Making Small Hydro Development Affordable and Acceptable

The authors are working on an approach — called standard modular hydropower — intended to standardize the process to develop small hydro in the U.S. and reduce costs across a variety of sites.

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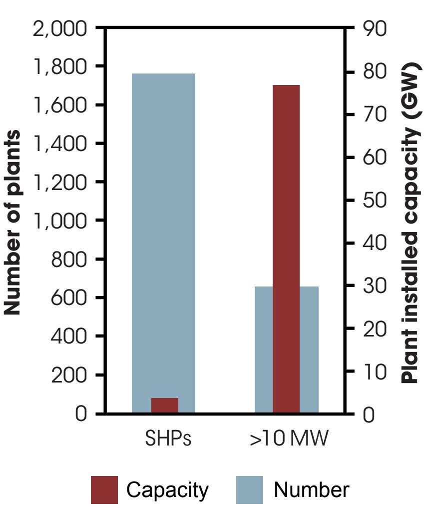
Recent small low-head hydropower development in the U.S. has occurred at non-powered dams and irrigation canals, a significant break from historical development at sites without existing hydraulic and dam structures. The latter is termed greenfield development or new stream-reach development (NSD). These sites are the bulk of the existing technical hydropower resource potential in the country. The financial viability and feasibility of NSD is influenced by: development risk and uncertainty associated with the cost and duration of the licensing process, the cost of site-specific design and customization of equipment and structures, and evolving environmental constraints on design and operation.

Sustainable hydropower development must address these challenges with new thinking and transformational technology and facility design. The resulting hydropower deployments will necessarily feature significantly reduced costs, smaller physical and environmental footprints, and greater stakeholder acceptance than conventional hydro. Oak Ridge National Laboratory is leading a multi-year research and development effort to accelerate the progress of small hydropower development toward this end.

Figure 1 — Small/Large Comparison



Small hydropower by the numbers

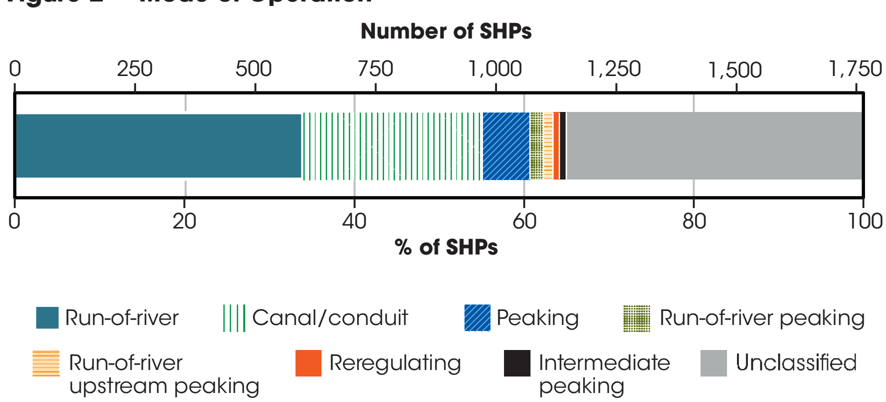
This article defines small hydropower projects (SHP) as having less than 10 MW of capacity. There is about 3.8 GW of SHP capacity in the U.S from more than 1,700 plants with roughly 3,500 units (see Figure 1). The SHP population represents 73% of all hydropower plants but only 4.7% of installed capacity. However, SHPs remain a valuable contributor to U.S. renewable energy supply. In 2015, SHPs generated 13.6 million MWh of energy, roughly equivalent to the aggregated outputs of the landfill gas, geothermal and small-scale solar PV sectors.

U.S. SHPs have median and mean capacities of 1 MW and 2.14 MW, respectively, and tend to be low- to medium-head (median of 23 ft, majority less than 100 ft). One in five SHPs are in canals or conduits; most others for which data are available are run of river (see Figure 2). The first SHP on record began operation in 1891, and SHPs played an important role in U.S. electrification to 1930. About half of operating SHPs were commissioned in a second development wave in the 1980s. SHPs are present in 46 states, with more than half of SHP capacity in California, New York, Idaho, Wisconsin and Michigan (see Figure 3, page 52).

