Unlocking Hydropower Potential from Environmental Flows for Energy-Water Resilience

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Focal Area(s)

This white paper explores how environmental flow (E-flow) releases mandated for ecological sustainability at hydropower dams can be harnessed to support renewable energy production and enhance energy-water resilience. This concept strengthens grid flexibility, supports environmental stewardship, and leverages untapped energy moving through licensed bypass systems at existing hydropower facilities, an otherwise wasted resource. Unlocking this potential requires foundational research, integrated modeling, operational optimization, and decision-support tools that balance ecosystem needs with energy goals.

Existing Challenge

Environmental flow requirements have become standard in U.S. hydropower licensing under NEPA, FERC regulations, and decades of ecological research [1]. These flows maintain aquatic ecosystems and water quality but often bypass turbines, resulting in lost renewable energy opportunities [2].

Hydropower plants frequently spill these flows around turbines due to minimum flow thresholds misaligned with turbine operation or economic factors, creating persistent energy gaps. Many facilities predate modern environmental flow regimes, limiting retrofit and operational flexibility [3]. Climate-driven hydrologic variability further complicates fixed flow prescriptions, stressing both ecosystems and energy systems [4][5][6]. Hydropower capacity factors have declined since 1980, primarily due to aging equipment and operational shifts toward nonpower objectives [7]. Harnessing environmental flows offers a chance to recover lost generation [8].

Case studies illustrate the potential and barriers. These ground research in operational reality, building stakeholder confidence and guiding investments. Example highlights include:

- Select U.S. plants operate small “minimum flow” turbines recovering energy from mandated releases at modest scale [3]. As of 2016, only 42 facilities use e-flow turbines [9], though the number is growing. More plants utilize operational flexibility [8]
- E-flow turbines have higher potential capacity factors than the current fleet; many facilities could operate them at 50% or greater capacity [8].

- Adding e-flow units is far cheaper per unit than new hydropower development.
- Multi-agency projects use integrated modeling to optimize flow schedules balancing fish habitat and power generation [10].
- Retrofit potential varies geographically due to ecological sensitivities and regulatory challenges [11]. In some cases, operation of an E-flow unit in a bypassed reach must consider fish survival and the potential for using a fish-friendly turbine.

Despite advances, deployment remains limited by economic, institutional, and regulatory hurdles. No standardized framework exists to integrate hydrologic, ecological, and power system data for optimizing energy recovery from e-flows. Other challenges include lack of comprehensive data, limited owner/operator awareness, and budgeting constraints.

Near-Term Opportunity (Next 3–5 Years)

Though major hydropower projects have long timelines, the next 3–5 years present a critical window to advance research and preparatory actions enabling energy recovery from environmental flows:

- Advanced resource assessments and cost modeling: [8] provided the most comprehensive assessment, but accurate generation data covers only 10% of facilities. Hydrologic modeling and data mining can improve estimates for the remainder. Cost modeling could incentivize development.
- Modular opportunities: Assess market potential for prefabricated small-scale units, like InPipe Energy's HydroXS, a compact pressure-reduction turbine generating power without altering permitted discharges or ecological flows [12].
- Advanced manufacturing: Explore cost and time savings from applying advanced manufacturing to hydropower components, and leverage existing opportunity through the ORNL Water Power Technical Collaboration Program.
- Integrated modeling: Advance coupled hydrologic-ecological-power system models simulating e-flow impacts on ecosystems and generation under current and future climate conditions [10][13]. Models quantify trade-offs and retrofit opportunities.
- Collaborative data sharing: Strengthen partnerships among federal agencies, academia, utilities, equipment manufacturers (e.g., InPipe Energy), and environmental groups to share operational data and expertise, supporting site-specific and scalable solutions.
- Pilot demonstrations: Test turbine operation on environmental flows at select sites with minimal infrastructure changes to gather data on performance, reliability, and ecological outcomes [14]. Develop 3-D renderings of modular units.

- Decision-support tools: Develop platforms like ORNL's NPD Explorer integrating hydrologic forecasts, ecological needs, and grid operations for adaptive management balancing ecosystems and energy [14].
- Streamlining regulatory pathways: Collaborate with permitting authorities to clarify guidelines and reduce barriers for environmental flow retrofits. Early stakeholder engagement can accelerate development [11].

Together, these activities will build the scientific, technical, and institutional foundation necessary for future deployment of hydropower projects that capitalize on environmental flows, without overpromising immediate capacity additions.

Success Measure

Progress will be assessed through quantitative and qualitative metrics grounded in research, partnerships, pilot results, and policy integration, supported by case studies.

Quantitative Measures:

- Completion and validation of integrated modeling frameworks demonstrating accurate flow, ecological, and energy outcome predictions at multiple pilot sites (e.g., >20% forecast error reduction).
- A measurable increase in energy from environmental flows and reduction in spill at demonstration sites.
- Adoption of decision-support tools by hydropower operators and regulators within 3–5 years.
- Publication and dissemination of detailed research and case studies documenting operational strategies, energy recovery, resource potential, impacts, affordability, and acceptability.

Qualitative Measures:

- Formation and engagement of multi-stakeholder partnerships via agreements, publications, and shared platforms.
- Inclusion of modeling tools in regulatory planning and relicensing studies.
- Positive stakeholder feedback on pilots and tool usability.
- Development and acceptance of streamlined technical standards.
- Increased policy recognition of environmental flows as a strategic energy-water resilience asset, reflected in federal research agendas and funding priorities.

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