Prefabricated Standard Modular Hydropower Installations for Low-cost Small Hydropower

FINAL TECHNICAL REPORT

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Executive Summary

Growth in hydropower capacity in recent years has been entirely through expanding existing facilities, adding power to non-powered dams, or adding power to conduits and canals. New stream-reach (i.e., greenfield) development makes up less than 10% of new hydropower (Uria-Martinez et. al. 2021). The U.S. Department of Energy (DOE) Water Power Technology Office (WPTO) identified that while small hydropower plants provide many benefits, including clean electricity, stable and predictable power output, non-consumptive water use, and reliance on a renewable and self-replenishing fuel supply, there will be limited if any growth of new hydropower facilities at greenfield locations unless there is transformational innovation and balance between efficiency, economics, and environmental sustainability (DOE 2018).

Intending to drive down the cost of small hydropower, Littoral Power Systems, Inc. (LPS) began research and development of a prefabricated, standardized, modular low-head hydropower system in 2015. The system was trademarked "h-Modulor," and patent protection was applied for and received (Duquette and Cox 2016). At about the same time, DOE-funded Oak Ridge National Laboratory (ORNL) carried out a project titled "Standard Modular Hydropower (SMH) Technology" to define standardization, modularity, and environmental compatibility as three enabling principals of a low-cost, environmentally sustainable hydropower growth strategy.

To understand the essential promise of SMH – of which h-Modulor is a variant – consider that a traditional hydropower facility design is developed by studying a site and then applying a stepwise process of site-specific design. The major civil, hydromechanical, electromechanical, and ancillary equipment packages consist primarily of bespoke equipment. In contrast, the h-Modulor approach replaces one-off gear with prefabricated, modular, standardized components. The approach is not dissimilar from the way the photovoltaic/solar industry has developed: while equipment is configured differently according to the particularities of each site, the equipment is entirely standardized.

The goal of the present project is to investigate the potential savings in greenfield hydropower project costs across sites having vastly different characteristics. LPS undertook the project described herein to explore the promise of SMH to transform the processes of site identification, conceptual design, detailed design, and construction planning to support low-cost, environmentally attractive development of small hydropower facilities at new stream-reaches. This report includes descriptions of the work to develop these processes, the resulting facility designs achieved using these processes and the projected economics. The main activities discussed in this project are:

- Site identification: Sifting through 7,000 potential sites the process narrows it down to 168 with the lowest cost potential and selects two of these for detailed facility design. One is Balcony Falls on the James River near Glasgow VA, and the other is LPS 566 on the Spokane River just west of Spokane WA.
- Module design: The baseline h-Modulor system, as it existed at the beginning of the project, is made up of prefabricated modules including (i) a generation module which includes the turbomachinery and plumbing, (ii) a water passage module that includes a crest gate for spill and also serves as a downstream fish bypass, and (iii) a sediment passage module with a sluice gate to pass sediment or low water. This report describes the redesign of these modules as part of the project, and the substantial cost reductions resulting from that rethinking. Separately, a modular precast concrete foundation concept is designed, and an approach for safely passing recreational craft is selected.
- Facility design: The process that is developed and used for conceptual design begins with a low-resolution technical and financial model built as a multi-tab Excel workbook. The model uses a set of rules-based configuration steps to select the type and quantity of modules. A SolidWorks model of each facility is created. Detailed facility design factors in environmental assessment, energy generation, a detailed cost analysis, and a construction plan.
- Construction plan: The process for developing a construction plan for an h-Modulor facility turns out to be significantly different than the traditional process. An h-Modulor facility is created by installing shop-built engineered products, whereas the traditional approach consists entirely of onsite construction. The construction plan for a given h-Modulor facility consists of (i) a product specification, (ii) an installation, operation, and maintenance (IO&M) manual for each type of module selected for the facility, and (iii) the appropriate construction specifications for local sub-trades. The construction sequence itself has a lower environmental impact than the traditional way, as there is no need for extensive laydown areas and the limited dewatering process maintains natural flows downstream.

Installation cost estimates for the resulting conceptual greenfield facility design at the two locations come in at $3,419/kW for Balcony Falls and $2,124/kW for LPS 566. The installation time from site preparation to commissioning-ready is estimated to be 58 weeks for the conceptual facility at Balcony Falls and 42 weeks for the conceptual facility at LPS 566.

A real challenge to any hydropower facility – not only the two cases studied here – is that environmental and social conditions can change, and as such, the facility may be required to change. The h-Modulor modules connect uniquely and are structurally independent, enabling site configurations to be changed on the fly, as needed.

The h-Modulor SMH approach delivers an attractive balance between efficiency, economics, and environmental sustainability for small hydro greenfield sites.

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Table of Acronyms

Acronym	Meaning
AACEI	Association for the Advancement of Cost Engineering International
AEP	annual energy production
AIT	Reakt turbine with adjustable vanes
BOM	bill of material
CapEx	capital cost
cfs	cubic feet per second
C_G	cost associated with a generation module stack
CP	fixed project cost
C_S	cost associated with the sediment module stack
C_W	cost associated with a water passage module stack
DO	dissolved oxygen
DOE	U.S. Department of Energy
EDES	Exemplary Design Envelope Specifications
FERC	Federal Energy Regulatory Commission
FIBCS	flexible intermediate bulk containers filled with sand
FIBCS	flexible intermediate bulk containers
FIT	Reakt turbine with fixed vanes
FOA-1836	Funding Opportunity, Announcement DE-FOA-0001836
GHG	greenhouse gas
GWh	gigawatt-hours
HMI	human-machine interface
HPU	hydraulic pressure unit
I/O	input/output
ICC	modeled installed capital cost
IEC	International Electrotechnical Commission
IO&M	Installation Operation & Maintenance
kip	1000 pounds force
kWh	kilowatt, unit of power
kWh	kilowatt-hour, unit of energy
LCOE	levelized cost of electricity
LPS	Littoral Power Systems, Inc.
MW	megawatt, unit of power
MWDG	McLaughlin Whitewater Design Group
NEMA	National Electrical Manufactures Association
N_G	number of generation module stacks

NOAA	National Oceanic and Atmospheric Administration
N_S	number of sediment module stacks
NSD	New Stream-reach Development
N_W	number of water passage module stacks
ORNL	Oak Ridge National Laboratory
P&L	profit and loss
PLC	programable logic controller
PMG	permanent magnet generator
Q	hydraulic flow
Q30	30% exceedance
q_G	hydraulic capacity of each generation module stack
Q_{weir}	hydraulic flow over a weir
R&D	research and development
SMH	Standard Modulor Hydropower
smHIDEA	Small Hydropower Integrated Design and Economic Analysis
USACE	US Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VFD	variable speed (frequency) drive
WPTO	Water Power Technology Office
ZAO-Attractor	Zero Ascend Omnispecies fish passage attraction system

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1.0 Introduction

1.1 Background of FOA-1836 SMH

According to Funding Opportunity, Announcement DE-FOA-0001836 (FOA-1836) issued in August of 2018 (DOE 2018) small hydropower plants provide many benefits including clean electricity, stable and predictable power output, non-consumptive water use, and renewable and self-replenishing fuel supply. There are significant growth opportunities, but as predicted in the Hydropower Vision Report (DOE 2016), no hydropower development will take place at previously undeveloped sites without innovative – even transformational – advances in technologies to reduce costs and meet environmental performance objectives. The Hydropower Vision Report analysis indicates approximately $16\ GW$ in the capacity of hydropower growth at new stream-reaches (greenfield locations) could be possible with the development of technology solutions that balance efficiency, economics, and environmental sustainability.