Project cost

Total installed costs for conventional low-head SHPs can be double or triple those of larger or

Figure 2 — Mode of Operation



high-head facilities on a dollars-per-kilowatt basis. An assessment of recently installed low-head SHPs, even those built on existing infrastructure, shows civil works (site preparation, hydraulic structures, water conveyances, and a powerhouse) account for more than 50% of total installed cost, with electromechanical equipment typically a minority fraction of costs.[1] Site-specific design and construction are primary cost drivers — an estimated 75% of SHP costs arise from activities and components tailored to location and site conditions, with 25% arising from equipment design, manufacturing and acquisition.[2] The uncertainty and expense associated with site-specific civil works — i.e., design and construction of a custom large impoundment structure — makes development rare, with only three SHPs greater than 1 MW constructed in the past decade.[3]

Environmental impact mitigation

Environmental assessment and prevention or mitigation of significant impacts is a necessary part of hydro development. An analysis of relicensing proceedings over the past 15 years,[4] including more than 300 SHPs, sheds light on the breadth and complexity of environmental and recreation mitigation requirements developers of greenfield SHPs may encounter (see Table 1 on page 52). Common mitigation requirements include recreational management plans, minimum flow releases and water quality monitoring. This analysis only includes mitigation that was identified in each facility's operating license; other mitigation can arise later from required studies and plans that do not necessarily become license conditions.

Regulatory approval timelines

Since the 1980s boom (see Figure 4 on page 54), greenfield development of SHPs has stalled. Of the more than 1,500 hydropower applications filed with the Federal Energy Regulatory Commission (FERC) since 2000, preliminary permits have been requested for 127 greenfield SHPs. Only seven plants, totaling 24.4 MW and mostly in Alaska, have received a license, with many of these yet to be commissioned. The mean time from preliminary permit application to license receipt for SHPs is more than five years (see Figure 5 on page 54). This lengthy process, uncertainty of success, and expensive site-specific design and construction make SHP development challenging and uncompetitive in an evolving energy landscape with low-cost natural gas and decreasing costs for wind and solar.

Opportunities and challenges

Greenfield development of SHPs is at a crossroads. While pursuit of SHPs on non-powered dams and canal and conduit infrastructure continues, the more significant potential from NSD of SHPs is not being pursued. A 2014 study suggests roughly 29 GW of technical SHP potential across more than 10,000 sites,[5] but the *Hydropower Vision Report* predicts no deployment of new SHPs over the next 30 years under a business-as-usual modeling scenario.[6]

The report also presents scenarios in which technology costs can be reduced and environmental challenges addressed to enable development of more than 10 GW of greenfield SHP. The extent to which this opportunity can be realized is a function of how well R&D can

Table 1: Environmental Impact Mitigation Measures at SHPs Relicensed between 1998 and 2013

Mitigation Requirement	Number of SHPs where Required	Percent of SHPs under Study
Recreational management plan study or monitoring	234	71
Run-of-river tailrace	161	49
Operations compliance monitoring plan	158	48
Sediment and erosion control plan or monitoring	143	43
Water quality monitoring plan	142	43
Species conservation management monitoring	119	36
Other day use area improvements	117	36
Tailrace flow monitoring plan	115	35
Canoe portage launch	98	30
Parking	89	27

address the fundamental challenges of project economics and environmental complexity.

