Cost-Disruptive, Low Impact, Modular Form Factor Low-Head Hyropower System

FINAL TECHNICAL REPORT

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Prime Recipient:	Littoral Power Systems, Inc., New Bedford, MA
Teaming Members:	GZA GeoEnvironmental, Inc., Norwood, MA Alden Research Laboratory, Inc., Holden, MA and Fort Collins, CO University of Massachusetts – Dartmouth, MA National Renewable Energy Laboratory, Golden, CO AECOM, Seattle, WA

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Team Members Contributing to the Project

Littoral Power Systems, Inc. (LPS) develops and sells equipment to help government, municipalities, utilities, and power developers build new or expanded facilities to harness electricity from water in new ways that reduce costs, environmental impacts and regulatory timelines as compared to traditional hydropower. LPS personnel (employees/contractors) that supported the project are:

David Duquette, Co-PI, concept leadership, commercialization focus, LCOE
Katherine Leighton, Project Manager
Wayne Dyok PE, hydropower consultant
John Ashbure, financial consultant, LCOE
Jeff Glick, CFO
Alex Matathia, intern summer 2016
Haines Duff, intern summer 2016
Brandon Xu, intern summer 2016
Kelvin Nguyen, intern summer 2018, leakage tests

GZA GeoEnvironmental, Inc. (GZA) is an engineering consulting firm with over 50 years of experience in geotechnical, environmental, dams, and water resources engineering. GZA's expertise in dams and hydropower engineering includes inspection, analysis, and design work. GZA has designed new dams, rehabilitated existing dams, and removed obsolete dams. GZA has also worked extensively in the small hydropower field, assessing and designing hydropower facilities and helping in the testing of new turbine technologies. GZA has 28 offices throughout the Northeast and Great Lakes areas and employs over 550 engineers, scientists, and support staff. Headquarters, and the majority of its dams and hydropower staff, are located in Norwood, MA. GZA personnel who supported the project are:

Chad Cox PE, Co-PI, technical and engineering leadership
Bin Wang PE, geotechnical and dam safety analysis
James Guarente, PE, project management

Alden Research Laboratory, Inc. (Alden), Founded in 1894, is the oldest continuously operating hydraulic laboratory in the United States. Alden provides project conceptual design, detailed design, biological/fisheries studies, analytical modeling, CFD, field measurements, physical modeling, precision flow meter calibrations, structural analysis, FEA, and field- testing. Alden has extensive experience in providing specialized hydraulic engineering services in support of hydropower facility and dam design; includes regulatory support, facility upgrades, facility design, and analysis in support of dam removal. Alden is a U.S. leader in providing these services for reservoirs, intakes, spillways, outlet structures, penstocks, and fish passage facilities. Alden personnel who supported the project are:

David Schowalter PhD, project manager
Mark Graesser PE, structural design lead, project manager
Rhonda Young PE, structural design and analysis
Greg Allen PE, turbine module development
Will Fay, hydraulic engineering
George Hecker, PE, Technical consultant on turbine/penstock, fish safety
Mitch Peters, CFD modeling
Brian McMahon, seal design and testing
Hannah Densten, intern summer 2016, turbine survey

College of Engineering
UMass Dartmouth

University of Massachusetts – Dartmouth (UMass-D) has deep strengths in fluid mechanics and hydraulic analyses across a wide variety of marine and river settings. The Coastal Engineering and Fluid Mechanics (CEFM) Laboratory, directed by Dr. Daniel MacDonald, is active in hydraulics related research associated with fossil fuel and renewable energy applications. The Director's experience also includes dam break and dam safety analysis. UMass-D personnel who supported the project are:

Prof. Daniel McDonald PhD, PE, PI for spillway module
Michelle Winchell, student obtained her MS in CE, hydraulics and spill analysis
May May Khin, undergraduate student, LCOE site screening

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

National Renewable energy Laboratory (NREL) includes an experienced team that develops computational models and exercises them to assess the impacts of technology innovations on the levelized cost of electricity for many renewable energy technologies, including marine and hydrokinetic, offshore wind, land-based wind, and solar. Team members are leaders of national projects investigating scenarios for the US to have 80% of its power from renewable sources by 2050. Leveraging long term experience from land based-wind, lessons learned during the past decade about marine energy and offshore wind, and what has been learned in worldwide marine and hydrokinetic device testing, NREL has developed a risk management framework to speed commercialization. NREL personnel who supported the project are:

D. Scott Jenne, LCOE model development
David Snowberg PE, PMP, risk register guidance
Elise DeGeorge, coordination, reference site selection guidance

AECOM is an international engineering and construction firm that includes expertise in the planning, permitting, design and construction of dams and hydroelectric generating facilities backed by more than 100 years of experience in the water-resources market. AECOM supported the project by developing a detailed description of the steps in a construction process, schedule and engineering cost estimate for an h-Modulor facility. AECOM personnel who supported the project are:

Tom Young, PE, supervising civil/mechanical engineer
David Staley, PE, Chief Engineer
Nausherwan Hasan, Supervising civil/structural engineer
Douglas Hartsock, PE, Chief Engineer
Amgela Kangas, project control
Adam Carlton, engineer, project management

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Executive Summary

Littoral Power Systems, Inc. (LPS) is writing a new story when it comes to turning the natural power of water into electricity. h-Modulor™ is a new way of designing and building hydropower plants that addresses the crucial issues of cost, environmental impact and regulatory time frames.

For decades hydropower developers, owners and operators have struggled to build new or expanded facilities that didn't cost so much, were friendlier to the environment and didn't take so much time to license or build. The problem is particularly acute in smaller installations. The burdensome regulatory pathway for projects under 10MW in capacity have eased the licensing requirements for small hydro projects. But in small projects are still very hard, because capital costs are a much larger percentage of the generation revenues than they are in large facilities. There is an acute need for a cost effective solution.

Understanding this need and opportunity, LPS conceived a new type of hydropower equipment – a kit of standard, pre-fabricated modular parts for dam safety, power generation, spill control and other hydropower facility functions to be used to build and operate a hydro plant at substantially lower costs than are currently achievable. This system of prefabricated parts also showed promise to reduce environmental impacts, reduce engineering time involved in the licensing process, and possibly provide a new way for regulators to think about licensing that could lead to reduced regulatory timeframes.

Because of this invention's compelling and intriguing promise the Department of Energy's (DOE) Water Power Technology Office (WPTO) awarded funding to LPS through the Office of Energy Efficiency and Renewable Energy (EERE) to develop this new type of hydropower equipment to meet a levelized cost of energy (LCOE) goal and analyze it for dam safety.

LPS teamed with professional engineers, PhDs, and geotechnical consultants from GZA GeoEnvironental, Inc. (GZA), Alden Research Laboratory (Alden), University of Massachusetts – Dartmouth (UMass-D), the National Renewable Energy Laboratory (NREL) and AECOM. In collaboration with the engineers and managers at the WPTO and EERE they matured the concepts through substantial design shifts.

The project exceeded the original goals and delivered designs beyond the proof-of-concept stage backed up by thorough professional engineering analysis of stability, seepage, and structural integrity. A full-scale section with seals successfully retained water in full-head leakage tests. Construction plans and professional engineering cost estimates indicated an LCOE half of the original LCOE goal. A system of these modules is now on track to be used in a 4.5 MW commercial installation.

Introduction

Fueled by renewable energy policy, incentives and state mandates, photovoltaic solar power and wind power have gone mainstream. These sources, however, impose fundamental problems on managing electricity supply when they are connected to the electrical grid. They only produce energy when the sun shines or the wind blows and the amount of electricity they produce is unpredictable. Grid operators say it is not dispatchable; they cannot just turn it on and off when they need it. To accommodate this variability and unpredictability grid operators usually keep excess reserves of fossil fuel, nuclear or hydropower generators running.

Hydropower plants, on the other hand, provide a renewable fuel supply that provides more stable and predictable power output than solar or wind. In addition, realistically achievable capacity factors at hydroelectric plants typically far exceed those of other renewable energy facilities. Despite these advantages, the growth of hydropower generation in the U.S. has slowed considerably while the growth in other forms of renewable energy -- especially wind -- have accelerated. The primary reason for the small amount of new hydroelectric capacity in the US is the complex and lengthy regulatory pathway and environmental pushback associated with blocking fish and recreational passage in rivers, combined with the cost implications. Hydropower developers, owners and operators have been struggling to navigate through the environmental concerns and regulatory requirements in a timely fashion and to face the daunting task of securing financing once they have authorization.

Policy is beginning to allay the regulatory burdens. The Hydropower Regulatory Efficiency Act of 2013 eased the licensing regulations for qualifying conduit facilities exempting them from FERC licensing. It also expanded the definition of small hydroelectric power projects at existing dams to include facilities up to 10 MW making them exempt from licensing requirements.[1] The America's Water Infrastructure Act of 2018 implemented an expedited licensing process for eligible hydroelectric projects at non-powered dams ensuring a maximum licensing timeline of two years. It also expanded the definition of a qualifying conduit facility from a maximum of a 5 MW capacity to include up to a 40 MW capacity.

Small hydropower imposes a small environmental impact since these facilities impound so little water, especially if they are run-of-the-river facilities where by definition the flow of water into the facility equals the flow of water out of the facility in real time. Those small hydropower facilities that incorporate existing infrastructure such non-powered dams or conduits have an even smaller environmental impact. For certain small hydropower facilities (<10 MW capacity) associated with non-powered dams, financing is easier to come by since they may qualify for loans from the US Government at discounted interest rates.[2] The problem is that in

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[1] Per Section 405 of the Public Utility Regulatory Policies Act of 1978

[2] Sections 402, 403 and 404 of the Public Utility Regulatory Policies Act of 1978

this small hydropower regime it becomes harder and harder to make a profit because capital costs are a much larger percentage of the generation revenues than they are in a large hydropower facility.

The US Hydropower Market Research Report 2018 Update prepared by Oak Ridge National Laboratory for the WPTO indicates that reform is working (Figure 1). The pipeline of new hydropower projects is growing and the large majority of this growth is in conduits, non-powered dams, and small hydropower.[3] More and more projects are being authorized, e.g. by FERC license or exemption, but they are not being built. A wall is forming at "Issued Authorizations" and it is more than just a timing issue. LPS personnel have had numerous conversations with developers and owners of some of these sites in the pipeline and learned that the construction delay is almost always because of the interrelated issues of facility capital costs, financing and power prices. Hydropower project developers, owners and operators are struggling to make a profit at small hydropower facilities.

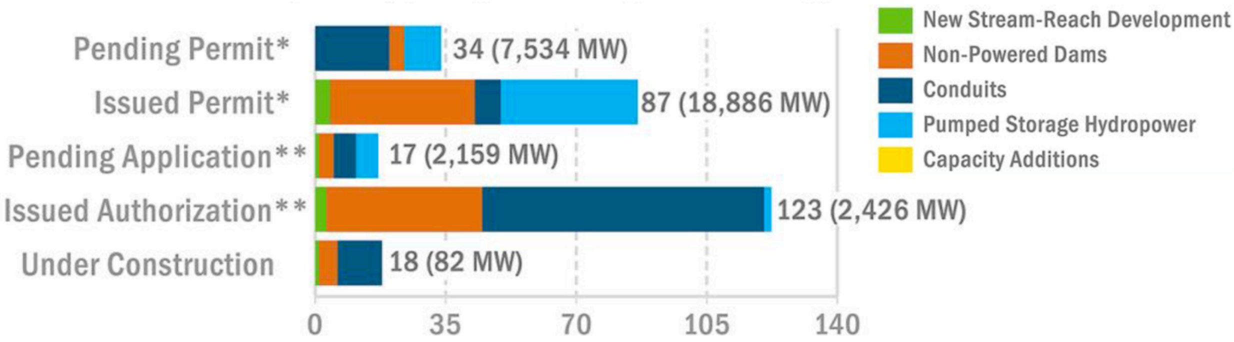

Figure 1: *U.S. hydroelectric power project pipeline as of the end of 2018. Figure taken from U.S. Hydropower Market Research Report 2018 Update (April 2019).*

If innovative equipment and processes can solve the cost problem, there is an immediate market opportunity to sell this equipment into the hydropower development pipeline. In the long term the opportunity is even greater, but so are the challenges. The DOE 2016 Hydropower Vision Report[4] analysis indicates potential for approximately 17 GW in capacity of hydropower growth at new stream-reaches (i.e., greenfield sites), but only if there are innovative – even transformational – advances in technologies to reduce costs and meet environmental performance objectives.

