Digital Twin and HIL Framework for Grid-Interactive Microgrids in Non-PRASA Aqueducts: Enhancing Energy–Water Nexus Resilience

Authors/Affiliations:
Jesus D. Vasquez Plaza, and Jin Dong - Oak Ridge National Laboratory (ORNL), Electrification and Energy Infrastructure Division, Grid Interactive Controls (GIC) Group

Fabio Andrade – University of Puerto Rico–Mayagüez (UPRM), Department of Electrical & Computer Engineering, Sustainable Energy Center.

Focal Area
This white paper addresses the energy for water focal area by developing and validating grid-interactive microgrids for aqueducts which operate outside the centralized Puerto Rico Aqueduct and Sewer Authority (non-PRASA). These aqueducts depend on electricity for pumping and treatment, and their vulnerability to grid outages represents a direct energy-water nexus challenge. The proposed work emphasizes Digital Twin modeling and Hardware-in-the-Loop (HIL) validation as the technical foundation to design, optimize, and replicate grid-interactive microgrid solutions that ensure operational resilience under grid disturbances and adverse weather events.

Existing Challenge
Puerto Rico has more than 200 non-PRASA aqueducts, which operate outside the centralized Puerto Rico Aqueduct and Sewer Authority (PRASA/AAA). These systems rely almost entirely on electrically powered pumps and small treatment units [1]–[4].
Their most critical vulnerability lies at the energy–water nexus: without electricity, there is no water. When the grid fails—as in Hurricanes Irma, María, and Fiona—non-PRASA aqueducts immediately lose pumping capability, interrupting potable water supply for extended periods. This interdependence highlights how fragile water security is in insular systems when electricity supply is disrupted.
Backup strategies are typically diesel generators, which are costly, unreliable during disasters, and environmentally unsustainable. For islands such as Puerto Rico, where fuel supply chains are frequently disrupted during extreme weather, diesel is not a viable long-term option to sustain continuous operation of critical pumping and treatment processes.
This underscores the urgent need for grid-interactive microgrids that tightly integrate on-site distributed energy resources (DERs), energy storage systems (ESS), and advanced controls, validated through Digital Twin and Hardware-in-the-Loop (HIL) platforms. Such an approach directly addresses the energy–water nexus challenge, ensuring that reliable electricity supply translates into uninterrupted water delivery under both normal and extreme conditions.

Near-Term Opportunity (3–5 years)
Non-PRASA aqueducts clearly exemplify the energy–water nexus: without electricity, there is no water. Their dependency on electrically powered pumps and treatment units makes them highly vulnerable to grid outages and adverse weather events. This project leverages grid-interactive microgrids, validated through Digital Twin modeling and Hardware-in-the-Loop (HIL) simulation, to establish a near-term pathway for ensuring reliable water delivery through enhanced energy resilience.
By integrating DERs, ESS, and advanced control, this effort will not only secure water services under extreme conditions but also improve energy efficiency, operational independence, and technical replicability. The following actions will be pursued:

1. **Partnerships & Site Selection:** Work with non-PRASA aqueduct operators through UPRM's established relationships to identify 2–3 representative pilot sites in rural and coastal areas. Engage local leadership to co-design systems that meet both energy reliability and water supply requirements, ensuring operational alignment.

2. **Digital Twin Development:** Build digital twins of aqueduct energy-water systems, including ESS, pumping loads, and water demand. Use these digital twins to simulate how disruptions in electricity propagate into water shortages, and test microgrid interventions.
3. **Advanced Energy Control Design:** Develop predictive and adaptive control algorithms (e.g., Model Predictive Control (MPC) + estimation) to optimize pump operation, battery dispatch, and inverter coordination. Treat aqueducts not only as water assets but also as active, grid-edge energy loads capable of providing demand flexibility. Explicitly optimize both energy availability and water delivery, introducing resilience metrics that tie the two domains together.
4. **Real-Time Simulation and HIL Validation:** Use real-time simulation platforms at UPRM and ORNL to evaluate aqueduct digital twins under realistic conditions: storms, multi-day outages, solar variability, inverter faults. Conduct HIL experiments connecting controllers, batteries, and pump drives to real-time simulators. This ensures that energy solutions are field-ready, reducing risk during deployment and de-risking investments DOE.
5. **Pilot Deployment in Puerto Rico:** Install solar + battery microgrids at pilot aqueducts validated through digital twin/HIL testing. Monitor both energy system metrics (DERs fraction, ESS efficiency, diesel reduction) and water availability. Train students and community members as local operators, with emphasis on energy system operation and maintenance.
6. **Technical Report:** Deliver a technical framework with validated procedures, performance metrics, and reproducible methods for DOE and national replication.