A new approach: rationale for standardization and modularity

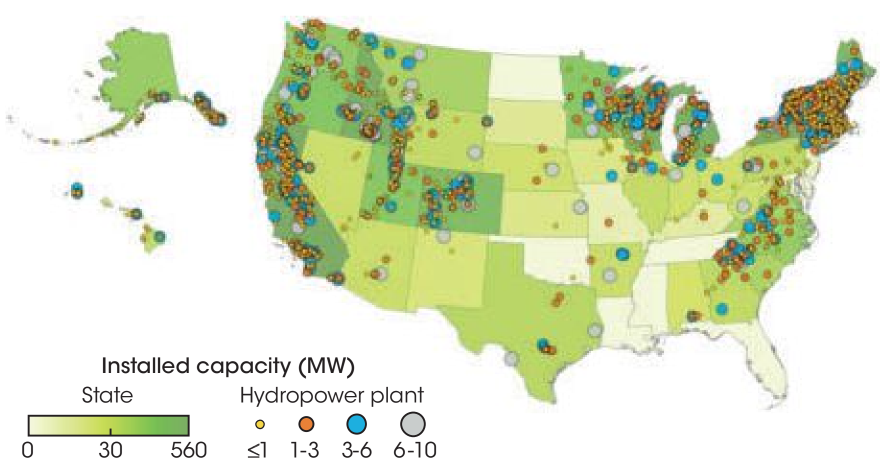
SHP development will remain stalled unless a new approach to assessment, design, installation, commissioning and operation emerges. Research funded by the U.S. Department of Energy is advancing such an approach, called Standard Modular Hydropower (SMH). It is not a design, but a standard approach to classify potential sites and specify the necessary and salient features of modular hydropower designs.

A standard modular facility can be conceptualized by deconstructing an SHP into discrete functional units, each with a dedicated purpose and a common interface. These units are defined as generation, passage, foundation and interconnection modules. The generation module contains a turbine, generator, and all equipment and systems necessary to convert moving water into electrical energy. Passage modules ensure the safe, consistent and reliable transport of water, fish, sediment and small recreational craft across the facility. Foundation modules provide structural resistance and reliably interface with the streambed to support and stabilize the generation and passage modules. Interconnection modules encapsulate the equipment and systems that connect the facility to the grid or electricity consumers.

The combination of modules required at a site is derived from energy characteristics, environmental context and stream-reach functionality — a modular facility must deploy at a competitive total installed cost while maintaining the integrity of specified stream-reach functions and producing sufficient revenue streams to ensure economic feasibility. The SMH hypothesis is that a limited number of rigorously validated modules can be designed to integrate with minimum cost and maximum value at a single site and across multiple sites.

The main goals of SMH research are to develop standardization and modularity as essential principles for SHP cost reduction, accelerate the development of new structures and machines that ensure important stream functionalities are maintained at a site, and achieve wide stakeholder acceptance and approval to enable increased deployment.

Figure 3 — Geospatial Distribution



Modularity for design efficiency, scalability

The most visible form of modularity in SHP development is turbine-generator modules that form a comprehensive "water-to-wire" package, including bulb, tubular and rim-rotor packages. In contrast, civil works and passage structures are regularly designed using custom specifications following site-specific assessments, often with great cost. Modularity across the balance of plant is not a proven or accepted concept.

The SMH approach assumes assembly of the entire SHP from prefabricated modules that scale across a single site and across multiple sites. For example, a weir or water passage module validated and designed with a common form factor could be deployed in parallel across a stream, creating a modular civil structure. This module could be deployed at sites that share similar hydrologic and geotechnical characteristics. Similarly, most fish ladders are composed of modular form factors, with baffles, orifices, or small pools and weirs that repeat in series at a pre-determined length along a pre-determined slope. A fish passage module could be scalable by increasing or decreasing the number of these internal structural elements to change the overall length or slope. It is common practice to scale installed capacity by increasing or decreasing the number of turbine-generator units. A standard modular approach expands this practice by integrating generation, passage and foundation modules into a modular facility.

Wide adoption of modularity in SHP development would yield benefits throughout the project life cycle. Prefabrication of modular units enables offsite construction and the potential for accelerated construction timelines. Limiting "in-the-wet" construction time at a site reduces risks to equipment and personnel. Design and cost efficiency is achieved at large volumes when modular designs can be repurposed at multiple sites. Upgrades and refurbishments can be made simpler and more cost-effective if individual modules can be easily removed and replaced.

Modularization of the facility will not yield significant cost reductions or environmental performance improvements, however, without a standard approach to classify sites based on environmental variables and use of the classification system to specify consistent technical, economic and environmental design criteria.