LPS has invented and patented a kit of standardized parts i.e. modules, and a process to assemble them into a hydropower facility that solves this cost problem to make low-impact,

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[3] Pumped storage hydropower, also shown in the figure, is a separate topic and is not addressed herein.

[4] https://www.energy.gov/eere/water/downloads/hydropower-vision-report-full-report

small hydro profitable. The kit of modules is based on the scale and proportions of standard shipping containers and is trade named h-Modulor.

This report summarizes the development of h-Modulor under an award from the DOE by discussing:

- The products and processes that were developed;
  - design and performance;
  - construction & assembly;
  - cost analysis;
  - summary of benefits; and
- The project objectives, activities and accomplishments.

Products and Processes

Overview of h-Modulor

h-Modulor is a pre-fabricated, standard kit of modules and parts that can be rapidly assembled to create a low-cost, low-impact, low-head hydropower facility. The modules are manufactured in the shape and size of standard multimodal shipping containers for low cost transport and pre-assembly. These container-modules can be assembled into three primary functional stacks: a Dam Module Stack, a Spillway Module Stack and a Power Module Stack. The Power Module Stack also includes a non-structural downstream extension container-module that contains the draft tube. Figure 2 shows these stacks in the center image left to right – Dam Module Stack, Power Module Stack with a Draft Tube Extension behind it (see the left hand image of Figure 2), another Dam Module Stack, then two Spillway Module Stacks with the crest gates open, i.e. laying flat down against the top of the Spillway Module Stack. The right most image of Figure 2 shows a cylinder gate over the turbine/generator that is used to open and close flow into the turbine. It also shows the spillway gates closed, i.e. in their most vertical position stopping the flow of water.

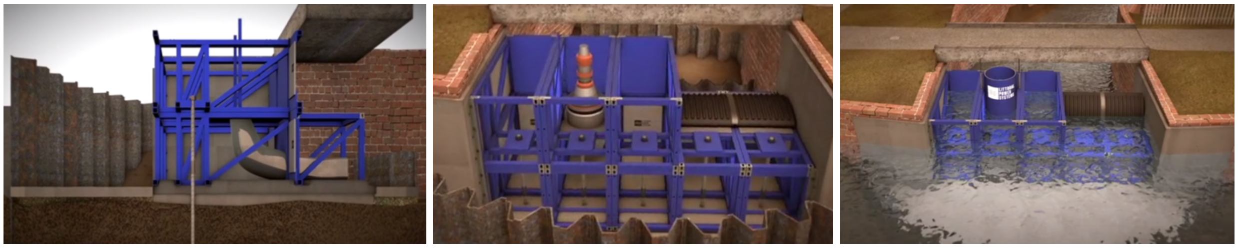

Figure 2: *A small h-Modulor hydropower facility featuring two Dam Module Stacks, one Power Module Stack with a Draft Tube Extension Module, and two Spillway Module Stacks.*

These three types of stacks are placed side by side to build a hydropower facility. h-

Modulor may be freely configured to suit the specifics of each site. Stacks may be two container-modules high or three container-modules high. Since each stack has been designed to be structurally independent there is no practical limit to the breadth of a site that could be served by the h-Modulor system. Figure 3 illustrates this flexibility showing the transformation from a very small site with one turbine generator and five two-container-module high stacks to a larger site with six turbines and 18 three-container-module high stacks.

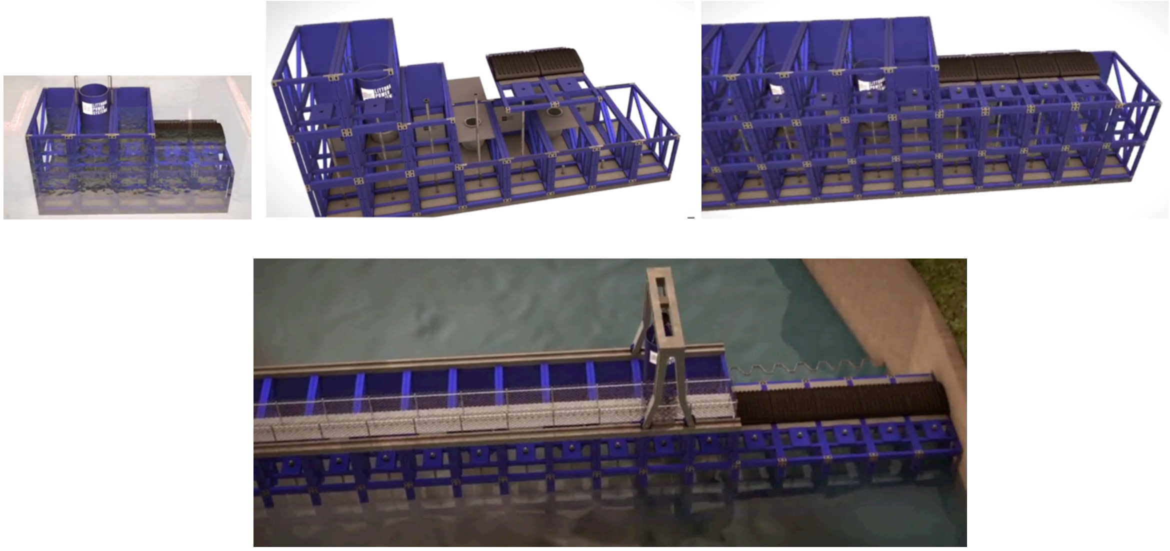

Figure 3. *Flexibility of the h-Modulor system to build a small one-turbine site or a larger six-turbine site all with the same standardized modules.*

Dam Module Stack

The Dam Module Stack is made up of two or three container-modules stacked on top of each other. Each stack is oriented with the long dimension parallel to local flow. A water-retaining bulkhead is located at the downstream face of the stack. Each stack can be used to house systems such as the turbo machinery or water release gates to create a Power Module Stack or Spillway Module Stack. Adding a knife valve or slide gate to the water-retaining bulkhead at the bottom of the Dam Module Stack allows it to serve for low water release and/or sediment release.

A three-container-module high stack is 29.5 ft tall and 8 ft wide. For this stack configuration, civil engineers from GZA analyzed the stack for global stability including sliding, overturning, uplift, seepage and leakage.

Global Stability

Since h-Modulor is site-agnostic – a characteristic leading directly to cost benefits - the stability analysis did not tie the h-Modulor dam to a specific site. Rather, engineers assumed boundary loading conditions related to the loading diagram shown in Figure 4 to evaluate the maximum allowable loads under each foundation type (soil and bedrock) to meet the required factors of safety (FOS) according to Federal Energy Regulatory Commission (FERC)[5] and US Army Corps of Engineering (USACE)[6] standards. Table I presents the results of the calculations showing that a three container-module high Dam Module Stack secured according to design specifications meets safety standards for stability (including sliding, overturning and uplift) for four different loading conditions on two different type of foundations. While assumptions need to be verified for specific sites this approach reduces the engineering effort that will be required for determining stability at future hydropower projects.

Table I: Results of global stability analysis

Foundation	**Load Case**	**FOS Against Sliding**	**Overturning Stability – Location of Resultant Load**	**FOS Against Flotation**
Concrete on sand/gravel	Normal pool at 27’ above base	2.5 (≥ 1.5)	Middle 1/3	> 2
Concrete on sand/gravel	Flood pool at 37’ above base	1.5 (≥ 1.5)	Middle 1/2	> 2
Concrete on sand/gravel	Normal pool + 3’ ice thickness	1.5 (≥ 1.5)	Middle 1/2	> 2
Concrete on sand/gravel	Normal pool + earthquake acceleration of 0.32g	1.3 (≥ 1.3)	Within base	> 2
Concrete on bedrock	Normal pool at 27’ above base	3.1 (≥ 1.5)	Middle 1/3	> 2
Concrete on bedrock	Flood pool at 37’ above base	1.5 (≥ 1.5)	Middle 1/2	> 2
Concrete on bedrock	Normal pool + 3’ ice thickness	1.5 (≥ 1.5)	Middle 1/2	> 2
Concrete on bedrock	Normal pool + earthquake acceleration of 0.32g	1.3 (≥ 1.3)	Within base	> 2

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[5] **FERC, 2016**. Engineering Guidelines for the Evaluation of Hydropower Projects, Federal Energy Regulatory Commission (FERC), March 2016.

[6] **USACE, 1995**. Gravity Dam Design, EM 1110-2-2200, U.S. Army Corps of Engineers (USACE), June 1995.

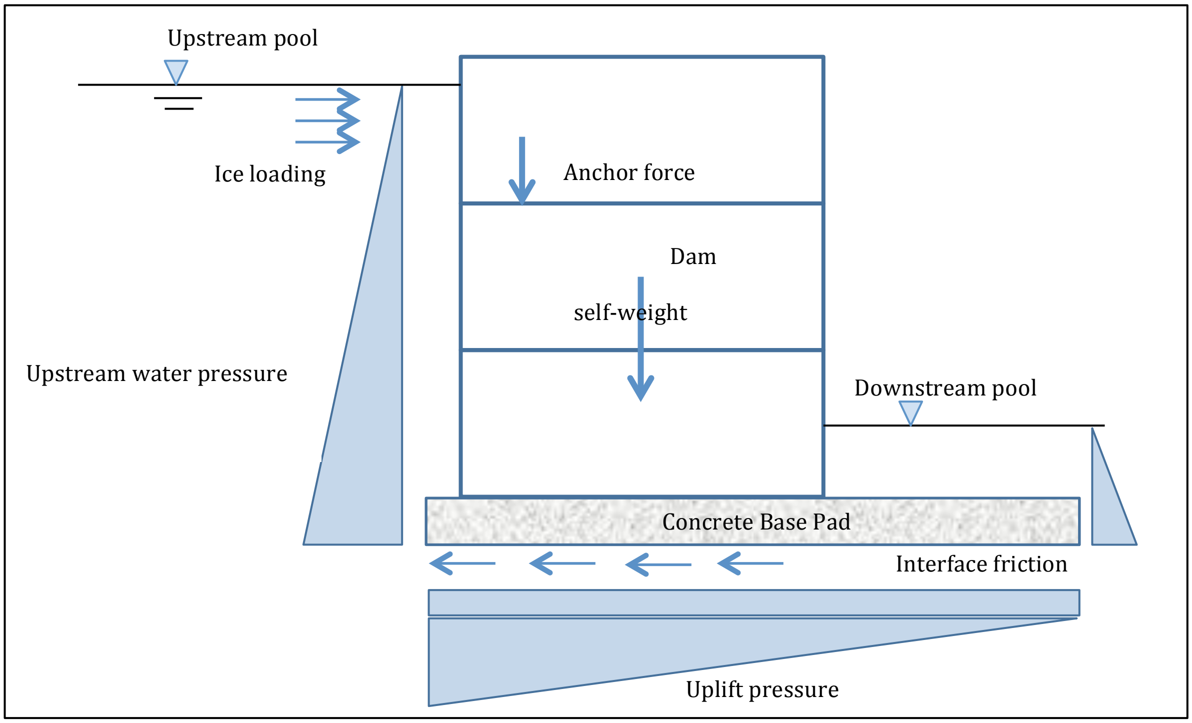


Figure 4: *Free-body load diagram for Dam Module Stack comprised of three container-modules stacked on top of each other. Note the flood water level is not shown for clarity and the earthquake loading not shown.*

Seepage

Seepage of water from upstream through the soil under the dam can induce unsafe conditions if it is not managed. It causes uplift pressure (see Figure 4) that if too high can destabilize the dam. If the seepage rate increases too much as the flow exits from under the dam it can cause regressive erosion until a continuous pipe is formed – a process called piping. h-Modulor manages seepage at sites with soil (i.e. not bedrock) foundations by using sheet pile cutoff walls that are driven into the soil upstream and downstream of the dam. Initially the walls are left standing above the streambed and serve the dual purpose of a cofferdam. After construction is complete they are cut off flush with the streambed. They also help prevent scour or erosion.

The effectiveness of the h-Modulor seepage management system was analyzed for the three-container-module high stack with a 27-ft deep normal head and 8-ft deep tailwater. The steady-state ground water calculations were performed by SEEP/W, a 2-dimensional finite element seepage model from GeoStudio. Eleven different conditions were modeled including four sheeting embedment levels: none, baseline depth, 2/3rds deeper than the baseline, and 1-1/3rd deeper than the baseline. Each depth was modeled in clay, sand, and sand with a cracked concrete base slab.