FOA-1836 also pointed out that ORNL began a DOE-funded effort, titled “Standard Modular Hydropower (SMH) Technology” in 2016 to define standardization, modularity, and environmental compatibility as three enabling principals of a low-cost, environmentally sustainable hydropower growth strategy (DOE 1836).

The project reported on herein addresses the issues of cost and environmental sustainability at greenfield sites by developing an SMH facility design based on previously developed LPS standard module stacks [Duquette and Cox (2016), Duquette and Cox (2019)] that can deploy across multiple small hydro greenfield locations. The module stacks making up the greenfield facility are also useful for upgrades at existing hydropower facilities and for adding power to non-powered dams.

1.2 LPS Project Planning, Vision & Approach

This project achieved small hydropower facility designs using the h-Modulor system; an SMH system that streamlines installation and reduces cost by producing an engineered product that transforms the conceptual and detailed design phases of a hydropower project and that can be made, shipped, and installed on-site in a matter of weeks not years.

The h-Modulor system, using the module stacks that were redesigned under this project, provides flexibility for installation, and contains all the components needed for the required functions of hydropower operation. Whereas a traditional hydropower approach usually takes multiple years and high cost to build a power plant, h-Modular lowers the time, cost, and risk of hydropower development while bringing net social and environmental benefits.

This final technical report describes the project performed to achieve conceptual facility designs that meet the metrics outlined in the table below, and that can be replicated at two sites with no major changes to design features while maintaining environmental compatibility. These are referred to as "conceptual" facility designs since they are being developed to research the promise of SMH, not for actual project development. Importantly, the methods developed and used in the project are useful simplifications for site selection, scoping, and conceptual design. The outcomes inform but do not replace hydraulic analysis or hydrological risk assessment methods as prescribed by the Federal Energy Regulatory Commission (FERC).

2.0 Overview of Project Objectives, Facility Goals & Tasks

The development of an SMH facility is the primary objective of this project for supporting FOA-1836. To guide the design of detailed concepts/approaches that integrate passage and generation modules for the development of a hydropower facility in an economical and environmentally conscious manner for the future, a set of facility-specific DOE goals from FOA-1836 are used and depicted in Table 1. These goals serve as the target, which the design, construction, and installation process aim to achieve for an SMH facility.

Table 1: Facility Goal Metrics of the SMH Facility

Goal Characteristic	Goal Metric
Nameplate capacity (Flow and hydraulic head)	≤ 10 megawatts (MW) e.g., up to 5,000 cubic feet per second (cfs) cfs and up to 30 ft. hydraulic head
Modeled installed capital cost per nameplate capacity	< $3,500/kilowatt (kW) Stretch goal <$2,000/kW
Estimated construction timeline	< 2 yrs. site prep. to commissioning
Replication – the same type of modules	Multiple (2 or more) U.S. sites
Passage – water, fish, recreation craft, sediment	Safe and timely
Water quality	No degradation
Co-Development Opportunity	At least one

In addition to these FOA-1836 specified goals, the targets for the LPS h-Modulor system specifications include all the components needed for the required functions of hydropower operation and provide flexibility for installation including equipment and configurations to:

- Ensue effective power range between $0.5 - 40\ MW$,
- Operate economically from $12\ ft$ – $35\ ft$ in a Powerwall configuration,
- Operate up to much higher head ranges in an alpine site (those with a penstock),
- Provide a hydraulic capacity of 300 – $500\ cfs$ for each generation module stack,
- Support up to a $2\ MW$ generator, at which the associated infrastructure becomes a limiting factor on the benefits of the modular approach, and
- Support a levelized cost of electricity (LCOE) of $\$0.05 - \$0.07$ per kilowatt-hour (kWh); this range is for a greenfield site and should be significantly less when adding power to non-powered dams where much of the infrastructure exists.

For supporting the efforts towards reaching these facility goals for an SMH facility, a specified set of distinctive tasks are defined by LPS and represent important steps in the facility development process and are as follows:

- **Task 1** – Site Selection & Criteria
- **Task 2** – Module Development
- **Task 3** – Facility Development
- **Task 4** – Environmental Assessment
- **Task 5** – Performance Analysis
- **Task 6** – Techno-Economic Analysis

Each of these tasks represents the main components for the development of an h-Modulor SMH facility.

3.0 Project Task Discussion

In this section, each of the main project tasks are discussed with respect to their objective's relevance towards supporting the development of an h-Modulor SMH facility, the approach and methodology behind the thinking and evolution of concept to final products, the results, and outcomes, whether and how the facility goal metrics are achieved and/or supported, and finally, the lessons learned through the process.

3.1 Task 1: Site Selection & Criteria

3.1.1 Task Objective

The objective for Site Selection and Criteria is to establish a methodology for searching and selecting sites with characteristics that support an h-Modulor SMH facility that meets the goals presented in Table 1. Of the goals, those on the head and flow requirements are most relevant to determining the capacity at sites.

3.1.2 Approach and Methodology

The process used to perform site selection is depicted in Figure 1. The process is characterized by an initial filtering exercise followed by an iterative refinement based on cost and site characteristics.

The initial screening was performed on a previous research and development (R&D) project, project 7243 [Duquette and Cox (2019]. It used a regression curve that related site characteristics of head, flow, and stream width to the estimated LCOE of a conceptual h-Modulor project installed at a site. The research on that project used it to screen through 7000 potential sites on the ORNL New Stream-reach Development (NSD) database, a restricted dataset provided by ORNL for R&D purposes only. The NSD database includes estimates of potential hydraulic head, mean annual flow, 30% exceedance flow, and total potential capacity monthly flow as determined using the NSD methodology [Kao et. al. (2014)]. The researchers on project 7243 screened through over 7,000 potential sites and identified 1,054 greenfield sites where the LCOE was estimated to potentially be $0.18/kWh or less [Duquette and Cox (2019)].

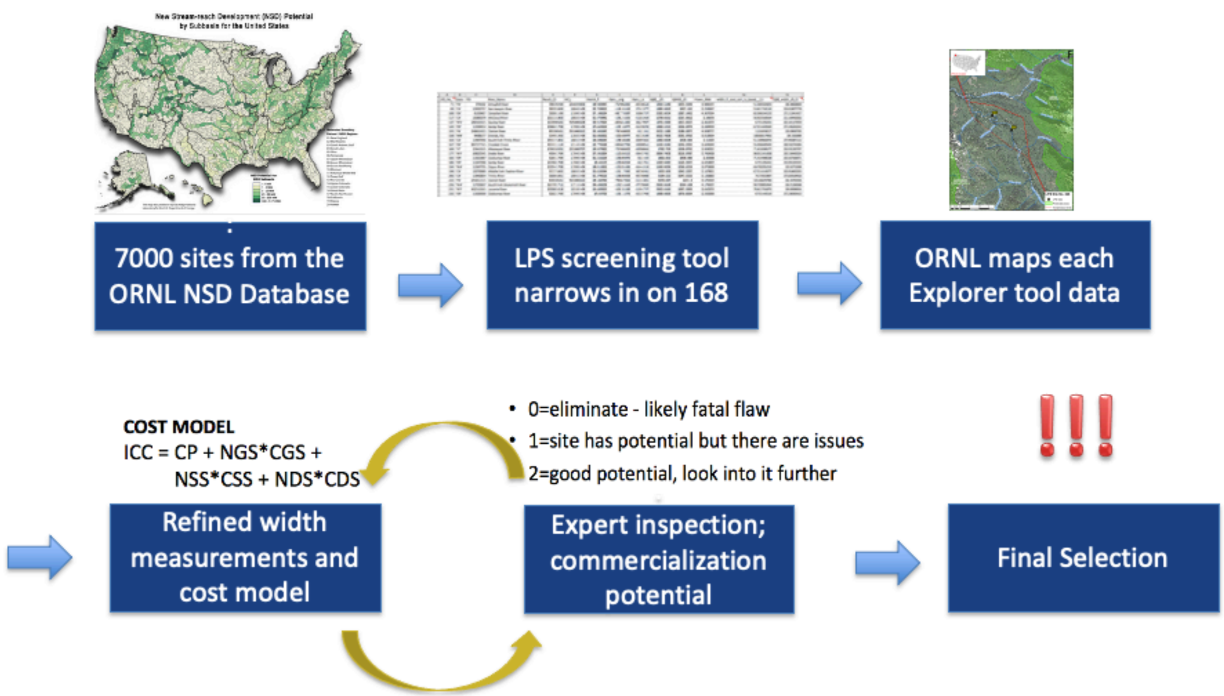


Figure 1: Site selection process.

