m^3 under optimal conditions; however, this typically excludes the energy required for pretreatment, pumping, and distribution[4].

Decentralized water treatment facilitates the on-site use of brackish water sources for agriculture and reduces the impacts of water scarcity, groundwater salinization, and agricultural productivity demands. However, implications relating to energy are underexplored. Key research and implementation gaps include:

- Insufficient deployment and on-site validation of decentralized, energy-efficient treatment systems designed for brackish sources.
- Limited integration of renewable or hybrid energy systems coupled with treatment and distribution networks for irrigation water.
- Lack of quantitative metrics that integrate energy consumption (kWh per m^3 of water produced) and water supply delivered (m^3 to field) with resilience (ability to maintain supply under stress) for decentralized treatment systems.

Near-Term Opportunity: During the next 3 to 5 years, decentralized treatment and distribution systems can be evaluated on site within one or more selected agricultural irrigation districts. The systems will integrate low-energy water treatment, a renewable/hybrid energy supply, smart pumping/distribution, and fit-for-purpose irrigation delivery for treated product water. The opportunity will focus on "energy for water reuse" by enabling field operations to access brackish sources via systems with low-energy demands, thus enhancing resilience and water supply flexibility for the agricultural sector.

Description of the Opportunity:

- **Decentralized treatment units:** Modular treatment systems configured to meet the demands of one or more growers within an agricultural irrigation district will be installed close to brackish aquifers. The systems would utilize advanced low-energy technologies (e.g. next-generation membrane systems and/or novel solar-thermal/desalinization hybrid systems) designed to mitigate brackish-salinity levels. The opportunity has been historically supported by joint initiatives such as the National Alliance for Water Innovation (NAWI) and the U.S. Department of Energy (DOE) to improve the energy efficiency of brackish/nontraditional water treatment.
- **Hybrid energy supply and smart pumping/distribution:** Treatment units will be paired with renewable energy (solar, wind) and energy-storage/pumping systems to manage variable irrigation demand and minimize grid interruption effects. For example, treatment systems designed for brackish water can operate during off-peak hours or when the renewable energy sources are available. Treated water can also be stored in a gravity feed irrigation system for later use. Real-time controls will minimize the energy requirements needed to distribute product water to the fields. Smart thermal and electrical storage systems can be deployed to optimize performance.
- **Fit-for-purpose irrigation distribution:** The treated brackish water will be delivered via micro-irrigation systems (e.g. drip) or existing infrastructure with optimized scheduling to reduce energy requirements for water delivery and improve water-use efficiency in the test field zone(s).
- **Digital integration and co-optimization:** A decision-support platform, or digital twin, will model energy supply, decentralized treatment system operations, irrigation demand, and delivery of treated water to the test plots to achieve whole system optimization under the lowest energy requirements.
- **Stakeholder partnerships:** Implementation will promote key collaboration among academic labs, agricultural irrigation districts and growers, water utilities, energy utilities, national laboratories [e.g., National Renewable Energy Laboratory (NREL), energy consultants, and finance/contractual entities (e.g., public-private partnerships or energy-water service agreements)].

Implementation Timeline (Years 1–5):

- **Year 1:** Candidate locations will be selected within arid or semi-arid agricultural districts in proximity to brackish groundwater sources. A stakeholder consortium of growers will be convened to discuss the project aims and to recruit participants. A baseline audit will be conducted prior to implementing treatment to calculate water demand, salinity, conductivity, system energy costs, and to assess existing irrigation infrastructure. Design and engineering schematics of the modular water treatment and renewable energy supply system coupled with smart pumping, energy storage, and field delivery options will be finalized.

- **Year 2:** Participation agreements will be formalized among stakeholders. System components are delivered to the selected study site(s) and builds are initiated.
- **Year 3:** The pilot study is implemented for one-year with a subset of stakeholders. System performance is monitored, and data is collected regarding water production, energy consumption, and volume of irrigation water delivered. System operation metrics are then modified to optimize performance.
- **Years 4-5:** The pilot study is elevated to full-scale by including additional growers in the district. Energy-water-resilience metrics are documented to assess whole system efficacy, and a roadmap is developed for broader deployment.

The provision of decentralized treatment for non-conventional water sources will provide agricultural stakeholders with a reliable supply of irrigation water and decrease energy vulnerability by use of renewable or hybrid systems. This will increase coordination across the energy and water sectors and advance resilience at the energy-water nexus.

Success Measures: Success will be measured by tracking and analyzing the following quantitative and qualitative metrics.

Quantitative Metrics

- Volume of treated brackish water delivered for agricultural irrigation (e.g., m^3/year) compared to baseline or current minimal usage.
- Energy requirements for water treatment and delivery by irrigation (kWh per m^3 delivered) compared to conventional freshwater irrigation (or a baseline irrigation system).
- Reduction in grid electricity consumption for current irrigation pumping/treatment (kWh and %) practices.
- Number of hectares (or acres) of farmland served by the treated water source.
- Irrigation reliability metric to determine the number of days per season that are fully sustained by the treated water supply source compared to conventional sources.
- Projected cost savings for decentralized brackish water treatment compared to baseline water use.

Qualitative Metrics

- New cross-sector partnerships formed (agriculture, energy, water utilities) and documented contracts to enable integrated energy-water operations.
- Institutional change: adoption of decentralized energy-water systems and implementation of energy-water planning practices that incorporate non-conventional sources.
- Replication potential: number of other growers and agricultural districts expressing interest in deploying the technology based on the pilot and full-scale studies.
- Resilience improvement: qualitative assessment of how the system will respond to stress events including drought, grid outage, further increase in salinity, and water supply disruptions.

Success will be demonstrated when a decentralized brackish water treatment system operates reliably at or below the energy intensity of conventional freshwater supply systems, demonstrates replicability across agricultural regions, and supports irrigation at scale.

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