The results presented in Table II show that without the cutoff walls seepage is not effectively managed and would be a safety concern, but even with the lowest depth of sheeting embedment, the double line cutoff wall is likely sufficient to control both seepage rate and exit gradients for the soil scenarios modeled. With the two rows of cutoff walls the calculated uplift pressure profile is relatively uniform under the base of the dam section (See Figure 5.) The uplift pressure head under the concrete pad is approximately the average value of the headwater and the tailwater. The use of a linear uplift profile used in the stability calculations is therefore judged appropriate and conservative.

When the LPS system is constructed on a bedrock foundation, no sheeting is required. Seepage through the rock foundation will be dependent on the hydraulic conductivity of the bedrock, which is largely governed by the characteristics of the bedrock, such as spacing and orientation of fractures that are present in the bedrock. Assessment of the nature of the specific bedrock at the site is necessary to determine the potential need for grouting or other remedial measures.

While site-specific studies may be necessary to refine the foundation seepage results at future installations, overall, these general analyses confirm that the foundation seepage, including uplift, seepage rate, and piping resistance associated with h-Modulor on a soil foundation is manageable provided that two rows of cutoff sheeting are installed to a proper depth per site-specific analysis/design for soil foundations.

Table II. Summary of seepage analysis results

Category	Sheeting Embedment Depth	Estimated Seepage Rate (gpm/lf)	Maximum Uplift Pressure Head at Base (ft)	FOS Against Piping
Clay	none	0.0009	27.0	< 1
	baseline	0.0009	18.9	> 3
	1-2/3 x baseline	0.0007	18.2	> 3
	2-1/3 x baseline	0.0006	18.0	> 3
Sand	none	0.09	27.0	< 1
	baseline	0.09	18.9	> 3
	1-2/3 x baseline	0.07	18.2	> 3
	2-1/3 x baseline	0.05	18.0	> 3
Cracked concrete and sand	baseline	0.09	19.5	> 3
	1-2/3 x baseline	0.07	19.0	> 3
	2-1/3 x baseline	0.06	18.8	> 3

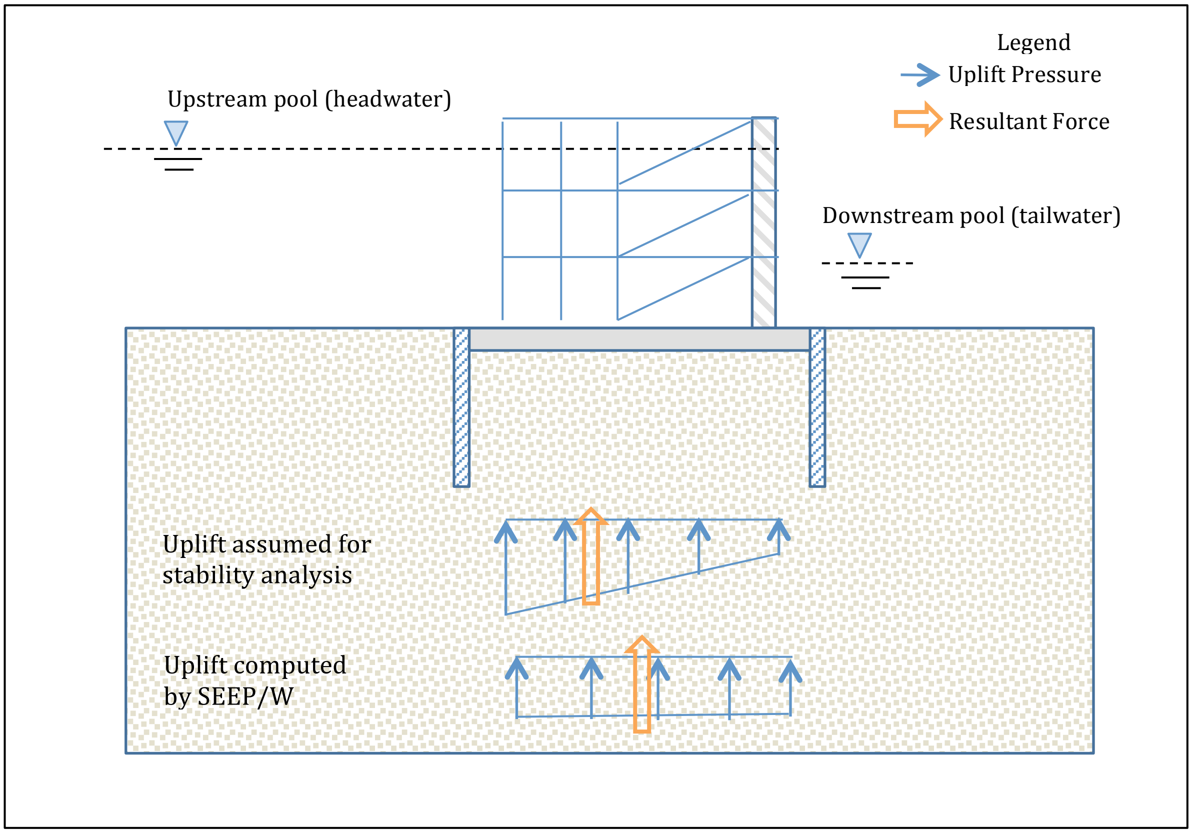


Figure 5: *Comparison of uplift pressure profiles. Not to scale.*

Spillway Module Stack

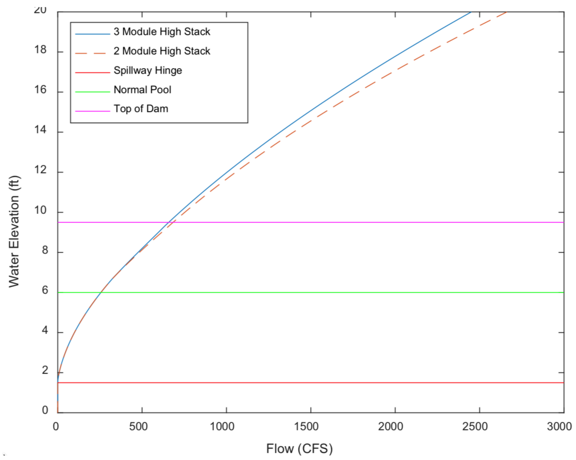
The Spillway Module Stack serves three functions. First, it is used to maintain a constant water surface elevation within the impoundment behind the dam. A consistent water surface elevation provides a constant head for turbine operation, which is necessary to optimize power production and efficiency. This maintenance of constant water surface elevation also supports the ability to operate the hydropower system in “run-of-river” mode. Run-of-river operation is when, under typical (non-flood) conditions, the amount of flow released by the hydropower project is the same as the flow rate entering the impoundment. Thus the spillway design, in conjunction with the operating turbines, must be capable of passing the range of natural flows expected at any given site.

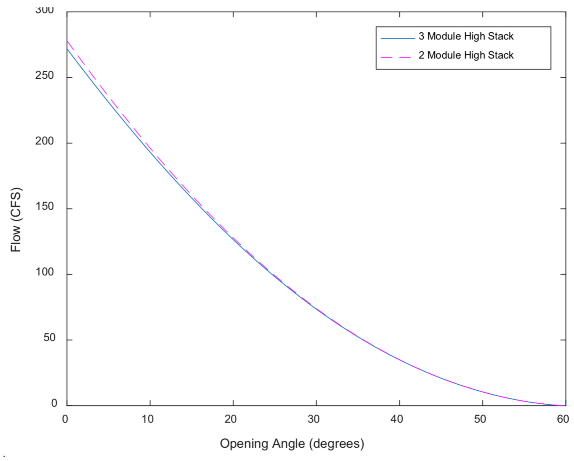
Second, the Spillway Module Stack design must be able to pass extreme flood events without compromising the functional integrity of the structure. Based on FERC guidelines, the 100-year flood is considered the minimum acceptable design flood for low hazard dams. Ideally, the design flood should be able to be conveyed through multiple Spillway Module Stacks, without conveyance of water through, or over, the Power Module Stacks. However, stability analyses described above indicate that an impoundment of water of up to 10 feet above the top of the dam is allowable without compromising the structural or stability aspects of the dam system. This represents an “emergency spillway” capacity above the top of the dam for its entire width.

Third, the Spillway Modular Stack serves the dual purpose of a surface bypass for downstream fish passage. The h-Modulor facility design includes a tailwater that is maintained at a depth that is sufficient for a safe drop.

The Spillway Module Stack is made up of one or two shipping container modules stacked on top of each other with a flat frame stacked on top of them. The top flat frame includes a bottom-hinged pneumatically operated crest gate for water control. The hydraulic capacity has been verified as a function of reservoir depth by using standard hydraulic engineering practice. Figure 6 left, presents the rating curve for a single Spillway Module Stack for both a two container-module high stack and a three container-module high stack. It represents the flow rate through the module when the gate is fully open (horizontal axis) at various elevations measured from the base of the top flat frame of the Spillway Module Stack (vertical axis). The hinge is located 1.5-ft above this base.

As shown in the right hand image of Figure 6, the crest gate provides up to 275 cfs conveyance per Spillway Module Stack at normal pool. Flow as a function of gate opening angle derived from those rating curves are shown in Figure 6 and can be used to select the number of Spillway Module Stack for a site to safely convey required flood levels.[7] An important note is that as shown in Table I, h-Modulor is stable even if flood waters up to 10-ft higher than the top of the dam flow over the dam. This stability provides extra flood passage in the case of an unusually severe condition.





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[7] Winchell ML under advisor MacDonald D. “Conceptual Spillway Design for Low Impact Modular Hydropower System,” Master’s Thesis in Civil and Environmental Engineering UMass-Dartmouth, Aug. 2018.

Figure 6: *Rating curve – flow rates accommodated as various head pond elevations.* Right: *maximum conveyance through a single Spillway Module Stack as a function of the gate opening. Both images are from Winchell (2018).*[7]

Erosion and Scour Control

High velocity flow from spillway discharge, turbine flow and potential overtopping creates the potential for toe erosion within the tailrace plunge pool area. Vulnerability to scour is a function of the type of soil or rock material present, but potential high velocity flows will result in the need for surface protection between the dam stacks and the tailrace weir in most situations.

h-Modulor includes multiple features to mitigate downstream scour. The system uses a reinforced concrete base slab, which is capable of providing the highest level of scour protection. Beyond the concrete slab scour protection materials such heavy-duty Articulated Concrete Block (ACB) mattresses are indicated by manufacturer literature to be suitable for expected velocities, are premanufactured similar to modules, can be placed in wet conditions, and could be relatively easily removed in the future. ACBs are judged to be a suitable means of additional scour protection to be used in conjunction with the LPS system.

The downstream tailrace weir also provides an important function in scour protection and serves as the downstream connection point for the ACB mats. Based on the computational fluid dynamics (CFD) analysis performed by Alden (see Figure 7), locating the tailrace weir 30-35 feet downstream of the downstream toe sheet pile line accounts for the trajectory of the overflow nappe at extreme conditions.

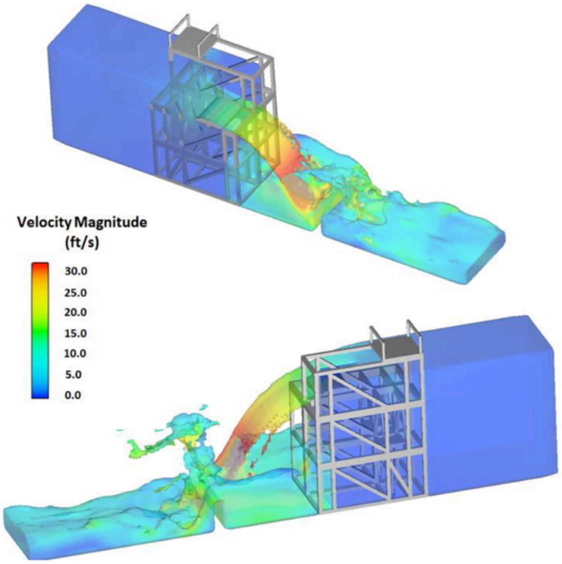


Figure 7: *CFD results showing the need to move the weir forming the plunge pool to a position about 30-35 feet downstream of the toe of the dam.*

Power Module Stack

The Power Module Stack contains an intake, turbine, generator, and outlet. It consists of a base shipping container module that contains a preinstalled draft tube, a middle module with a seating plate for the turbine, and a top module with guide rails for a sliding cylinder gate to open/close the turbine intake. In general, a Power Module Stack is adjacent to a Dam Module Stack for optimal flow through the turbine. A separate, non-structural Draft Tube Module is attached to the downstream base of the Power Module Stack.