Since the present R&D is focused on replication at multiple sites, the site selection process narrows down the initial 1,054 sites by hydraulic head to match the head that is most appropriate for the designs of the h-Modulor module stacks that existed at the beginning of the project (See Figure 2); first over a range of 13 ft to 28.5 ft, then more narrowly to a range of

19 ft to 28.5 ft. Other sorting criteria include eliminating sites located in wild or scenic rivers, or with any threatened or endangered species within the watershed. This information is available by using SMH Explorer.[1] The final site selection is made based on these criteria, estimated installation costs (discussed below), LCOE estimates from the initial screening, and a final inspection of the site characteristics by a hydropower expert.

Figure 2: First generation h-Modulor facility including the module stack types at the start of the project. Flow direction for the expanded module stack images is from right to left.

A simple cost model was developed to screen sites based on modeled installed capital cost (ICC) per nameplate capacity. A rough assessment of ICC per nameplate capacity is based on facility width, i.e., stream width, along with the potential capacity to estimate cost per kW. Stream widths are estimated from Google Earth or Google Maps as described in more detail in Section 3.1.5. Potential plant capacity is available in the NSD dataset.

[1] https://smh.ornl.gov/wp-content/uploads/2021/02/SMH_Explorer_User_Guide.pdf accessed 10/28/22.

The simple ICC cost model uses a fixed cost that includes costs such as demobilization, site prep, and testing/commission, described in further detail below, then adds the cost for each module stack used at the site. The design process uses standard module stacks which simplify the estimation of ICC. Since there are a limited number of types of different module stacks to choose from (see Figure 2), adding the module stack costs is simply the sum of the product of the number of module stacks of a given type multiplied by the cost for that type of module stack.

The cost model is based on module stack designs existing at the start of the project as shown in Figure 2. These include, as shown left to right in Figure 2: i) sediment module stack so named because it contains a gate to pass sediment or low water; it also functions as a dam module to create a head with or without the gate, ii) water passage module stack that also serves as a surface bypass for passing fish downstream and for passing debris downstream, and iii) generation module stack that also includes a draft tube extension frame (not shown). The module stacks are placed next to each other to make a hydropower facility. The wall of generation module stacks, interspersed with sediment module stacks makes up a powerwall. These three module stacks, see Figure 2, are assumed to be used with a cast-in-place concrete foundation. Detailed information is available in Duquette and Cox 2019.

The rough estimated initial capital cost is calculated by:

$$ICC = CP + NGCG + NWCW + NSCS \quad (1)$$

CP is the fixed project cost indirectly dependent on the number of module stacks,

C_G is the cost associated with a generation module stack,

C_W is the cost associated with a water passage module stack,

C_S is the cost associated with the sediment module stack, and

$N_{G,}$ $N_{W,}$ and N_S are the number of generations, water passage, and sediment module stacks, respectively.

CP is assumed to be $\$1{,}000{,}000$ for a baseline facility of 21 module stacks [Duquette and Cox (2019)] and is increased by $\$48{,}000$ for each additional module stack on any project. The items included in this variable are listed below. Not all of these depend on the number of module stacks, and the researchers recognize that the $\$48{,}000$/module may overestimate these costs.

- Staff, management, supervision,
- Mobilizing team and equipment,
- Furnishing and installing a coffer dam,
- Dewatering,
- Completion, testing, commissioning, and
- Demobilization.

Costs exclude:

- Electrical interconnection
- Site preparation other than modest excavation for the foundation,
- Contractor's builder's risk insurance,
- Escalation,
- Loss during construction,
- Land and land rights,
- Other owner's costs (FERC licensing, permits, engineering, CM, etc.),
- Upstream fish passage, and
- Recreation passage.

$C_{G,}$ the cost associated with a generation module stack (right-most image in Figure 2), includes:

- Steel frame, weldments, coating, connectors, seals,
- Turbine/generator/controls and electrical connection,
- Cylinder gate and lifting gear,
- Draft tube, draft tube extension module,
- Gantry crane portion and installation,
- Trash rack portion and installation, and
- Foundation portion and installation.

C_W the cost associated with the water passage module stack (center image in Figure 2), includes:

- Steel frame, weldments, coating, connectors, seals,
- Spillway gates with pneumatic controls, and installation,
- Gantry crane portion and installation,
- Trash rack portion and installation, and
- Foundation portion and installation

C_S, the cost associated with the sediment passage module stack (left-hand image in Figure 2), includes:

- Steel frame, weldments, coating, connectors, seals,
- Sluice gate, stem, operation, and installation,
- Hydraulic, and controls connections,
- Gantry crane portion and installation,
- Trash rack portion and installation, and
- Foundation portion and installation.

As stated above, $N_{G,}$ $N_{W,}$ and N_S are the number of generation, water passage, and sediment passage module stacks, respectively. The number of generation modules is estimated as:

$N_G = \frac{Q30}{q_G}$, rounded up to the nearest whole number, (2) Where q_G is the hydraulic capacity of each generation module stack (approximately $500\ cfs$), and 30% exceedance ($Q30$) is the flow from the ORNL NSD database.

Regarding $N_{W,}$ and N_S, all three of the module stacks have a common width of $8\ ft$, specified by Duquette and Cox (2019), to match the dimensions of a standard shipping container to ensure easy transport. The rough cost model estimates that the total number of module stacks at a site is the river width, W in feet, divided by $8\ ft$ rounded up to the nearest whole number, and the number of sediment and water passage module stacks combined is estimated as the total number of stacks minus the number of generation module stacks.

$$N_{Total} = \frac{W}{8}, \text{ rounded up to the nearest whole number} \tag{3}$$

$$N_W + N_S = N_{Other} = N_{Total} - N_G \tag{4}$$

Assuming for this screening purpose, the cost of the sediment module stack is the same as the cost of water passage module stack, which is C_{other}, then the rough screening cost model becomes,

$$ICC = CP + CG\ roundup(Q30/500) + Cother\ (roundup(W/8) - roundup(Q30/500) \tag{5}$$

Which is a rough screening calculation that relates initial capital cost to two main site conditions, river width where the facility would be installed and the $Q30$ at that site.

The site selection process narrows down the options using this rough cost model for ICC along with the following parameters that are available in the ORNL NSD database: $Q30$, capacity, head in the range of $19 - 28.5\ ft$ to best fit the module stack capability, a high ($> 40\ cfs/ft$) $Q30$ to stream width ratio, lack of any threatened or endangered species within the watershed, and location other than in a wild or scenic river. The refined list of sites is then inspected and assessed for commercialization potential. This process identifies potential flaws and issues such as fish species of concern, local opposition or resistance to development, site access, transportability of equipment to the site, and low levels of capacity that may incur additional and unexpected costs and risks. Following this level of refinement, a final selection of sites is made.