Standardization for cost efficiency and consistent development outcomes

The SMH approach challenges the assumption that all SHPs are site-specific. While site-specific assessments and concerns are unlikely to disappear completely from SMH development, a hypothesis is that there are opportunities to address many heretofore site-specific issues with standard processes and components that are validated to preserve stream functionality.

Drawing on concepts and methods used to classify and organize river ecosystem complexity, site classification relies on a standardized statistical analysis to classify more than 100,000 U.S. stream reaches into a finite number of clusters based on environmental inputs. Site classification reveals common relationships among groups of stream reaches with differing environmental characteristics – for example, a recent hydrologic classification study identified 12 distinct clusters of hydrologic behavior across the U.S.[7] Clusters are identified based on:

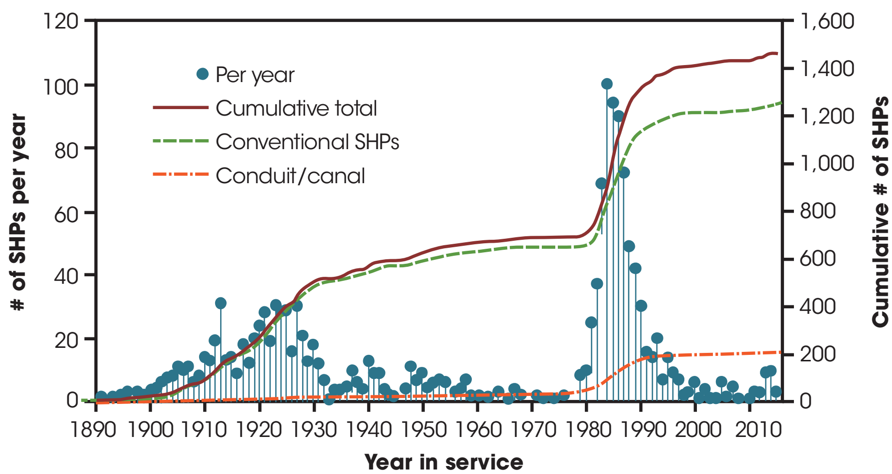
- Physical and biological characteristics (e.g., mean annual flow, stream gradient, types of resident and migratory fish species);
- Natural functions they support (e.g., spawning habitat for fish, downstream sediment transport regimes); and
- Watershed and stream network processes that influence stream processes (e.g., riparian cover and shading, nutrient loadings from watershed runoff).

Clusters provide a template to generalize how standard design specifications can be formulated to sustain common stream functionalities. For example, five to 15 clusters could be used to define the variability in sediment load and transport throughout the country. Sediment passage module design specifications are developed to ensure modules deliver the specific functionality demanded of each cluster.

To enable cost efficiency, standard modules must deliver specific functionality at many stream-reaches within a given cluster, with little or no modification to their design features. This is easiest to envision for generation modules, which exhibit a standard performance curve for a given range of head and flow. Hydroelectric energy can be delivered reliably by the same module design (e.g., same blade shape, runner diameter and distributor alignment) at many sites by deploying an appropriate number of generation modules and developing an optimized unit dispatch curve for each site. A standard design envelope specification would set bounds on installed cost, unit efficiency, safety, size, maintainability and design life that must be achieved by each module.

This same concept can be applied to foundation and passage modules. For example, standard upstream fish passage modules

Figure 4 — Year in Service



must possess favorable geometry and create consistent hydraulic conditions that encourage fish to cross the facility in a safe and timely manner. To guide early stage research, a standard modular design envelope specification has been developed that outlines the requirements, constraints and performance measures for all modules.[8] ORNL is working with industry to identify and validate exemplary modules that meet the design envelope specifications for performance, cost, safety and reliability.

A desired outcome of standard site classification and module design envelope specification is consistency, predictability and acceptability of SHP development outcomes. Standard modules known to reliably deliver passage, generation and foundation functionalities could accelerate the technology selection process, agency consultation process, environmental review and approval process, and state and local certification approval. Success in this endeavor will require not only demonstration and validation of modular facilities and their limited impacts, but sustained communication and collaboration across multiple SHP stakeholder groups.

