

Title: Adaptive 3D Printed Micro-Hydropower for Resilient Grids: Digital-to-Deployment Framework

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Focal Area: Water for Energy

We propose to enhance the resilience of the U.S. electricity grid by enabling the rapid, adaptive, and on-demand manufacturing of site-specific micro-to-small hydropower systems for low-head dams (Fig. 1). This approach directly addresses the nation's untapped 85,000+ non-powered dams (NPDs) and low-head sites for resilient, distributed energy assets (Fig. 2). Specifically, the Department of Energy (DOE) has identified 51,000 dams as potential microhydro sites [Ref. 1], a resource that largely remains undeveloped because a majority of such sites lack a cost-effective solution for conversion. This challenge is compounded by the fact that over half (51%) of all U.S. dams are classified as very low head (17 feet of gross head or less) [Ref. 2].



Fig. 1 Low-head dam

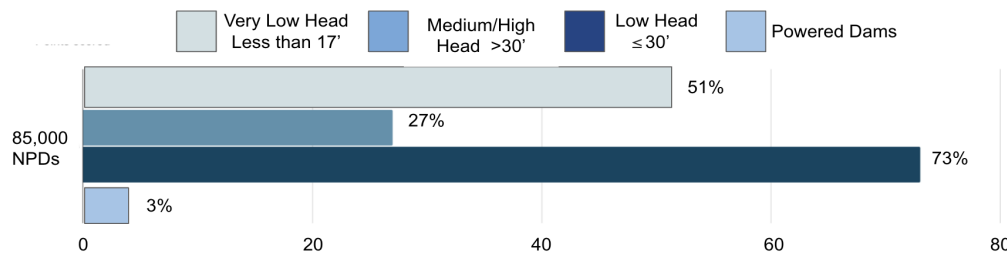


Fig. 2. U.S. Dam Head Distribution: The Low-Head Challenge and Micro-Hydro Potential. Ultra-low head is $\leq 10'$. [DeNeale, et al., 2022]

Existing Challenge: Hydropower systems, especially small-scale ones, are vulnerable to outages from precipitation change, floods, and damage to a turbine from debris which can lead to months or even years of downtime due to the long lead times for conventionally manufactured replacement parts [Ref. 3-4]. This is a critical issue for reliable local power and also our national resilience strategy.

Moreover, hydrological conditions are not static. For example, upstream land use, long-term weather change, seasonal variations cause changes in water flow rates over time. A turbine optimized for a site's 2025 conditions may be highly inefficient by 2035, becoming a depreciating asset that fails to deliver reliable power. This chronic inefficiency undermines the economic viability and long-term resilience of these installations [Ref. 5]. We propose a

solution that moves beyond static, one-size-fits-all hardware to an adaptive system that can adapt to and recover rapidly from disruptions.

Near-Term Opportunity: We propose to establish a complete digital-to-deployment (D2D) framework that leverages an award-winning collaboration between Oak Ridge National Laboratory (ORNL) and Cadens Hydro [Ref. 6-9]. This framework integrates high-performance computing, advanced manufacturing, and a robust domestic supply chain to deliver cost-effective, adaptive, and resilient hydropower systems. This effort addresses both components of the LCOE (cost and revenue) in a potentially significant manner. The generation portion of the LCOE is improved by designing turbines tailored for site specific conditions while cost is kept low with Additive Manufacturing (AM).

Partnership: ORNL possesses world-leading expertise in materials science, high-performance computing (HPC), and advanced manufacturing, including the Big Area Additive Manufacturing (BAAM) platform. Cadens Hydro is a U.S. company pioneering cost-effective, low-head hydropower solutions. Cadens utilizes modern engineering tools (CFD, FEA) and AM to create site-specific systems.