3.1.3 Results & Outcomes

Using the approach described in 3.1.2 and shown in Figure 1, two sites were selected for the facility: a site on the James River near Glasgow VA referred to as Balcony Falls ($37.62111, -79.441519$), and a site on the Spokane River ($47.68055, -117.464167$) just west of downtown Spokane WA, referred to as LPS Site 566.

Balcony Falls and the surrounding area are shown in Figure 3. The James River begins in the Appalachian Mountains and flows about 340 miles through VA where it discharges into the Chesapeake Bay near Newport News and Portsmouth VA. Bosher's Dam is a water storage weir about 55 miles upstream from the mouth of the James River. The next dam upstream is Scotts Mill Dam, about 125 miles upstream from Bosher's Dam. Beyond Scott's Mill Dam, there are six hydroelectric facilities within a span of about 26 miles as the James crosses the Blue Ridge Mountains. Balcony Falls site, about 4 or 5 miles upstream of Cushaw, would be the 7^{th} in a span of about 30 miles.

The Spokane River site, LPS site 566, is shown in Figure 4. The Spokane River flows out of Lake Coeur d'Alene in Idaho, through the region of Spokane WA to the confluence with the Columbia River - about 100 miles. There are several dams on the Spokane River, all associated with seven different hydroelectric generation facilities. One is owned and operated by the City of Spokane while all the others are owned by Avista. LPS 566 site is west of Spokane, downriver from Latah Creek, between Avista's Nine Mile Plant (downstream) and Monroe Street Bridge Plant (upstream), situated between a golf course (right bank) and community college (left bank).

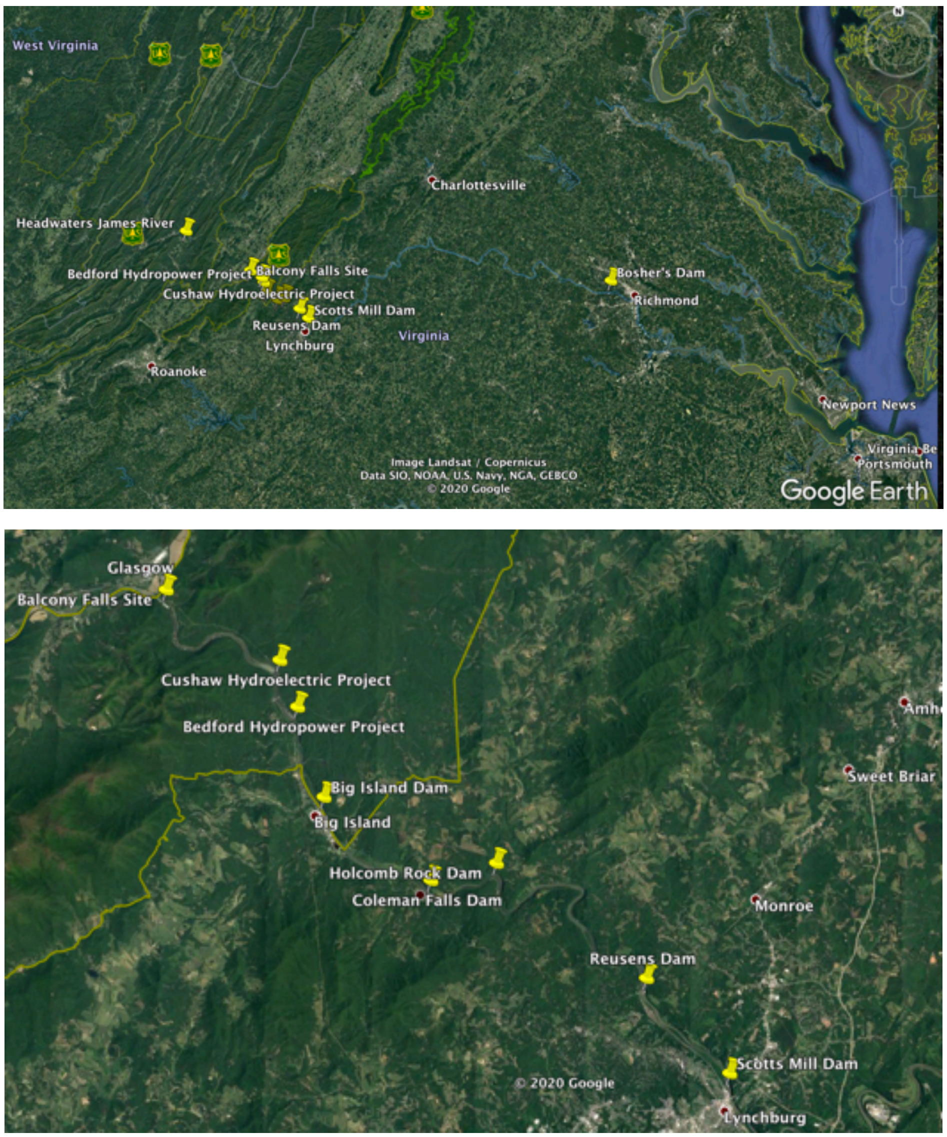


Figure 3: Balcony Falls site and surrounding area.

Figure 4: LPS 566 site and surrounding area.

3.1.4 Metrics Related to the Goal Metrics

The development and application of a site selection process yielded two sites, Balcony Falls and LPS 566, that satisfy and support the goals outlined in Table 1 as described below and summarized in Table 2. The section below describes how each site supports the goal metrics following the order they are listed in Table 2. The discussion of how the site selection supports the cost goal is discussed last so that it takes place in the context of how the facility selections support the other goals.

***Table 2: Summary of characteristics of two selected sites and how they support goal facility metrics.*[2]**

Goal Characteristic	Goal Metric	Balcony Falls Site Supports Goal Metric	LPS 566 Site Supports Goal Metric
Nameplate capacity (flow and hydraulic head)	≤ 10 MW (e.g., up to 5,000 cfs and up to 30 ft. hydraulic head)	Initial estimate: 20 ft head, Q=3,500 cfs, the capacity of 5.2 MW.	Initial estimate: 19 ft head, Q=7,000 cfs, the capacity of 9.9 MW.
Modeled installed capital cost per nameplate capacity	< $3,500/kW Stretch goal <$2,000/kW	Estimate $4,308/kW, motivation to engineer modules for a lower cost.	Estimate $3,085/kW, potential to reach the stretch goal
Estimated construction timeline	< 2 yrs. site prep. to commissioning	A simple construction model yields 63 weeks.	A simple construction model yields 76 weeks.
Replication – the same type of modules	Multiple (2 or more) U.S. sites	Both sites use the same three basic modules – generation, sediment, and water passage.	
Passage – water	Safe and timely	Estimated maximum conveyance = 81,445 cfs Estimated 1000-yr flood = 75,148 cfs	Estimated maximum conveyance = 66,430 cfs Estimated 1000-yr flood = 50,753 cfs
Passage – fish	Safe and timely	Presently no anadromous migrations; supports facility design if that situation changes.	

[2] Note, the characteristics of the final facility design described in Sections 3.3 and 3.5 may be different than the values in this table since these values correspond to the site selection task not the final facility design.

Passage – recreation craft	Safe and timely	Opportunity for recreation modules.	Opportunity for recreation modules.
Passage – sediment	Safe and timely	Minimal sediment issues expected.	Opportunity to investigate significant sediment issues.
Water quality	No degradation	Supports ROR facility	Supports ROR facility
Co-Development Opportunity	At least one	Supports possible safe exit for kayakers, whitewater park, and head pond recreation.	Supports head pond recreation, and irrigation or sediment control system.