As mentioned above, the lowest impact small hydropower projects at greenfield sites are for run-of-the-river plants – where net outflows equal net inflows in real time – as opposed to sites involving storage and the environmental impact of inundation. For the most economical operation of a run-of-the-river plant the turbomachinery package needs to be responsive to extreme variations in head and flow, i.e. it needs to produce power efficiently under widely and constantly varying hydraulic conditions. Consequently, the overall turndown ratio, needs to be very high. A traditional unregulated reaction turbine has a turndown ratio of about 1.25. That is to say, the turbine will not produce power efficiently once hydraulic flow drops below about 80% of maximum. By contrast, a fully regulated unit has a turndown ratio of about 5. This turndown ratio means that a turbine which is designed to handle 500 cfs of flow can go down to a flow of 100 cfs with no appreciable loss in efficiency. Traditionally, this consistency is accomplished by means of mechanical adjustment to the guide vanes and blade pitch. Recent innovations, however allow the use of a combination of adjustable guide vanes and a variable frequency drive (VFD) to monitor and adjust operating peak and deliver the performance of a fully regulated turbine without the mechanical complexity and at a lower cost.

The mechanical control of the adjustable inlet guide vanes is critical to maximize turndown ratio but it adds an additional 35% with respect to the cost of an unregulated unit. The h-Modulor system only uses a single adjustable-vane “stepper” Power Module Stack, while the other Power Module Stacks in the array contain less costly turbines with fixed vanes. Overall, this approach allows a hydropower plant to inexpensively and efficiently be responsive to extreme variations in flow. For example, such a package is currently being specified in LPS’s first commercial project, a 4.5MW non-powered-dam retrofit in Virginia: the array is designed to efficiently span a flow band from 100 cfs to 4,500 cfs, with water-to-wire efficiency at all times of approximately 80-83%.

The h-Modulor generation system consists of an array of small Kaplan-style direct-drive turbines with 54” fixed-blade runners and adjustable guide vanes. For domestic markets, the system outputs 3-phase 480V 60 hz electrical power, which can then be stepped up to local grid/substation voltage using an off-the-shelf transformer. Output obviously varies according to head and flow at a specific site, but at sites where net head of 15-29 feet can be developed,[8] hydraulic capacity is roughly 500 cfs per Power Module Stack and power output is roughly 500kW per Generation Module.

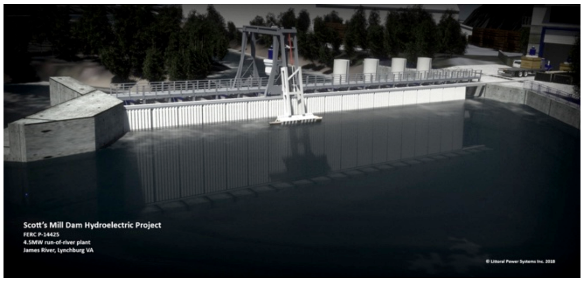
It should be noted that the LPS interconnection and control module schemes allow overall systems to be freely scaled up and down because each generation unit contains all of the power electronics needed for interconnection. Overall plant logic control is contained in the stepper unit's electronics.

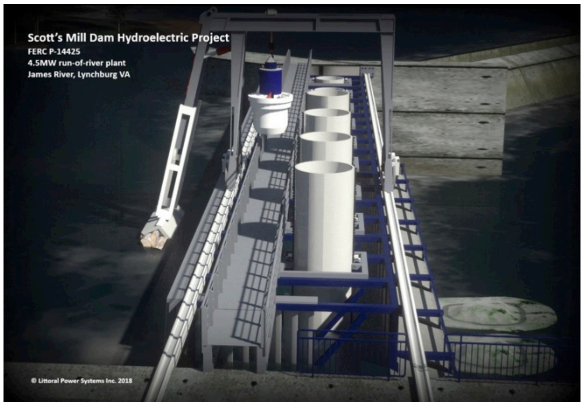
h-Modulor Facility

The features of a small 4.5 MW hydropower project that may be achieved using an h-Modulor system are illustrated in Figure 8, where artistic renderings illustrate the first commercial power project LPS is supporting with h-Modulor equipment. This facility includes ten Dam Module Stacks and nine Power Module Stacks lined up in alternating fashion to form a power wall. At the end of this wall near the bank there are two modified Spillway Module Stacks being used as a surface bypass for fish, not for spill control since this site has a pre-existing spillway.

Flow through the turbines is controlled by cylinder gates that are opened and shut via a gantry crane that travels along the top of the dam. The gantry crane is also used to install and remove the turbine/generator units. The turbine/generator units can be swapped out with the overall facility in "semi-hot" status – meaning that the other turbines continue to operate. The gantry crane also controls the lateral motion of the trash rake, which is attached to the upstream side.

The lower right image in Figure 8 shows the facility inundated by a severe flood. The h-Modulor system has been designed to survive complete inundation/overtopping to a depth of 10 feet above the top of the dam as discussed with respect to Table I.





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[8] According to the NSD Report, this head range represents over 85% of contemplated greenfield hydropower site opportunities in the USA

Figure 8: *Illustration of a 4.5 MW power project using an h-Modulor facility.*

Structural Design and Analysis

For all three primary stacks, professional structural engineers from Alden developed detailed designs and analyzed the stacks and connections for structural integrity using STAAD, one of the most widely used structural analysis and design software applications. The Structural STADD model used beam framing members for the steel frame and separate finite element plate elements for the steel plates and concrete slab. Springs were used to model the foundation; stiff ones to simulate a rock foundation and weaker springs to simulate a soil foundation. Stick models for each type of modular stack are shown in Figure 9.

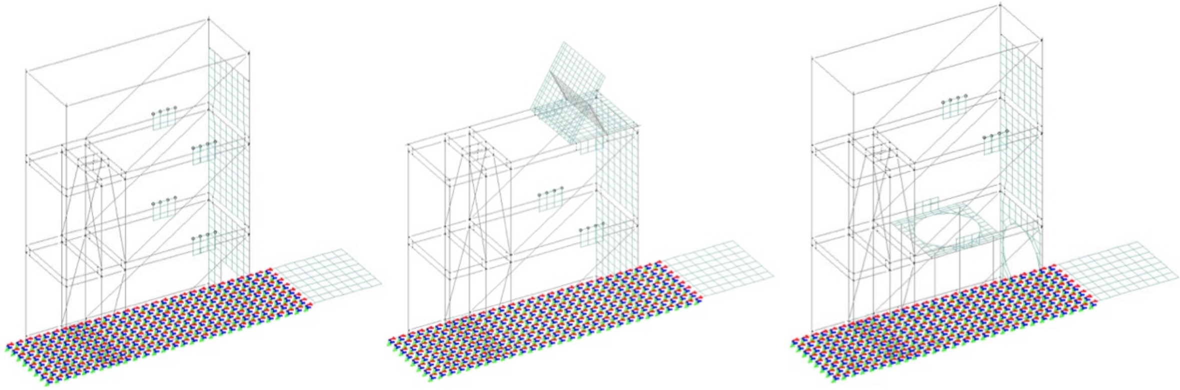


Figure 9: STAAD stick models for the (left to right) Dam Module Stack, Spillway Module Stack and Power Module Stack.

The design codes and standards that were used included:

- American Society of Civil Engineers, ASCE 7 that provides guidance for loading and load combinations;
- American Institute of Steel Construction, AISC – Steel Construction Manual used for steel design for members and connections;

- American Concrete Institute, ACI 350 - Code Requirements for Environmental Engineering Concrete Structures - also used ACI 318, but ACI 350 is more stringent since ACI 350 is used for hydraulic structures, water-type of structures (e.g. concrete tanks) where limited cracking is important; and
- U.S. Army Corps of Engineers, USACE ETL 1110-2-584 Design of Hydraulic Steel Structures for guidance in load combinations and its Appendix E Vertical Lift Gates, is viewed to be most applicable to h-Modulor. This standard includes a steel design, performance factor equal to 0.85, which makes it more conservative than the AISC code.

The general loading conditions considered included the following, a few of which are illustrated in Figure 10:

- flood load (flood elevation = 39’) and the earthquake load (acceleration = 0.38g) were back-calculated from GZA based on global stability;
- crane load is the load applied by the wheels, but it was applied at several different locations due to the crane movement and also included;
    - dead load – self weight of the crane;
    - live load – based on the payload equal to the rated capacity of the crane;
    - impact load which is a 25% increase on the payload;
    - lateral load (inertia load from swinging equal to 20% of payload);
    - longitudinal load (inertia load from swinging from stopping equal to 10% of payload; and
- load combinations considered probability of occurrence (e.g. no crane with flood, but crane load is included with ice) and were based on engineering judgment and USACE ETL 1110-2-584, Appendix E (as applicable).

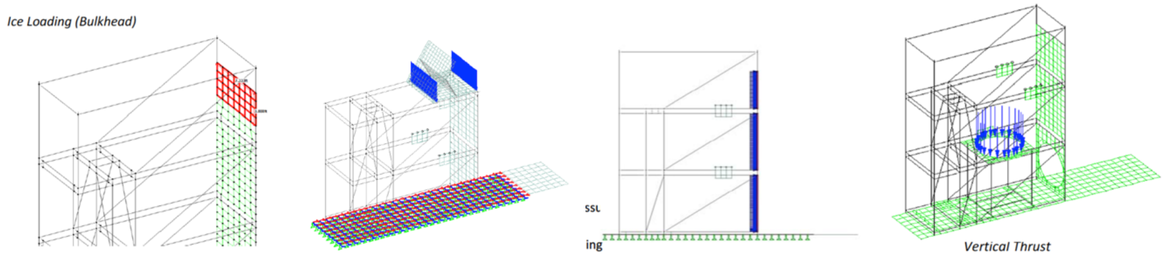


Figure 10: *Examples of loading conditions analyzed using STAAD. Left to right: ice loading on Dam Module Stack bulkhead, flood loading on Spillway Module Stack gate, earthquake load on the Power Module Stack, vertical thrust on the Power Module Stack.*

Specific to the Dam Module Stack the loads included dead load, water loads (normal, uplift, flood), ice loading, earthquake, crane/deck loads and combinations of these.

For the Spillway Module Stack the loads included dead load, water loads (normal, uplift, flood), ice loading, earthquake, and vertical/uplift load on the horizontal plate that is near the gate.

Specific to the Power Module Stack the loads included dead load, water loads (normal, uplift, flood), ice loading, earthquake, crane/deck loads, turbine loading (including thrust, which is the dynamic component), and cylinder gate loads. The gantry crane system loads and sizing were controlled by the weight of the turbine. The turbine OEM provided the thrust loads (dynamic water loading at the elbow).

Design and strength checks followed the load and resistance factor method of USACE ETL 1110-2-584 where each load on a member is increased by a load factor and all of these factored loads on a member for a loading scenario are added together. At the same time the resistance of the member is reduced by a resistance factors. To satisfy the standard the sum of the factored loads on a member must be less than the factored resistance of the member. The typical load factors used were 1.2 for dead load, 1.4 for water, 1.6 for live load. Earthquake and ice are rather extreme loads and are already amplified so the load factors used were only 1.0. The service load factor used was 0.7 Per ASCE 7 code and USACE code. The member capacity was based on a reduced value for yield strength, 0.85 * 0.9 * Fy. The STAAD generated utilization reports for each loading combination on each stack. Utilization is the ratio of the member capacity / member stress based on the factored load. In all cases the designs resulted in utilization less than 1.

Leakage Test

Crucial to any modular structure that purports to safely impound water are the interfaces between modules and especially leakage through these interfaces. The h-Modulor container-module interface design was tested for leakage at Alden using full-scale interfaces and seals (see Figure 11). Head pressures up to 25' were applied to the sealed interfaces. Leakage was approximately half of that dictated by AWWA guidelines. This is a de minimus level of leakage. The observed leakage represents less than 0.0007 times the anticipated flow through the turbines.