Importance of Community Aqueducts and Distributed Energy Resources Integration

Non-PRASA aqueducts in Puerto Rico represent more than just water infrastructure; they are lifelines for rural and mountainous populations who live outside the centralized utility system. These non-PRASA systems serve nearly 90,000 residents [1]–[4], yet they remain among the most vulnerable infrastructures on the island. Their dependence on electrically powered pumps and treatment systems creates a structural fragility: whenever electricity fails, potable water access is disrupted.

Ensuring reliable energy supply for these systems is therefore a public health and resilience priority. Traditional reliance on diesel generators is not sustainable due to high operational costs, limited fuel availability during disasters, and negative environmental impacts. DERs combined with ESS offers a sustainable, cost-effective, and resilient alternative. By coupling DERs directly with community aqueducts, these systems can:

- Provide continuous potable water during prolonged grid outages.
- Reduce operational expenses for small community-managed organizations.
- Decrease dependence on external fuel supply chains, which are often disrupted during emergencies.
- Contribute to enhance grid resilience while improving local quality of life.

In this context, DERs is not just an environmental solution—it is the core enabler of water security for some of Puerto Rico's most underserved populations.

Broader Applicability Across U.S. Regions and Sectors

While Puerto Rico presents a uniquely compelling case, the results of this project are highly transferable across the United States. The integrated energy-water resilience framework combining digital twin development, grid-interactive microgrids, and HIL validation can be applied in multiple regions:

1. **U.S. Island Territories:** U.S. Virgin Islands, Guam, and American Samoa face challenges nearly identical to Puerto Rico's, with remote communities relying on vulnerable energy and water infrastructure.
2. **Rural Mainland Communities:** Small water utilities and cooperatives in Appalachia, the Midwest, and the Southwest often struggle with aging infrastructure and high energy costs. Applying validated microgrid solutions can reduce costs and improve reliability.

3. **Agricultural and Irrigation Systems:** Lessons learned from powering pumps in community aqueducts are directly applicable to irrigation districts in the western U.S., where water pumping for agriculture is one of the largest energy consumers.
4. **Critical Community Services:** The approach can be extended to health clinics, schools, and emergency shelters, ensuring that critical public services remain operational during outages through microgrids.

By positioning Puerto Rico as a living laboratory, this project creates a national model for energy-water resilience. The combination of DERs, advanced control, and digital twin validation ensures that solutions are not only technically sound but also scalable and replicable across diverse U.S. contexts.

Impact at the Energy-Water Nexus

- **Energy Resilience First:** Reliable electricity ensures continuous operation of pumps and treatment, transforming water access into a function of energy availability.
- **Dual Optimization:** Solutions explicitly co-optimize energy efficiency (cost, DERs penetration, ancillary services) and water availability (uptime, storage).
- **Innovation in Validation:** Use of digital twins + HIL for aqueducts ensures DOE-supported pilots are technically robust and scalable.
- **Community Empowerment:** Builds capacity not only for water management but also for local energy system management, bridging the knowledge gap in rural energy resilience.
- **Scalability:** Demonstrations create a framework for energy-secure water systems in other U.S. islanded and rural regions.

Success Measure

Evaluation will focus strongly on energy performance as the enabler of water resilience:

- Resilience: >95% uptime of potable water services; ≥7 days autonomous operation using solar + storage.
- Energy Efficiency & Independence: DERs penetration; reduction in diesel use; improved inverter and storage utilization via advanced controls.
- Grid Contribution: Ancillary services (volt/var, frequency response) from aqueduct loads validated in HIL and demonstrated in pilots.
- Societal & Economic Impact: > residents benefit from reliable water and energy services; > jobs created in installation and O&M of energy systems; stronger institutional cooperation between energy and water sectors.

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