3.1.4.2 Balcony Falls site supports the goal metrics.

The James River site, Balcony Falls, is characterized primarily as having a Q30 of $3{,}271\ cfs$ based on U.S. Geological Survey (USGS) gauge data as shown in the flow duration curve in Figure 5. The number of generation modules is calculated using Equation 1, which results in seven generation module stacks, each with a turbine having a hydraulic capacity of $500\ cfs$. Assuming a facility constructed head (H in feet) of 20', which seems reasonable based on elevation measurements taken from Google Earth, with the maximum hydraulic capacity (Q in cfs) of $3{,}500\ cfs$ operating at 88% efficiency (η) the corresponding generation capacity (P in MW) is $5.22\ MW$, using the standard hydropower equation (see equation 6).

$$P = (H\ x\ Q\ x\ h)/11{,}800 \quad (6)$$

These results, obtained during the site screening task, support a facility goal of having flows up to $5{,}000\ cfs$ and 30' of the head. And less than $10\ MW$.

Construction time for the facility at Balcony Falls is estimated following the construction sequence and timing developed for the first-generation modules by seasoned professional engineers from the AECOM company, who estimated it would take 30 weeks to install a first-generation h-Modulor facility comprised of 21 modular stacks including nine generation module stacks [Duquette and Cox (2019)]. Assuming the generation module stacks take 50% more time than the other stacks, a simple construction time model is that the construction time is 1.8 weeks per generation module stack and 1.2 weeks for each of the other types of module stacks. The number of module stacks for a site is estimated using the river width as described above in Equations 3 and 4. The estimated river width at the Balcony Falls site, as measured from Google Earth, is $352\ ft$, which requires 44 stacks plus approximately five more for abutments yielding an estimated total of 49 stacks; seven generation module stacks and 42 other stacks. Thus, the estimated construction time is $1.8 * 7 + 1.2 * 42 = 63$ weeks, which is less than the goal metric of fewer than 2 years.

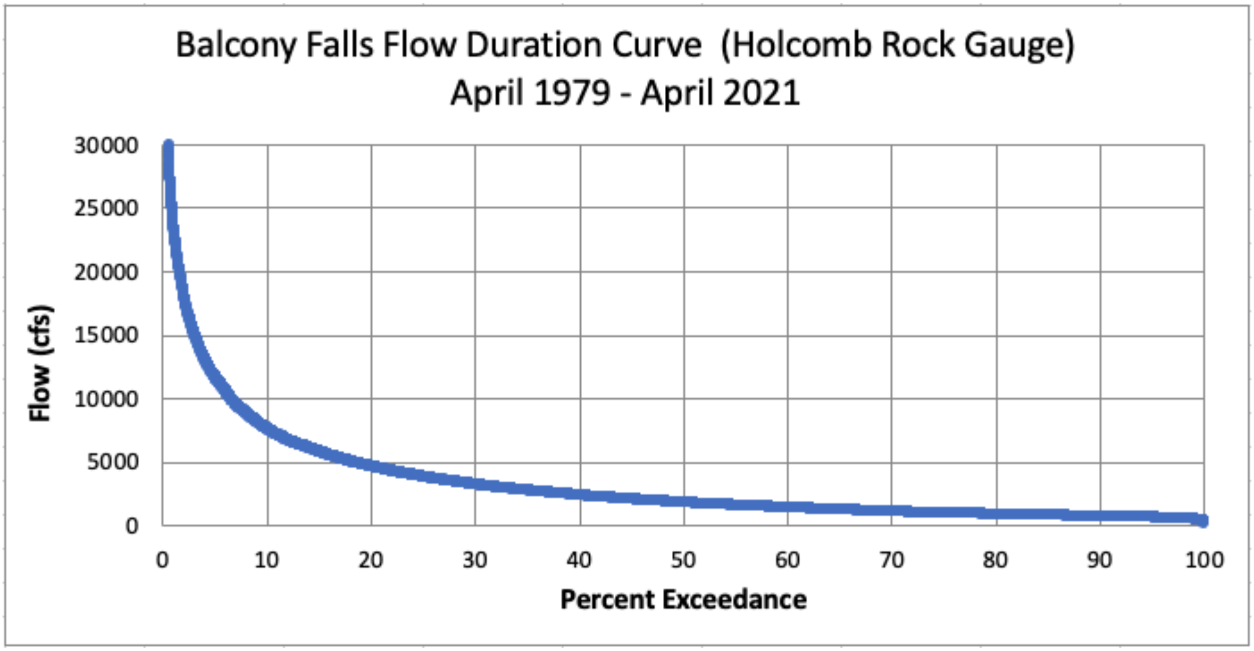


Figure 5: Flow duration curve for the Balcony Falls site.

Elements of the facility at Balcony Falls that support the metric for the safe and timely passage of water, fish, recreation craft, and sediment are discussed next in that order. For the facility metric for safe and timely water passage, the estimated 1000-yr flood level at the site is compared to the estimated maximum flow that can be safely passed by the facility. When the crest gate on the water passage module stack is open there is approximately 9 ft of space above the gate for conveyance. In addition, each of the three modules is designed to withstand 10 ft of overtopping (Duquette and Cox 2019). The maximum flow over each module stack is estimated using a simple weir equation:

$$Q_{weir} = 3.3 * B * h^{\frac{3}{2}} \tag{7}$$

where Q_{weir} is the flow in cfs conveyed over the section of the facility, B is the effective length of the weir in feet for that section and h is the effective height of the water traveling over that section in feet. For each water passage module stack, the maximum height of water that could flow over it when the crest gate is completely open is the 9 feet of gate opening plus the 10 feet of overtopping equaling 19 feet. For each of the other module stacks, the maximum height of water that can flow over it safely is 10 feet. Using Equation 7 and remembering that the width of every module is $8\ ft$ [Duquette and Cox (2019)], the maximum flow over the water passage module is 2,186 cfs and the maximum flow over each of the other types of module stacks is 835 cfs. Assuming, from above, that there are seven generation module stacks and five abutment stacks and that each of the generation module stacks has an accompanying sediment module stack [Duquette and Cox (2019)] so there are seven sediment module stacks, that leaves enough space for 30 water passage module stacks. The estimated maximum conveyance for the whole facility then is $30 * 2{,}186 + 19 * 835 = 81{,}445\ cfs$.

A quick way to assess safe and timely water passage is to treat the flow duration curve as a normal distribution using the exceedance values to define the distribution and compare the flows from this statistical distribution to the percentiles for the various flood levels as shown in Table 3. Based on this analysis, the estimated maximum facility conveyance of $81{,}445\ cfs$ at the Balcony Falls site supports the facility metric for water passage to be safe and timely given the flood flows estimated from a normal distribution curve developed from the flow duration curve. Put more simply, the maximum flow of the facility, $81{,}445\ cfs$ exceeds the $1000 - yr$ flood level, $75{,}148\ cfs$, indicating it is a safe level of water passage.[3]

Table 3: Estimated flood flows at the Balcony Falls site.

Flood level	Percentile	Flow from Normal Distribution (cfs)
1000-yr flood	0.00000274	75148
500-yr flood	0.00000548	73596
100-yr flood	0.0000274	69853
50-yr flood	0.0000548	68174
10-yr flood	0.000274	64100

Regarding safe and timely fish passage, because of the proximity of the Balcony Falls site concerning downstream dams, it is unlikely that upstream fish passage will be necessary, and the standard facility has no upstream fish passage module. If upstream fish passage would become a requirement in the future, for instance, if fish passage were accomplished at all the other downstream dams, then American shad, alewife, blueback herring and American eel may be expected to be present at Balcony Falls (see details in *Appendix I*). In that case upstream fish passage could be added to the facility as described in Section 3.2.2, PASSAGE MODULE (UPSTREAM FISH).