Figure 11: *LPS full-scale seal test rig, in preparation for leakage test.*

Construction and Assembly

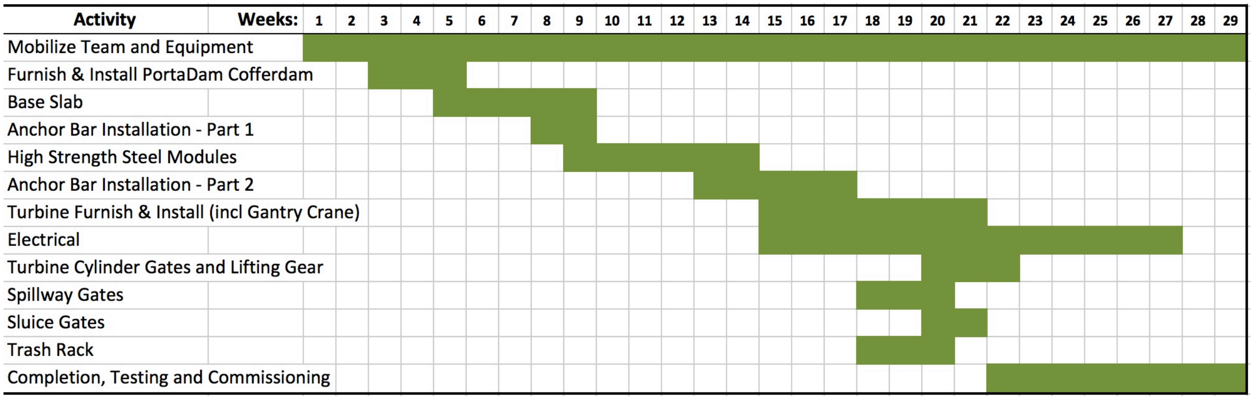
Considerable thought has gone into reducing on-site construction activity to a minimum. Construction is one aspect of a hydropower project where low cost and low environmental impact generally go hand-in-hand: reducing on-site construction activity leads directly to lower costs and more benign environmental impacts.

The standardization of the modules results in a two-part construction process where the first part is site specific and involves preparing the site to receive the modules. The second part is standardized and is better described as assembly, not heavy construction. The number of different type of modules will be different for different sites but assembling them into a hydropower facility involves the same assembly steps.

For a low risk, safe installation the subbase area is dewatered and prepared to receive the base slab. Dewatering half the stream course at a time allows preparation of the one half of the subbase in the dry and continuous stream flow around the dewatered half. The dewatering process depends on riverbed conditions. If the site is underlain by coarse-grained soils, the subbase is dewatered: a process that starts by driving interlocking steel sheet piles through these soils to refusal or bedrock. The piles extend from the upstream bank to the downstream bank in semi-circular fashion and extend high enough to prevent water from entering the dewatered area under normal flow conditions. When assembly is complete, the piles will be cut nearly flush with the bottom of the stream to return it to its full width. The portion of the piles that remain embedded in the coarse soils will act as a barrier to minimize seepage beneath the foundation. This approach avoids the extra costs of a separate cofferdam. The opposite half of the stream course would undergo a similar process as above to prepare the remaining subbase. Low-level outlet gates installed in the base module of the Dam Module Stacks would be opened to pass the diverted stream flow through them.

If the site is underlain by bedrock, it will not be possible to dewater the site using sheet piles. Instead, one half of the stream course may be dewatered using flexible intermediate bulk containers (FIBCS) filled with sand and installed in a semi-circular fashion. If necessary, steel plate can be sandwiched between the FIBCS to provide additional seepage control. The FIBCS will be removed following placement of the first phase of modules and the process repeated on the opposite bank. Either of the above construction processes will ensure continuous flow of the stream course during construction and should have minimal environmental impacts.

The construction schedule was estimated to be 30 weeks for a site using twenty-one h-Modulor stacks and is presented in Figure 12. Other sequences and activity overlaps are possible as well as double shift or round-the-clock assembly that could shorten the 30-week overall schedule by an estimated 30 percent, down to 21 weeks.



Activity	Weeks:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Mobilize Team and Equipment		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Furnish & Install PortaDam Cofferdam				🟩	🟩	🟩																								
Base Slab						🟩	🟩	🟩	🟩	🟩																				
Anchor Bar Installation - Part 1									🟩	🟩																				
High Strength Steel Modules										🟩	🟩	🟩	🟩	🟩	🟩															
Anchor Bar Installation - Part 2														🟩	🟩	🟩	🟩	🟩												
Turbine Furnish & Install (incl Gantry Crane)																🟩	🟩	🟩	🟩	🟩	🟩	🟩								
Electrical																🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
Turbine Cylinder Gates and Lifting Gear																					🟩	🟩	🟩							
Spillway Gates																			🟩	🟩	🟩									
Sluice Gates																					🟩	🟩								
Trash Rack																			🟩	🟩	🟩									
Completion, Testing and Commissioning																							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Figure 12: *Estimated construction schedule for a small hydropower facility using twenty-one h-Modulor three-module high stacks including nine Power Module Stacks.*

Cost Analysis

Three different approaches were used to estimate the costs of a hydropower facility constructed using h-Modulor. In the first, personnel from the NREL constructed an LCOE model to compare h-Modulor costs to a traditional concrete facility at greenfield reference sites using DOE's standardized System Cost Breakdown Structure (SCBS) for Hydropower technologies. Secondly, using the NREL model, personnel from UMass-D developed a regression curve relationship between site characteristics and the LCOE for an h-Modulor facility and used it to screen over 7000 greenfield sites for their low cost potential. Finally, AECOM personnel prepared an AACEI, an international certification activity for cost engineering, Level 4 estimate of construction costs at a non-powered dam site.

Cost Comparison Between h-Modulor and a Traditional Concrete Facility

To demonstrate the impacts of the h-Modulor system compared to a traditional concrete hydropower facility, a hypothetical baseline concrete project and project location were established for reference. Baseline, i.e. traditional concrete project, costs were estimated using parametric relationships developed through a combination of scaling relationships from ORNL,[9,10] vendor quotes, and aggregated estimates provided by GZA. The project costs were tracked using SCBS for Hydropower technologies developed under the WPTO. Annual Energy Production (AEP) was estimated using the exceedance flow data supplied by the USGS National Water Infor-

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[9] Zhang QF, Smith B, Zhang W "Small Hydropower Cost Reference Model," Oak Ridge National Laboratory, Oak Ridge, TN, 2012.

[10] O'Connor PW, DeNeale ST, Chalise DR, Centurion E, Maloof A "Hydropower Baseline Cost Modeling," Oak Ridge National Laboratory, Oak Ridge, TN, 2015.

mation System (NWIS)[11] and turbine efficiency data supplied by the Turbine Original Equipment Manufacturers (OEM). The estimated project costs and estimated AEP were then used to calculate LCOE using the following equation:

$$\mathrm{LCOE} = (\mathrm{CapEx} \times \mathrm{FCR}) + \mathrm{OpExAEP}$$

Where:

- **CapEx**, installed capital expenditures, represents all capital costs associated with the planning, design, manufacturing, deployment, and project management of a project;
- **FCR**, fixed charge rate, is the annual return, represented as a fraction of installed capital costs, needed to meet investor revenue requirements. It was 8.4% for this calculation;
- **OpEx**, Levelized operational expenditures including all operations, planned and unplanned maintenance, replacement costs, and any annual monitoring activity (i.e. non-depreciable);
- **AEP**, annual energy production, describes the average annual energy generated (after accounting for device or array availability) and delivered to the point of AC grid interconnection (i.e., the measurable basis for power purchase contracts).

A summary of the results is provided in Table III.

Table III: Summary of h-Modulor costs and variance from a baseline traditional concrete facility with 31,194 MWh/yr net annual energy production

Component	Baseline (USD)	h-Modulor (USD)	Variance (%)
1. Hydropower Generating Plant	**$37,046,224**	**$23,384,496**	**34%**
1.1 Site Prep	$981,818	$607,500	38%
1.2 Dams and Reservoirs	$9,353,128	$6,363,542	32%
1.3 Dam Installation	Included in 1.2	$2,310,000	-
1.4 Water Conveyance	$1,350,000	$135,000	-

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[11] USGS, "National Water Information System: Web Interface," USA.gov, 2018. [Online]. Available: https://waterdata.usgs.gov/nwis. [Accessed June 2018].

1.5 Powerhouse Structures	$11,392,857	$0	100%
1.6 Turbine Generators	$13,968,421	$13,968,421	-
2. Balance of Station (BOS)	**$12,623,701**	**$12,123,701**	**4%**
2.1 Development	Included in 1.2	Included in 1.2	-
2.2 Engineering and Management	$1,000,000	$700,000	30%
2.3 Electrical Infrastructure	$5,696,429	$5,696,429	-
2.4 Plant Commissioning	Included in 1.2	Included in 1.2	-
2.5 Site Access, Ports, and Staging	$4,927,273	$4,927,273	-
2.6 O&M Infrastructure	Included in 1.2	Included in 1.2	-
2.7 Environmental Mitigation	$1,000,000	$800,000	20%
3. Financial Costs (5% of 1 and 2)	**$2,483,496**	**$1,795,051**	**26%**
4. Decommissioning (@ year 20)	**$23,077,803**	**$7,106,042**	**64%**
4.1 Decommissioning (today's $)	$4,951,301	**$1,524,589**	64%
5. Total Capital Expenditures	**$53,938,686**	**$39,129,587**	**25%**
6. Operational Expenditures (USD/yr, today's $)	**$1,067,818**	**$1,067,818**	**-**

When estimating the project costs for the h-Modulor system it was assumed that many of the costs would stay the same as for a traditional concrete facility. The Electrical Infrastructure; Site Access, Ports, and Staging; and Licensing and Permitting were equivalent between the two systems. Additionally, the turbine/generator sets and attendant AEP were the same to make sure any cost and performance benefits weren't double counted. The following are the areas the LPS system was assumed to be different:

- Site Preparation: some of these costs were included in the Dam Installation;

- Temporary Water Conveyance: due to the unique ability to install the Dam Module Stacks with the base gates open allowing water conveyance, the cost of the water conveyance is significantly reduced and costs are assumed to be 10% of the baseline based on estimates from GZA;
- Dam: This is the primary difference between the baseline and h-Modulor system and the LPS Dam Module Stacks were estimated using 3rd party vendor quotes using the Alden and GZA structural design;
- Dam Installation: this is estimated separately for h-Modulor, while it's included in the baseline concrete Dams and Reservoirs total cost;
- Powerhouse: h-Modulor includes the powerhouse in the Power Module Stack;
- Environmental Mitigations: h-Modulor is assumed to be 20% less expensive than the traditional dam due to the low-impact nature of the system;
- Engineering Costs: the engineering costs are lower since they can be distributed over many projects due to the modular design;
- Financing costs: the financing costs are lower due to the total CapEx, but the 5% assumption is still used.

Given that the baseline system used the OpEx assumption prescribed by ORNL of 2% of the total CapEx, it was decided that the equivalent absolute value of this should be used to prevent any doubling of cost savings since the major maintenance activities for h-Modulor would likely still be the same, (i.e. turbine maintenance, annual lease fees, etc.). Although with h-Modulor the turbine/generators were designed to seat in the Power Module Stack in a way that one can be easily taken out with the gantry crane while the rest of the facility continues to produce power so the maintenance activities may have less cost impact. Using this assumption the OpEx costs for the LPS system end up closer to 3% of the total CapEx because the total CapEx costs are reduced.

The cost savings associated with the h-Modulor system vs. a traditional concrete facility is most evident when looking at the overall dam cost and the powerhouse structure. Being that the powerhouse is included in the modular turbine section, this category alone saves over $11M compared to the baseline system. This model does not account for any additional potential savings due to an accelerated installation timeline.

Table IV compares the LCOE of the two types of facilities as calculated using the LCOE equation on page 14 showing that the h-Modulor system impacts the project with a 26.8% reduction in LCOE.

Table IV: LCOE estimate comparing a baseline concrete facility to the h-Modulor system

Category	Baseline	h-Modulor
Net Annual Energy Production (MWh/yr)	31,194	31,194
Total CapEx (USD)	$53,938,686	$40,344,587
Total OpEx (USD/yr)	$1,043,068	$1,043,068
Fixed Charge Rate (%)	8.4	8.4
Percent Change	-	26.8%
LCOE ($/kWh)	$0.183	$0.134

Since the cost inputs used in the above analysis are estimates with room for significant refinement a cost sensitivity analysis was performed on all of the items within the SCBS. Each item was altered by a ± 25% to quantify the impact and determine which categories have the largest potential impact on the LCOE. The tornado chart below, in Figure 13, shows that the two categories with the most impact are Electro-Mechanical and OpEx. While the turbine OEM provided the Electro-Mechanical costs, LPS is currently making headway negotiating lower turbine costs and anticipate these costs will be reduced. The Electro-Mechanical costs are the least likely to increase as the system is developed further. For OpEx costs, these were assumed to be equal to the baseline dam, and because of this assumption are unlikely to have a significant impact on the economic feasibility. It should be noted that the next largest category has less than a 10% impact on overall LCOE. Therefore the sensitivity analysis provides an additional level of confidence that the LPS LCOE model provides a reasonable first order cost assumption for the prescribed location.