Proven record of collaboration [Ref. 7-9]: ORNL and Cadens proved the viability of this approach. Using ORNL's BAAM system, we successfully manufactured large-scale, end-use hydropower components (including conveyance: draft tubes, thimble adapters, and runner housing molds) from cost-effective, durable composites. These 3D-printed components have been in continuous operation at the Cadens Rome Mill Ultra-Low Head Test Facility for over five years without a single 3D-printed component failing. This real-world result demonstrates that AM-produced parts meet and exceed the durability requirements for the demanding hydropower environment.

WPTO Recognition: This approach was recognized by the Water Power Technologies Office as the top-placing winner of the Innovations in Advanced Manufacturing for Hydropower (I AM Hydro) Prize [Ref. 6], as in Fig. 3. This validation from WPTO confirms the high-impact potential of our approach to lower costs and fast deployment.

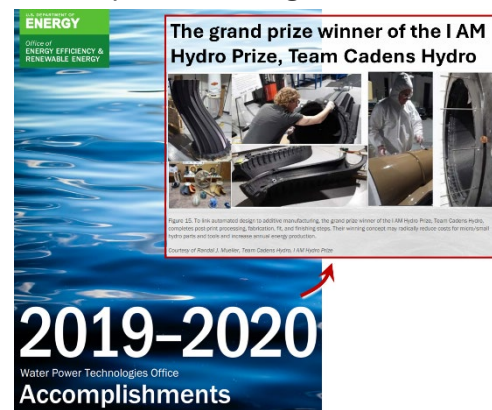


Fig. 3. Successful demonstration of the technology recognized by WPTO

Five-Step Solution: An Adaptive Manufacturing Framework

1. Create a Digital Library for Adaptive Design: We will leverage ORNL's HPC resources to dramatically expand an existing design library. We will perform extensive CFD simulations to create and validate a comprehensive digital inventory of turbine designs (runners,

blades, conveyance, casings). This library will be optimized for a wide matrix of site-specific flow parameters (e.g., flow speed, water volume, drop height, angle) [Ref. 10].

As a site's hydrology changes, the operator can simply order a new, re-optimized turbine from the digital library, ensuring peak efficiency and reliable power generation for the life of the dam. The digital design library and D2D framework enable the operator to rapidly order and install a new, optimally designed runner and inlet vane set to match seasonal or multi-year shifts in precipitation and flow.

2. On-Demand, Site-Specific Turbine Manufacturing: We will develop an on-demand manufacturing process and demonstrate the capability to select an optimal, site-specific turbine design from the digital library, manufacture it using 3D printing (Fig. 4, 3D-printed composite runner), and have it ready for shipment in days [Ref. 6-9].



Fig. 4. 3D-printed runner

A facility operator can report a damaged turbine and have a custom-fit replacement manufactured and delivered in under a few weeks, rather than the 6-12 month lead time from conventional casting or forging. This is a giant leap, especially for small-scale hydropower operations.

3. Field Deployment: We will select two to three non-powered dam or low-head sites from Cadens' pipeline. In partnership with site owners, we will install micro-hydropower systems featuring the new, adaptively designed and 3D-printed turbines.

4. Quantify Success Measure: We will continuously monitor the demonstration sites to gather the data on performance and resilience.

5. Build a Domestic Supply Chain: ORNL will connect Cadens with our established network of industry partners, including material suppliers (e.g., Techmer, Airtech) to ensure a scalable, low-cost supply of qualified advanced composite materials, and manufacturing service providers to create a distributed manufacturing network in US.

Success Measure: We will quantify success against multiple factors.

- Adaptation: >15% increase in Annual Energy Production (AEP) at a site with variable hydrology through installing an adaptively-designed AM turbine.
- Recovery: > 80% reduction in lead time for a critical turbine component.
- Cost: > 40% cost reduction as compared to the cast and machined equivalents.
- Durability: >10,000 cumulative operational hours across the new demonstration sites.
- Supply Chain: Establish formal agreements with at least two material suppliers and two manufacturing partners to validate the distributed manufacturing model.

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