For downstream fish passage, the water passage module serves the dual purpose of a surface bypass, and the facility includes a tailwater that is maintained at a depth that is sufficient for a safe drop [Duquette and Cox (2019)]. In addition, the facility includes upstream bar screens to exclude fish from entering the turbines and the inclusion of a sediment module stack in

[3] This approach is suitable for evaluation of sites at a selection and conceptual level. It is not intended to replace FERC dam safety analysis.

between each generation module stack with the intent to reduce the approach velocity to a level that is safe for fish.

Concerning the metric for safe and timely recreation passage, the Balcony Falls site lies within a region where a variety of water-based activities are actively pursued by numerous recreationists. Flatwater boating, whitewater boating, fishing, and swimming are all undertaken in the waters surrounding the project site. The Balcony Falls site is adjacent to existing boat ramps including the Glasgow Boat Launch which is located at the confluence of the Maury River and the James River. Selection of the Balcony Falls site supports the metric for safe and timely recreation passage by allowing for hand-carry launching of small boats such as canoes and rafts and the Balcony Falls facility contemplates replacing two or more of the water passage module stacks with recreation passage chutes for small water craft such as kayaks.

The Balcony Falls site selection supports the metric of safe and timely support of sediment in two ways. First, because it is so far up the watershed from the mouth at the Chesapeake Bay it is unlikely to contribute much to the sediment issues in the bay. However, for possible more local sediment control needs it supports using the sediment module stacks with a gate at the bottom of the stack. This gate allows controlled passage of bedload and other sediments via density current venting and flushing during periods of high flow and via sluicing during periods of impoundment drawdown as needed to manage sediment accumulation in the reservoir.

Regarding water quality, the Balcony Falls site selection supports the facility metric of no degradation in water quality since the site supports a run-of-river facility where reductions in dissolved oxygen are not a concern due to the short water residence times.

The selection of the Balcony Falls Site supports the facility metric of at least one co-development opportunity. Whitewater rafting is a popular recreation in the area and exit from the river is reported to be dangerous as it often involves boaters crossing active railroad tracks. One co-development opportunity is to improve the safety of this exit point. A more ambitious co-development is to develop a whitewater park where the recreation modules that provide passage through the facility are integrated into the whitewater park. A head pond recreation area for boating and fishing is a third possible co-development.

How does the Balcony Falls site support the cost goals? Using the cost model described above, Equation 1, for the facility at the Balcony Falls site results in an estimated initial capital cost of $\$4{,}770/kW$, which is significantly over the $\$3{,}500/kW$ goal. But this site offers an important opportunity to develop concept designs for recreation passage, which is expected to help address community push back against developing new greenfield hydropower. In addition, there is an opportunity for reduced costs since the water passage modules could probably be lower-cost fixed weir versions and still meet the $1000-yr$ flood safety goals.

3.1.4.2 LPS 566 site supports the goal metrics.

The Spokane River site, LPS 566, is characterized primarily as having a $Q30$ of 6,870 cfs based on USGS gauge data as shown in the flow duration curve in Figure 6. The number of generation module stacks is calculated using Equation 1, which results in 14 generation module stacks, each with a turbine having a hydraulic capacity of $500\ cfs$. Assuming a facility constructed head (H in feet) of $19\ ft$, which seems reasonable based on elevation measurements taken from Google Earth, with the maximum hydraulic capacity (Q in cfs) of $7{,}000\ cfs$ operating at 88% efficiency (η) with corresponding generation capacity (P in MW) of $9.9\ MW$, using the standard hydropower equation (see equation 6). These results, obtained during the site screening task, support a facility goal of having flows up to $5{,}000\ cfs$ and $30\ ft$ of head. And less than $10\ MW$.

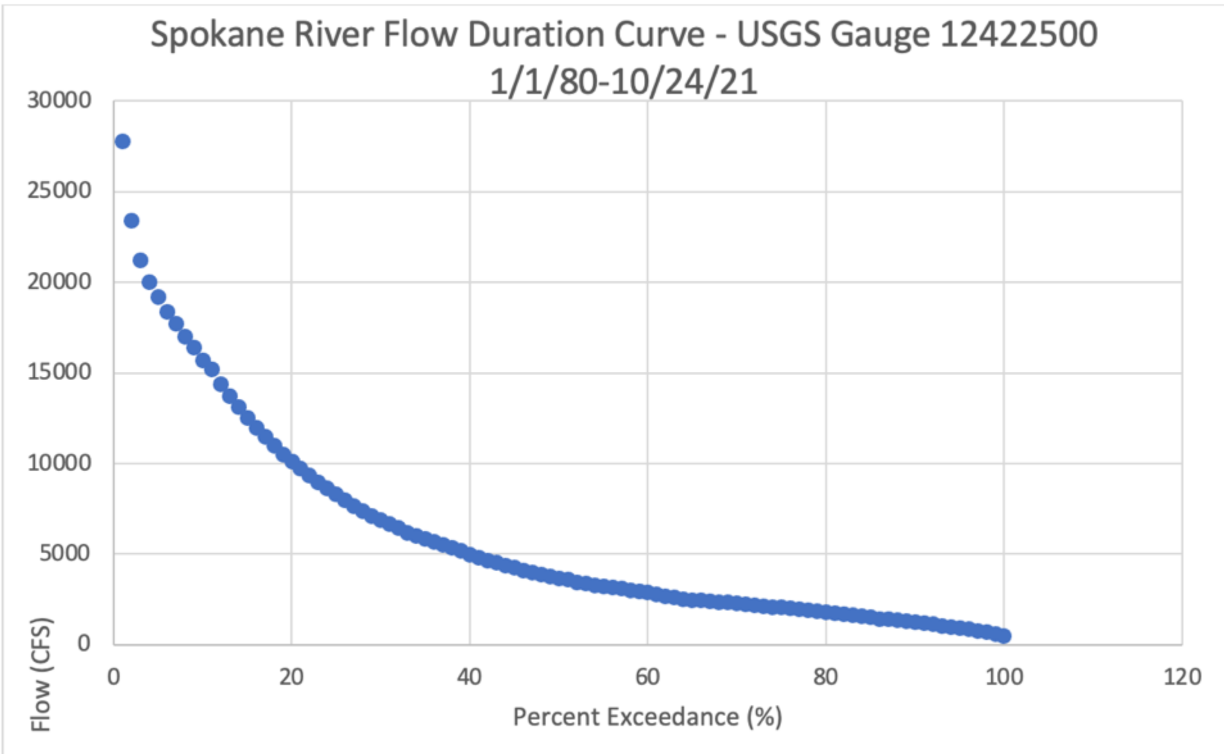


Figure 6: Flow duration curve for the LPS 566 site.

Construction time for the facility at LPS 566 is estimated as 1.8 weeks per generation module stack and 1.2 weeks for each of the other types of stacks as described above for the Balcony Falls site. The river width at LPS 566 site is $185\ ft$ as measured on Google Maps. At this site, the powerwall is angled to provide space for water passage modules, since if the facility were oriented perpendicular to the flow for all stacks there would only be room for 23 stacks, leaving no room for any water passage module stacks. The first cut at a module count for the facility at LPS 566 at this selection stage, is 14 generation module stacks, 14 sediment module stacks, and 14 water passage module stacks plus 14 more stacks for abutments, which equals 56 stacks in total. Thus, the estimated construction time is $1.8 * 14 + 1.2 * 42 = 76$ weeks, which is less than the goal metric of fewer than 2 years.