Screening Greenfield Sites Based on LCOE

In order to understand the possible breadth of application of an h-Modulor facility a civil engineering student from UMass-D working under the direction of a university professor and professional engineer developed a regression curve that relates site characteristics to the estimated LCOE of an h-Modulor project installed at the site. It was used to screen the sites from the New Streamreach Development (NSD) dataset, a restricted dataset provided by ORNL for R&D purposes only. To screen sites, the model uses heads and flows from the NSD dataset and stream widths measured from satellite images. The model screened 7000 sites in the continental US and from these identified 1,054 greenfield sites where the LCOE was estimated to meet the original goal of $0.18/kWh or less.

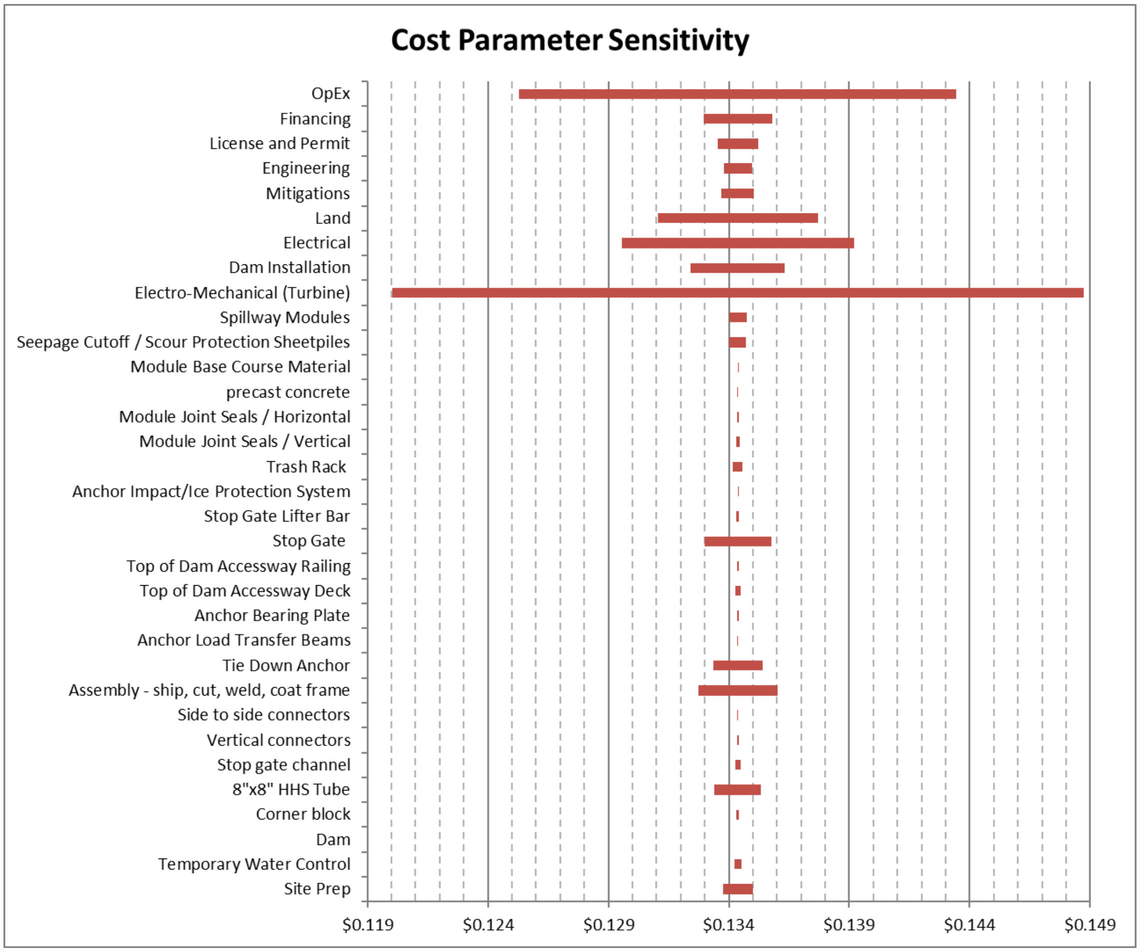


Figure 13: *h-Modulor cost sensitivity.*

Further sorting of the data showed over 3,500 MW of capacity in greenfield sites where an h-Modulor facility may very roughly have an LCOE less than $0.05/kWh (see Figure 14). It should be reiterated that this is a very high level and approximate estimate of costs intended for screening purposes and that many of these sites may not be able to be prosecuted for a variety of reasons.

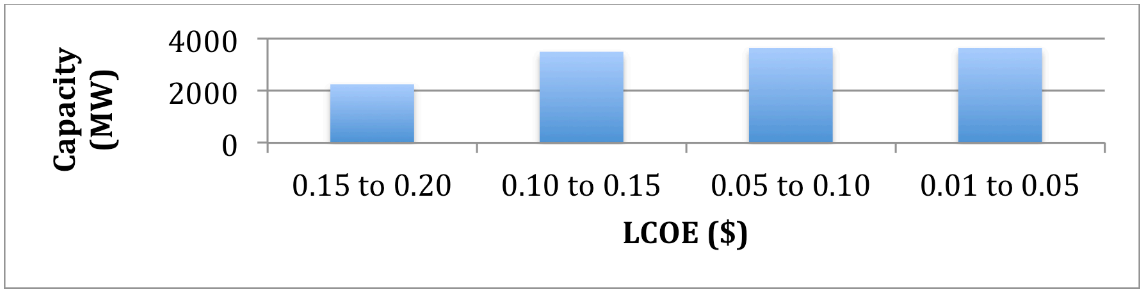


Figure 14: *Theoretical capacity at greenfield sites for low cost h-Modulor facilities.*

AACEI Cost Estimates

AECOM performed an AACEI Level 4 estimate of construction costs for an h-Modulor facility at a non-powered dam project with 4.5 MW of capacity.

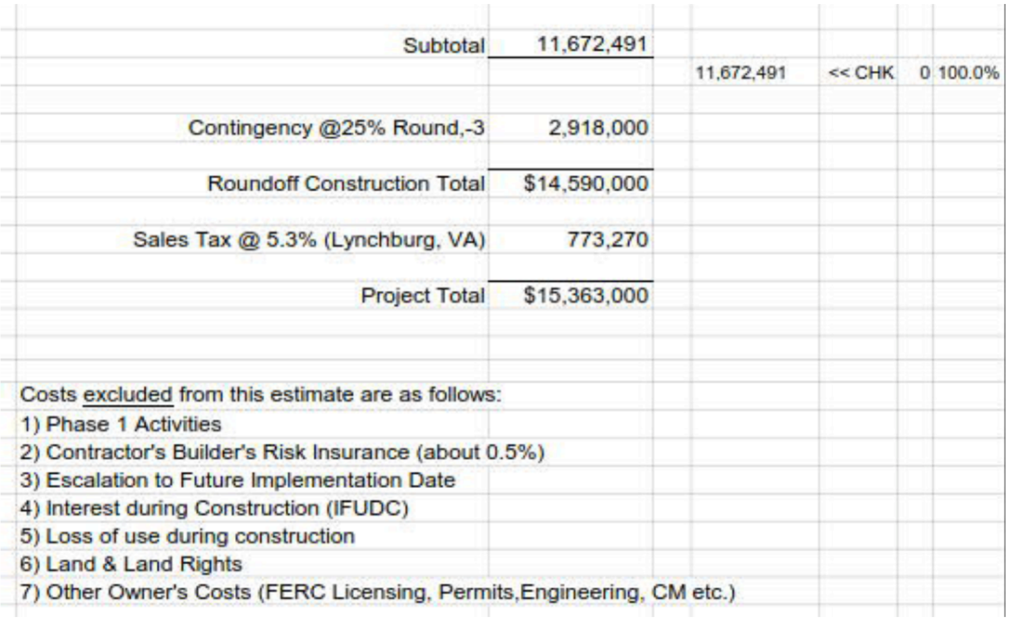
A Level 4 cost estimate is at the “study” or “feasibility” level of design and generally carries an expected accuracy range of -30% to +50%. A Class 5 is the least accurate cost estimate used for concept screening. A Class 1 is the most accurate cost estimate used to bid or tender work, and is based on a detailed unit quantity takeoff with detailed unit costs.

The cost estimate assumed two-phase construction:

- Phase 1 – Preparation of site access, all associated permitting, preparatory and protective activities for in-water work, modification of abutments, and construction of temporary facilities, laydown areas, temporary utilities;
- Phase 2 – Construction of cofferdams, excavation for base slab, base slab, assembly of modules, turbine-generator installation, connections, testing, and commissioning.

In preparing this cost estimate, AECOM’s previous similar work provided much of the basis for construction costs with some vendor input on high strength tube steel material and fabrication costs, turbine package costs, rebar, concrete and rubber bladder spillway gate costs. The cost estimated excluded results are presented in Table V. For a 4.5 MW capacity the total project cost estimate equates to $3414/kW.

Table V: AACEI Level 4 cost estimate for constructing a 4.5 MW capacity h-Modulor facility including 21 three-container-module high Modular Stacks at a non-powered dam site



Subtotal	11,672,491				
		11,672,491	<< CHK	0	100.0%
Contingency @25% Round,-3	2,918,000				
Roundoff Construction Total	$14,590,000				
Sales Tax @ 5.3% (Lynchburg, VA)	773,270				
Project Total	$15,363,000				

Costs excluded from this estimate are as follows:
1) Phase 1 Activities
2) Contractor's Builder's Risk Insurance (about 0.5%)
3) Escalation to Future Implementation Date
4) Interest during Construction (IFUDC)
5) Loss of use during construction
6) Land & Land Rights
7) Other Owner's Costs (FERC Licensing, Permits,Engineering, CM etc.)

Summary of Benefits

h-Modulor, as described above, delivers cost and environmental benefits because when used to construct a facility it:

- cuts construction time by about 50% compared to conventional concrete construction;
- minimizes or eliminates the need for a separate coffer dam;
- generally requires less excavation than traditional construction;
- uses standard modules and a standard assembly process applicable to multiple sites to minimize cost impacts of customization;
- can be assembled in the wet;
- is prefabricated offsite in a quality controlled factory and efficiently shipped to the site via truck, rail, barge or even helicopter;
- uses an array of turbines to maximize power output over a range of flows;
- mitigates the risk of downtime since individual turbine/generators can be replaced without shutting down the rest of the facility;
- is designed so the modules and turbines can be easily removed and replaced for repair, maintenance or upgrade;
- limits site preparation and need for on-site equipment;
- is designed to be removed at the end of it’s useful life leaving behind a minimal footprint;
- is designed to safely, timely, and effectively pass a variety of fish species downstream;
- is designed to integrate with systems for upstream fish transport;
- includes water quality features for sediment sluice and low water passage.

Summary of Project Activities

Objectives and Goals

The objectives of this project were (i) to develop proof-of-concept designs for four basic modules of LPS’s prefabricated, modular, low cost, low impact, low-head hydroelectric system that can be flexibly deployed, with particular emphasis on run-of-river installations and (ii) to perform analyses, numerical simulations, and laboratory tests validating the safe and functional integration of the system's basic Dam Module Stack.

Specific goals were to:

- develop proof-of-concept designs and prove the potential of the proposed system to meet industry standards for durability, safety, leakage, and structural integrity;
- analyze a full size dam section to evaluate the above features for structural integrity and ease of installation;
- test a full size dam section to evaluate leak resistance;
- develop proof-of-concept design for a prefabricated Spillway Module Stack to prove the potential of the proposed system to pass extreme flow events through adequate spillway capacity without compromising the safety and integrity of the structure;
- develop proof-of-concept design foundation system that can be removed leaving a very light footprint; demonstrating that the LPS modular dam system has the potential to be removed without leaving behind significant lasting visual traces or harmful materials;
- perform geotechnical and structural analysis for stability and seepage and analyze the proof-of-concept design based on standardized approaches to various sites;
- demonstrate an attractive reduction in LCOE vs. traditional approaches such as cast-in-place concrete water retaining structures;
- reduce engineering time involved in the licensing process and possibly provide a new way for regulators to think about licensing that could lead to reduced statutory time frames.

LPS with a team of professional engineers, PhDs, and geotechnical consultants from GZA, Alden, UMass-D, NREL, and AECOM worked in collaboration with the engineers at DOE to achieve these goals. This project like most innovative system development projects was messy and non-linear. It included no less than six substantial design shifts. The result was a low cost, environmentally friendly system that is now on track to be used in a 4.5 MW commercial installation.