Steps to SMH success

The envisioned end-state of the SMH research project is a stakeholder-validated and -used framework, including criteria, models, design tools and assessment protocols for specifying, designing, simulating, testing and demonstrating the efficacy of modular hydropower facilities. To achieve this outcome, ORNL is employing a systematic approach to demonstrate modularity, standardization and environmental performance.

Demonstration of modular technologies

SMH success relies on effective demonstration of modules developed and designed within the design envelope specification. Early stage demonstrations of generation and foundation modules have been supported recently by grants from DOE's Water Power Technologies Office. Further development of passage modules, simulation tools and testing capabilities is needed to assess and refine the SMH concept. Design simulations and rapid prototyping followed by scale modeling and field validation testing will establish baseline knowledge and proof-of-concept guidelines for hydraulic, electromechanical, structural and environmental performance.

Demonstration of modular facilities

Demonstration of a modular facility comprised of generation, passage and foundation modules would provide a much-needed benchmark for SMH technical and economic feasibility. Modules must work together to deliver their requisite functionalities with efficiency and consistency. The desire for enhanced functionality at lower cost demands innovative and disruptive new facility designs.

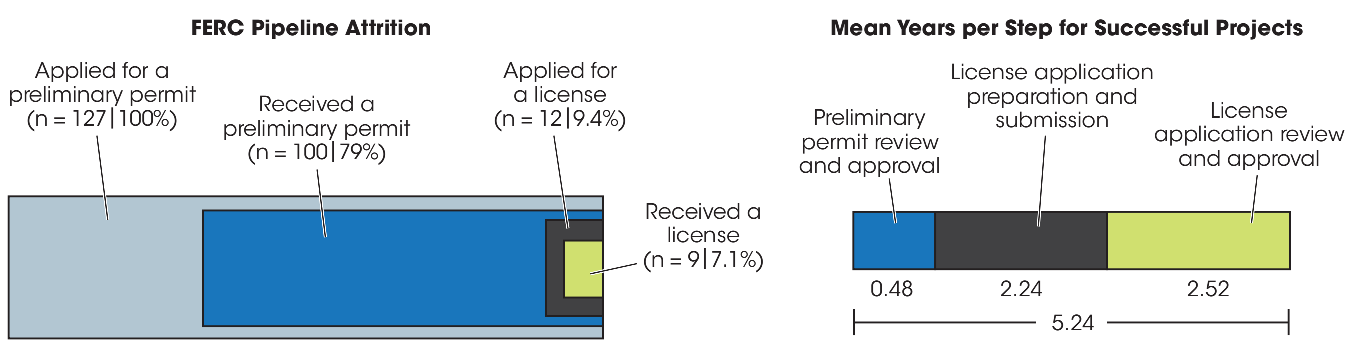
Validation of environmental performance

One key concept underpinning the SMH approach is minimizing environmental impacts from construction to operation. However, hydrologic, geomorphic and ecological responses can never be predicted with complete accuracy, and rigorous validation will be required to assess whether an SMH facility operates as intended. Validation and assessment could be required on a spatial scale of a module, facility, stream reach, or watershed, and on a temporal scale anywhere from minutes to years. In some cases, a combination of several spatial and temporal scales is appropriate. Coupled SMH-environmental systems modeling and simulation along with physical and laboratory testing can be used to guide pre-deployment environmental validation.

Communication and collaboration

Consultation with project stakeholders — including land owners, environmental and recreational advocacy groups, state and federal regulators, and financial institutions — is a fundamental requirement of the SHP development process. Each stakeholder maintains specific requirements, constraints, concerns, values and expectations that must be addressed for a project to receive a license. Stakeholder

Figure 5 — FERC Docket Activity for Small Hydro



acceptance hinges on how well the intersection of project economics and environmental complexity is defined and addressed with specific solutions. A standardized approach to modular development also demands a high degree of knowledge-sharing and collaboration across stakeholder groups, including a common understanding of different module designs, interfaces, impacts, functionalities and limitations.

We welcome feedback and collaboration. Visit http://hydropower.ornl.gov/smh. ■

Acknowledgements

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Notes

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