Elements of the facility at LPS 566 that support the metric for the safe and timely passage of water, fish, recreation craft, and sediment are discussed next in that order.

Concerning the facility metric for safe and timely water passage, the estimated 1000-yr flood level at the site is compared to the estimated maximum flow that can be safely passed by the facility. As described for the facility at Balcony Falls, the maximum flow over the water passage module stack is 2,186 cfs and the maximum flow over each of the other types of module stacks is 835 cfs. Using the module part count from the paragraph above the maximum facility conveyance is $14 * 2{,}186 + 42 * 835 = 66{,}430\ cfs$. As shown in Table 4, where the flood level flows were estimated by treating the flow duration curve as a normal distribution using the 70% and 3% exceedance values to define the distribution, this maximum facility flow exceeds the $1000 - yr$ flood level.

Table 4: Estimated flood flows at the LPS 566 site.

Flood level	Percentile	Flow from Normal Distribution (cfs)
1000-yr flood	0.00000274	50,753
500-yr flood	0.00000548	49,732
100-yr flood	0.0000274	47,204
50-yr flood	0.0000548	46,079
10-yr flood	0.000274	43,348

Regarding safe and timely fish passage, because of the proximity of the LPS 566 site to downstream dams, it is unlikely that upstream fish passage will be necessary, and the standard facility has no upstream fish passage module. The site lies within the historic range of anadromous salmon and steelhead but has been blocked for over 80 years since the construction of Grand Coulee dam on the Columbia River (see details in *Appendix I*). Should upstream fish passage be added to the downstream dams, then upstream fish passage could be added to the facility as described in Section 3.2.2, PASSAGE MODULE (UPSTREAM FISH). Safe passage downstream is accomplished as described for Balcony Falls. The angled powerwall in this configuration adds additional resistance against entrainment.

Concerning the metric for safe and timely recreation passage, the LPS 566 site lies within a section of the river that receives a substantial amount of water-based recreation, and the facility may include the construction of new or improved small boat access points and inclusion of one or more recreational boat passage chutes to facilitate downstream movement of small boats at the dam.

The LPS 566 site selection supports the metric of safe and timely support of sediment passage by providing a location with significant sediment passage challenges to investigate.

Regarding water quality, the LPS 566 site selection supports the facility metric of no degradation in water quality since the site supports a run-of-river facility where reductions in dissolved oxygen are generally not a concern due to the short water residence times.

The selection of the LPS 566 site supports the facility metric of at least one co-development opportunity. Its proximity to a college and golf course provides an opportunity for a behind the meter off-taker. The golf course may provide an opportunity for the co-development of an irrigation system. The location of the LPS 566 site concerning the downstream Nine Miles Falls project provides an opportunity to cooperate in sediment management.

Using the cost model described above (Equation 1) for the facility at the LPS 566 site results in an estimated cost of $\$3{,}085/kW$, which is less than the goal metric of $\$3{,}500/kW$ and possibly within range of the stretch goal of $\$2{,}000/kW$ with successful module redesign for cost reduction.

3.1.5 Lessons Learned

The site selection process involved gathering and processing information from different sources in a manner that is meaningful for estimating the cost per capacity ($/MW) as well as assessing site characteristics. Given there is not a formal and well-defined industry-accepted standard or approach for performing site selection, LPS had to develop methodologies for incorporating and utilizing existing data in efforts to assess and select potential sites for development. Through this process, some challenges were encountered.

A significant challenge was quickly and accurately identifying river width. Initial screening used ArcGIS to generate polygons of stream reaches for the sites in the NSD and used a Python script to estimate river width. This approach was used in a previous project [Duquette and Cox (2019)] to sort through thousands of data points in the NSD database and associate a river width with each of the data points. These thousands of data points were sorted using the rough cost model described above, which essentially relies on $Q30$ and river width to predict a facility cost. The data sets were reduced to the 168 lowest-cost sites. When inspected using Google Maps or Google Earth it turns out that a number of these sites have braided rivers and the screening tool had ascribed a much narrower river width, closer to the width of one of the braids, which led to an erroneous low-cost. Another challenge that limited the use of this rapid screening tool, is that some of the narrow rivers that resulted in reasonably low estimated costs, were located on very flat ground that would require many abutments to create a sufficient impoundment to achieve the facility head. The cost of these abutments was not included in the initial cost estimate. The screening approach was very helpful, narrowing down the list of possible sites from thousands to hundreds in a matter of a few hours. Adding parameters to the tool to search for braided rivers and identifying the amount of elevation rise outside of the river boundaries would improve the accuracy and speed to narrow down the number of potential sites from hundreds to tens.

Other challenges and recommendations are listed below.

- Availability of flow data for flow duration curve development in absence of flow gage data.
- The overall accuracy of the cost model includes the use of Google Maps for the determination of river widths and relying on flow from the NSD database. Incorporating the modeling described in Section 3.3.2 that is used for concept design may be able to be automated and used to improve the accuracy of the site screening approach.
- The site screening cost model could be improved by adding a check that the number of water passage modules has sufficient flow capacity to pass the spillway design flood. In addition, consider examining two capacities, one for normal operations and one for over topping.
- Electrical interconnection costs were not included in the screening cost model, and it is not clear where they should be included. Explorer SMH includes information on the distance to substations that may inform these costs.
- Combining the LCOE and ICC estimates into the same screening step may make the energy generation aspects of the screening more apparent. Consider including an estimate of capacity factor to inform economics for the potential projects.
- Accuracy of use of Google Earth for determining elevations to refine heads reported in the NSD database.
- Availability of river depths for estimating/determining the number of abutment modules needed. In most cases, the number is overestimated since it does not consider the elevation from the river bed to the surface of the water.
- Applicability/availability/accessibility of data for decision-making concerning land ownership, social, anthropological, etc., issues that may render sites unavailable and/or too complicated to develop.
- Availability and quick access to flood data for stream reach.
- Accuracy of flood estimates that anticipate climate change.

3.2 Task 2: Module Development

3.2.1 Task Objective

The objective for Module Development is to establish designs for developing standardized and modular equipment that are commensurate with supporting an SMH facility that meets the facility goals presented in Table 1. According to the Exemplary Design Envelope Specifications (EDES), modularity within a facility pertains to the use of different module types to construct an entire facility. The collective design of the modules acknowledges the alignment of stream functionalities of renewable energy, water flow, sediment passage, fish movement, and recreation with the generation, passage, and foundation modules [Witt et. al. (2017)].

The most significant finding of Task 1 is that meeting the cost goal of $\$3{,}500/kW$ at a considerable number of sites and attaining the stretch cost goal of $\$2{,}000/kW$ at any site requires lower cost modules. Meeting these economic goals is a driving objective of Task 2.

3.2.2 Approach and Methodology

Before the execution of this project, LPS already had an existing catalog of designs and some experience in the development and assembly of modules. Current designs and methods used to develop these are the result of years of disciplined and creative thought followed up with engaging industry experts to engineer the concepts into working products through a process of continuous expert assessment and improvement. The efforts and methodology for module design and development are described here.

LPS utilizes the h-Modulor approach introduced in Section 1.2, which replaces the bespoke equipment and process in a way that accelerates civil work and lowers risk. The design approach for each of the generation and passage modules adopt three philosophies. One is that they are prefabricated in a shop where tolerance and quality can be economically controlled. Second is the shipping container form factor, which boils down to making it easy to ship anywhere in the world since by its nature prefabricated, standard modules will need to be transported to the site. Each module contains the respective equipment about its functionality built into an ideally $8\ ft$ wide $*$ 9.5 ft high frame that is either $10\ ft$ or $20\ ft$ long to meet the shipping container form factor. It is not just housed in a shipping container form; it is the shipping container. This form factor allows for simplified selection, design placement/space planning, and transportability due to its standardized size and modular nature (Duquette and Cox 2016, [Duquette and Cox (2019)]. The third is novel structural independence. The module stacks are structurally independent of each other so that any stack can be removed and replaced without any structural effect on an adjacent stack. Planned removal and replacement extend the life of a facility indefinitely.