The project exceeded the original goals and delivered designs beyond the proof-of-concept stage backed up by thorough professional engineering analysis of stability, seepage, structural integrity, construction and professional engineering cost estimates indicating an LCOE half of the original LCOE goal. The seal design for the interfaces between the modules was proven effective through testing full size sections.

Initial Concept

The initial concept, Figure 15, for the modular system was to use ISO standard shipping containers with some modifications as building blocks from which to construct a dam, powerhouse and spillway. The advantage of such an approach is that these containers are pre-manufactured, standardized, easily transportable, stackable and cost effective.

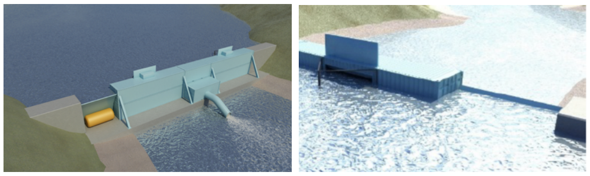


Figure 15: *Initial concept using shipping containers with some modification as modular building blocks.*

System Requirements, Engineering Criteria and Standards

The team developed a system requirements matrix with engineering criteria to guide the development beyond this initial concept. This requirement matrix essentially answered the following questions:

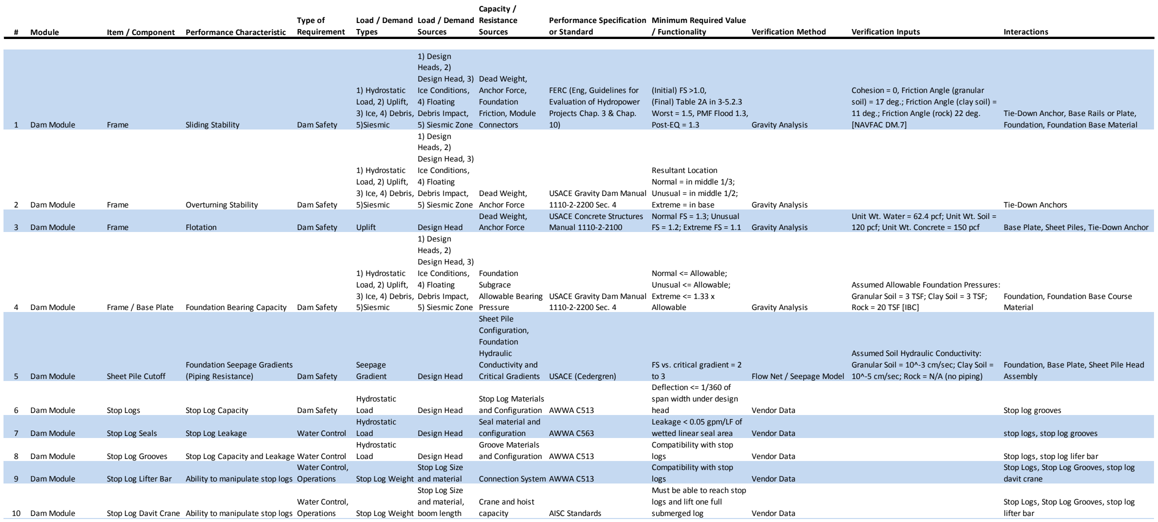
- What are we trying to achieve?
- What are the general categories of needs that must be met by the system?
- What are the loads on and capacities of various system components?
- What standards will we use for design?
- How will we verify the appropriateness of our designs?
- What are the assumptions that will be used in driving our designs?
- What are the key interactions between various system components?

The key considerations in the design process were identified as dam safety, dam functionality, water control, constructability, power generation, operation and maintenance (O&M), power transmission, environmental impacts, public safety, decommissioning impacts and adaptability across sites. These key considerations were defined as the Type of Requirement.

To address the seven questions above the System Requirement Matrix for each type of module, Dam Module Stack, Power Module Stack, and Spillway Module Stack included the following categories (see Figure 16 as an example):

- Type of Module Stack, e.g. Dam, Power, Spillway;
- Item/Component, e.g. frame, base plate, turbine, gate;
- Performance Characteristic, e.g. sliding stability, overturning stability, leakage;
- Type of Requirement, as discussed in the previous paragraph;

- Load/Demand Type, e.g. hydrostatic, uplift, ice, debris, seismic;
- Load/Demand Sources, e.g. design head, ice conditions, floating, seismic zone;
- Capacity/Resistance Sources, e.g. dead weight, foundation friction, module connectors;
- Performance Specification of Standard, see list in the next paragraph;
- Minimum Required Value/Functionality, from the specification;
- Verification Method, e.g. gravity analysis, seepage model, leakage test, vendor data;
- Verification Inputs, capturing assumptions;
- Interactions, key ones between system components.



#	Module	Item / Component	Performance Characteristic	Type of Requirement	Load / Demand Types	Load / Demand Sources	Capacity / Resistance Sources	Performance Specification or Standard	Minimum Required Value / Functionality	Verification Method	Verification Inputs	Interactions
1	Dam Module	Frame	Sliding Stability	Dam Safety	1) Hydrostatic Load, 2) Uplift, 3) Ice, 4) Debris, 5)Siesmic	1) Design Heads, 2) Design Head, 3) Ice Conditions, 4) Floating Debris Impact, 5) Siesmic Zone	Dead Weight, Anchor Force, Foundation Friction, Module Connectors	FERC (Eng, Guidelines for Evaluation of Hydropower Projects Chap. 3 & Chap. 10)	(Initial) FS >1.0, (Final) Table 2A in 3-5.2.3 Worst = 1.5, PMF Flood 1.3, Post-EQ = 1.3	Gravity Analysis	Cohesion = 0, Friction Angle (granular soil) = 17 deg.; Friction Angle (clay soil) = 11 deg.; Friction Angle (rock) 22 deg. [NAVFAC DM.7]	Tie-Down Anchor, Base Rails or Plate, Foundation, Foundation Base Material
2	Dam Module	Frame	Overturning Stability	Dam Safety	1) Hydrostatic Load, 2) Uplift, 3) Ice, 4) Debris, 5)Siesmic	1) Design Heads, 2) Design Head, 3) Ice Conditions, 4) Floating Debris Impact, 5) Siesmic Zone	Dead Weight, Anchor Force	USACE Gravity Dam Manual 1110-2-2200 Sec. 4	Resultant Location Normal = in middle 1/3; Unusual = in middle 1/2; Extreme = in base	Gravity Analysis		Tie-Down Anchors
3	Dam Module	Frame	Flotation	Dam Safety	Uplift	Design Head	Dead Weight, Anchor Force	USACE Concrete Structures Manual 1110-2-2100	Normal FS = 1.3; Unusual FS = 1.2; Extreme FS = 1.1	Gravity Analysis	Unit Wt. Water = 62.4 pcf; Unit Wt. Soil = 120 pcf; Unit Wt. Concrete = 150 pcf	Base Plate, Sheet Piles, Tie-Down Anchor
4	Dam Module	Frame / Base Plate	Foundation Bearing Capacity	Dam Safety	1) Hydrostatic Load, 2) Uplift, 3) Ice, 4) Debris, 5)Siesmic	1) Design Heads, 2) Design Head, 3) Ice Conditions, 4) Floating Debris Impact, 5) Siesmic Zone	Foundation Subgrace Allowable Bearing Pressure	USACE Gravity Dam Manual 1110-2-2200 Sec. 4	Normal <= Allowable; Unusual <= Allowable; Extreme <= 1.33 x Allowable	Gravity Analysis	Assumed Allowable Foundation Pressures: Granular Soil = 3 TSF; Clay Soil = 3 TSF; Rock = 20 TSF [IBC]	Foundation, Foundation Base Course Material
5	Dam Module	Sheet Pile Cutoff	Foundation Seepage Gradients (Piping Resistance)	Dam Safety	Seepage Gradient	Design Head	Sheet Pile Configuration, Foundation Hydraulic Conductivity and Critical Gradients	USACE (Cedergren)	FS vs. critical gradient = 2 to 3	Flow Net / Seepage Model	Assumed Soil Hydraulic Conductivity: Granular Soil = 10^-3 cm/sec; Clay Soil = 10^-5 cm/sec; Rock = N/A (no piping)	Foundation, Base Plate, Sheet Pile Head Assembly
6	Dam Module	Stop Logs	Stop Log Capacity	Dam Safety	Hydrostatic Load	Design Head	Stop Log Materials and Configuration	AWWA C513	Deflection <= 1/360 of span width under design head	Vendor Data		Stop log grooves
7	Dam Module	Stop Log Seals	Stop Log Leakage	Water Control	Hydrostatic Load	Design Head	Seal material and configuration	AWWA C563	Leakage < 0.05 gpm/LF of wetted linear seal area	Vendor Data		stop logs, stop log grooves
8	Dam Module	Stop Log Grooves	Stop Log Capacity and Leakage	Water Control	Hydrostatic Load	Design Head	Groove Materials and Configuration	AWWA C513	Compatibility with stop logs	Vendor Data		Stop logs, stop log lifer bar
9	Dam Module	Stop Log Lifter Bar	Ability to manipulate stop logs	Water Control, Operations	Stop Log Weight	Stop Log Size and material	Connection System	AWWA C513	Compatibility with stop logs	Vendor Data		Stop Logs, Stop Log Grooves, stop log davit crane
10	Dam Module	Stop Log Davit Crane	Ability to manipulate stop logs	Water Control, Operations	Stop Log Weight	Stop Log Size and material, boom length	Crane and hoist capacity	AISC Standards	Must be able to reach stop logs and lift one full submerged log	Vendor Data		Stop Logs, Stop Log Grooves, stop log lifter bar

Figure 16: Example page out of the system requirements matrix.

Engineering relied on similar structures and similar applications with heavy reliance on the standards and design approach used for hydraulic steel gates, which have exposure, temperature, and static/dynamic loading conditions similar to the LPS modular hydropower system. Standards that were used to guide the design and engineering of the system are presented in Table VI.

Table VI: Standards and specifications used to design h-Modulor

- 2010 ASCE 7 - MINIMUM DESIGN LOADS FOR BUILDINGS AND OTHER STRUCTURES
- AISC MANUAL OF STEEL CONSTRUCTION, 14TH EDITION
- ACI 350-06, CODE REQUIREMENTS FOR ENVIRONMENTAL ENGINEERING CONCRETE STRUCTURES
- USACE ETL 1110-2-584, DESIGN OF HYDRAULIC STEEL STRUCTURES
- ACI 318-11, BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE, BY THE AMERICAN CONCRETE INSTITUTE.
- PTI GUIDE SPECIFICATIONS FOR POST-TENSIONING MATERIALS, 6TH EDITION
- FEDERAL ENERGY REGULATORY COMMISSION (FERC) ENGINEERING GUIDLINES FOR THE EVALUATION OF HYDROPOWER PROJECTS, CHAPTER 3 GRAVITY DAMS AND CHAPTER 10 OTHER DAMS. FERC GUIDELINES REFERENCED FOR REQUIRED FACTOR OF SAFETY FOR GLOBAL STABILITY UNDER SPECIFIED LOAD CONDITIONS.

Design Shift to Container Form Factor

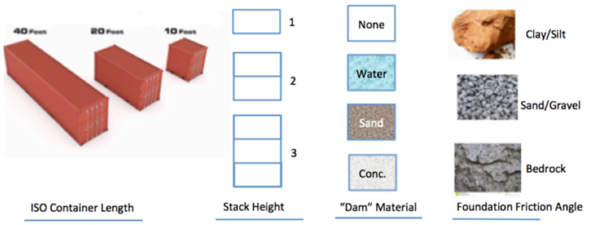


Figure 17: *Characteristics considered in analyzing the shipping container dam concept for dam safety stability.*

The shipping container dam concept was analyzed for dam safety stability using parametric studies and sensitivity analysis. The analysis considered containers filled with nothing, water, sand and concrete using three different foundation friction angles to represent three different foundations: clay/silt, sand/gravel and bedrock. The analysis included three container lengths (10-ft, 20-ft and 40-ft) and three stack heights (single container, two container high stack, and three container high stack). These categories are illustrated in Figure 17. The results indicated that stacked shipping containers, even when filled with concrete, would not satisfy the stability criteria.

This result led to a transformative shift in the concept away from actual shipping containers, even heavily reinforced ones, to a concept of modules made of structural steel frames with the form factor of shipping containers. The modules are in the shape of shipping containers and with the same corner geometry to connect like a shipping container. This approach retains the key advantages of shipping containers -- they have a standard shape, are pre-manufactured, are easy to transport and are stackable – and offers the new advantage of being designed specifically for the loads and desired functions in a hydropower application. This shipping container form factor concept is illustrated in Figure 18.

Figure 18: *Shipping container form factor concept.*

The initial stability analysis led to another shift in the design concept. Whereas the original concept envisioned the modules being aligned so their long axis was perpendicular to the river current, in the revised concept the container form factor modules are oriented with their long axis parallel to the flow for improved stability.

Dam Module Stack Design Evolution and Lessons Learned

The concept resulting from the initial stability assessment and analysis described above features three container-modules stacked on top of each other to form a three-module high dam stack, see Figure 19. The water-retaining bulkhead is in the center of the stack and made up of a set of sliding stop logs. In this view flow is from left to right parallel with the long axis of the modules. The second set of horizontal and vertical reinforcements on the upstream side are support structures for anchoring that will provide the required stability. The blue colored bottom indicates the concept that the foundation base slab would be prefabricated into the bottom module.

Through the remainder of the project the design evolved to that described in the Product section above. As the design matured the water retaining features were moved all the way to the downstream face for improved stability and easier access to sealing. The sliding stop logs were replaced with solid plate bulkheads for the water retaining features to minimize leakage and provide better module stiffness. The concrete base slab was separated from the base module and replaced with a cast-in-place reinforced concrete foundation slab. This change reduces the weight of the base module, mitigates potential differential settlement issues, provides better scour resistance and provides a robust, low risk foundation.

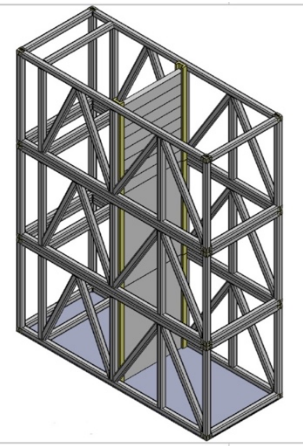


Figure 19: *Early frame and stacking concept for a dam stack.*

Spillway Module Stack Design Evolution and Lessons Learned

The design of the spillway module evolved to benefit the overall function, transport, constructability and cost of h-Modulor.

In the initial concept design the spillway function was located in the top container-module of a stack and included a bottom-hinged gate. The bottom-hinged gate created flexibility when considering design, shipping, and functionality, and is considered a conventional and well-understood configuration. This gate was to be operated by a winch that would be located above the top container-module. The winch system would be detachable in order to service multiple stacks in line and to keep the design modular and transportable. Side seal plates between stacks would be mandatory in order to effectively create a tight seal between the hinged plate and the sides of the container-module to eliminate potential leakage. Structural elements along the sides of each top container-module would also be required to access the top of the dam, and transfer loads to the lower container-modules.

There were several issues with this design concept:

- the structural side walls interfered with debris passage and trapped debris could limit hydraulic capacity and require manual labor for removal;
- the structural reinforcement required to transfer the force required for winch operation down to the underlying supports increases cost;
- in advance of anticipated storm events, workers would need to access the top of the dam, during potentially hazardous conditions, to configure the portable winch in each module and lower each gate slowly to avoid shock loading on the entire dam structure;
- raising the gates while flood waters were receding would either require tremendous force against the high water level and the associated costs to achieve this capability, or wait until the waters had receded and lose power generation and potentially harm the adjacent shoreline; and
- the equipment required above the top of the spillway module would have to be shipped separately or shipped within the top module, and assembled on site, reducing the advantages of the modular system.

To address these issues the final concept design eliminated the sidewalls and incorporated a bottom-hinged pneumatic gate operated using an air bladder on the downstream side of the gate leaf. The bladder is inflated and deflated by a compressor, which is housed on the streambank, separate from the dam. The gate is pushed into the upright position from below, rather than being pulled from above. The gate and bladder can be designed specifically to fit the 8 ft module width. Because there are no sidewalls separating the modular gates contained within each 8 ft segment, the modular gates of adjacent segments can be bolted together on site to create a single operational gate that is several modules wide. This operational gate would be controlled by one compressor system connected to multiple bladders. If multiple operational gates were desired a wiper plate to prevent leakage between gate panels would separate them. The desired number of modules included in a single operational gate could vary, depending on site conditions and requirements.

The benefits of this final concept design are:

- unobstructed passage of flow and debris;
- real-time adjustability;
- no manual labor from atop the dam;
- automatic computer controlled adjustment;
- emergency response where maximum discharge capacity can be accomplished by opening (i.e. lowering) the gates by deflation of the bladders which could be accomplished with out access to power;
- ideal modularity because the pneumatic can be constructed in eight foot sections, which are bolted together on site;
- flexibility with simplified installation and maintenance;
- lower fabrication costs (due to elimination of sidewall steel), and the ability to increase revenue through optimized head, and fewer disruptions to generation.

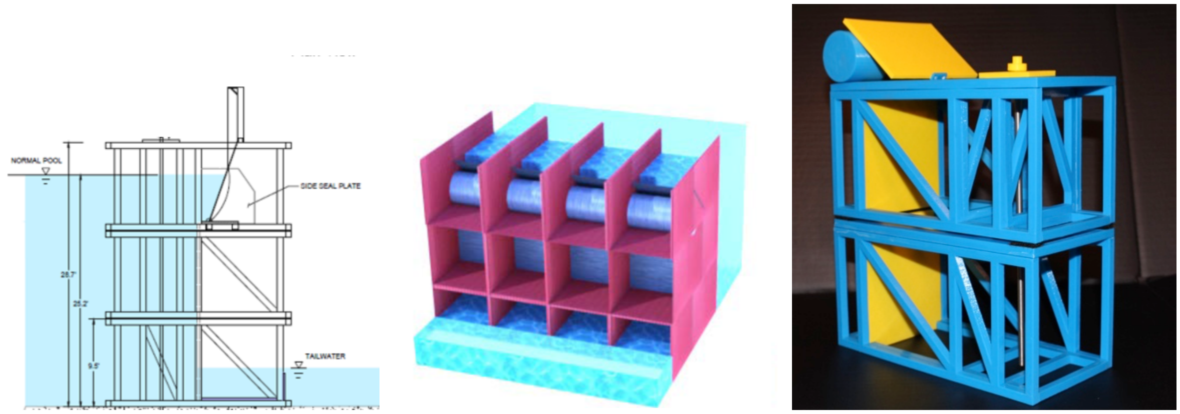


Figure 20: *Evolution of concept design for Spillway Modular Stack. Left to right: top module with sidewalls and overhead gate lift, to top module with sidewalls and pneumatic gate, to no sidewalls and pneumatic gate actuation (final concept design not shown).*

Power Module Stack Design Evolution and Lessons Learned

Following the initial stability sensitivity study leading to modules in a shipping container form factor oriented with the long axis parallel to flow, the Power Module Stack was envisioned to be made up of two, three or four container-modules stacked on top of each other (see Figure 21). The results of a more in depth stability analysis prescribed a design with a maximum of three container-modules in a stack for dam safety stability requirements. Discussion of the concept designs also involved weighing the pros and cons of an above grade vs. below grade turbine. An above grade turbine minimizes the amount of construction and the associated environmental impact and cost, the two major goals of the project. Excavating for draft tube exit was also discussed and agreed that it was desirable to avoid as much excavation as possible.

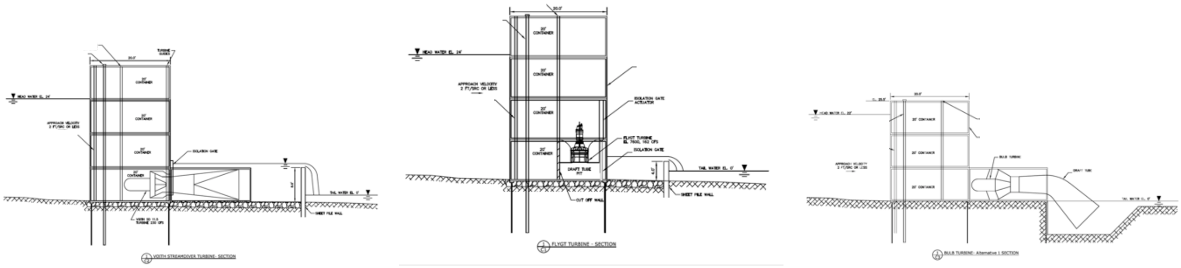


Figure 21: *Early concept designs for a three or four container-module high Power Module Stack using a Voith Streamdiver turbine, a pit turbine or a bulb turbine.*

The maximum three container-module high concept positioned the turbine downstream of the dam stack connected with a penstock and considered either a generator that could run wet or an extra container-module mounted above the turbine to house a dry generator. Alternative concepts at that time, shown in Figure 22, considered using a cross flow turbine and a generator in a dry container-module, or a siphon turbine with a dry generator mounted on top of the dam. One of the advantages of these two concepts is that they minimize the depth of the tailwater necessary for turbine operation. Some tailwater depth, however, is necessary for safe fish drop over the spillway and to protect against erosion.

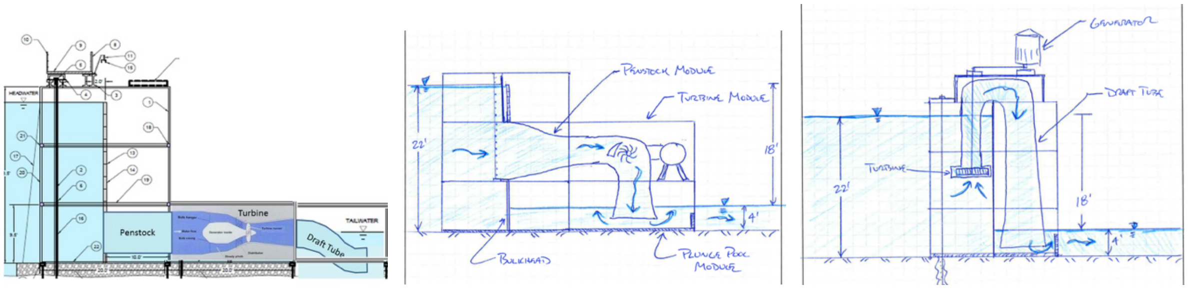


Figure 22: *Early concepts for the Power Module Stack considering an s-type turbine, a cross flow turbine and a siphon turbine.*

To select a design to take forward in the project, professional engineers from Alden who are specialists in hydraulics and flow, surveyed the industry for the best turbine for the modular system. They developed a criteria and a survey of questions based on the requirements document and the two MA reference sites. The content included head, flow, dimensions, runner elevation relative to tailwater, regulated vs. non-regulated, and cost. At least sixteen turbine suppliers were contacted. From this effort, they down selected three design configurations representing a range of cost, power output, fit into the container form factor and ease of installation and maintenance, Table VII.

Table VII: Characteristics of the turbines considered in the turbine down select

Turbine	Relative Turbine Cost	Units	Modularity	Head (ft)	Flow (cfs)	Relative Power	Relative Turbine Cost per KW
A	100%	8	High	19.2	~ 210	1.00	100%
B	104%	7	Med/High	15.2	~ 215	0.81	138%
C	201%	2	Low	16.5	500	3.34	68%

The team selected a vertical axis semi-Kaplan turbine with combined generator able to run in the wet to take into the detailed design efforts. The final turbine/generator was described in the Products section above.

For higher head sites up to 50 ft of head the team developed concept designs for alpine configurations as shown in Figure 23.

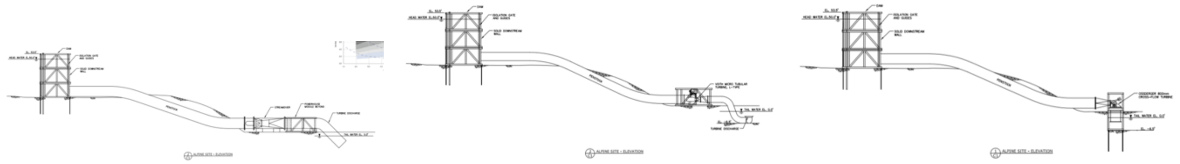


Figure 23: *Alpine configurations to achieve up to 50 ft of head considering three different turbines (left to right) a Voith Streamdiver, a Voith Micro Tubular L-type turbine and an Ossberger 800 mm cross flow turbine.*

Recommendations for Future Work

LPS conversations with hydropower developers, operators and consultants that serve them have made it clear that expanding the h-Modulor kit of parts to provide the following capabilities at the same LCOE less than $0.10/kWh are desired.

1. Expand and mature system flexibility to wider range of heads including an ultra low-head of 10 ft or less.
2. Develop a fully prefabricated foundation that can be floated into the site.
3. Develop products and processes for cofferdam-less construction.
4. Add modular fish-up capabilities.