LPS's system uses five different functional modules: (i) foundation module, (ii) generation module in a stack form or pressure box form, (iii) water passage module in a stack, which also serves as a surface bypass for downstream fish passage, (iv) sediment passage module in a stack form, which also serves for low water passage and impoundment with or without the passage function and (v) abutment stacks. Recreation passage modules are being specified under this project and modules to attract and transport fish upstream are being developed in collaboration with Whooshh Innovation, Inc. separately. To achieve full hydropower plant function, these modules are augmented with the switchgear, hydraulic pressure unit (HPU), control panel, and automation system instrumentation modules.

The h-Modulor system includes module components that are tuned to the essential stream functions. These modules can be selected, sized, and configured to fit a site. This approach affords the required diversity to apply the design to multiple sites with unique design constraints while allowing for the use of standard equipment and standardized design, specification, and installation processes.

Figures 7-9 illustrate the starting point for the module design effort. The facility image (Figure 7) is looking at the facility from an elevation view from upstream of the facility. On the far right, there are four water passage module stacks shown with the crest gate in the full raised position for a 22 ft normal pool. Next to them, right to left, are a sediment passage module stack and a generation module stack alternately arranged for a total of three and two, respectively. A gantry crane sits on top and is used to open/close the cylinder gates over the vertically oriented semi-Kaplan turbines.

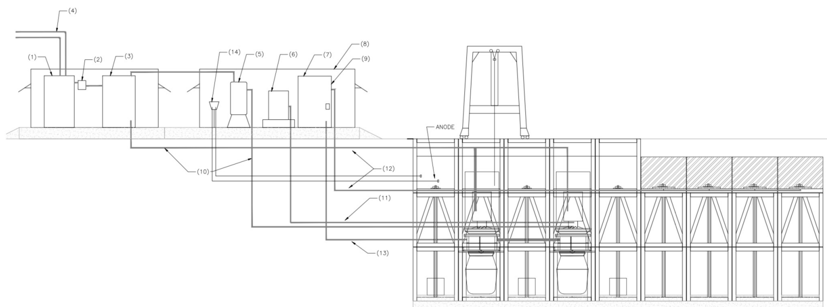


Figure 7: h-Modulor facility and modules at the start of the project.

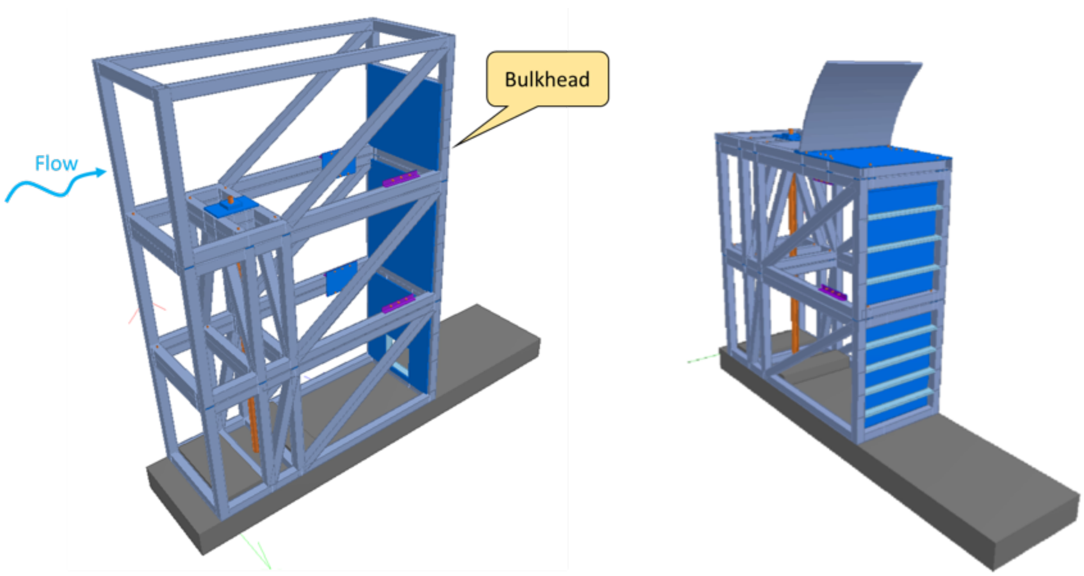


Figure 8: h-Modulor sediment module stack and water passage module Stack (pneumatic gate actuating system not shown) at the start of the project.

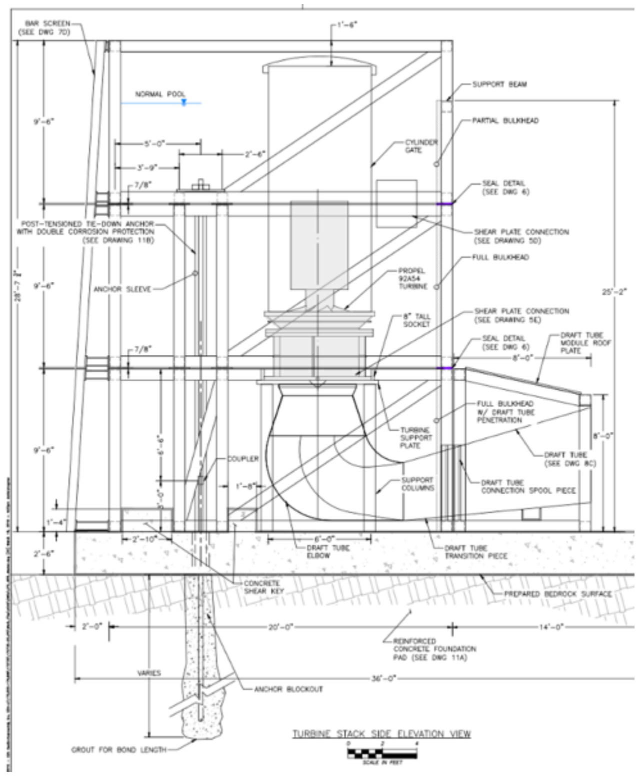


Figure 9: h-Modulor generation module Stack at the start of the project.

In general, the concept for the modules' design for generation and passage stems from the ability to stack box frames with the dimensions of ISO containers. Each frame shown in Figure 8 is $8\ ft$ wide, $9.5\ ft$ high, and $20\ ft$ long. The design allows for two or three box frames to be stacked to achieve the desired configuration. For the two-box-frame-high stacks, the sediment module stack is nominally $19\ ft$ and for the three-box-frame-high stack, shown in Figure 8, it is nominally $29.5\ ft$ tall. It is a rectangular-shaped stack of box frames with a bar screen assembly on the upstream side (not shown in Figure 8), bulkheads covering the downstream side of the box frames, and a gate at the bottom of the sediment module stacks to allow sediment or water passage. Each stack is secured to the cast-in-place concrete foundation and into the ground with a single tie-down anchor. The water passage module stack is a shorter stack that is only two box frames high $(\sim 19\ ft)$ with a pneumatically controlled crest gate making up the rest of the height to reach normal pond elevation in conjunction with the three-box-frame-high sediment or generation module stacks. The downstream face of the box frames of the water passage is covered in bulkheads to keep water on the upstream side. The generation module stack (Figure 9) uses the sediment stack as the base and adds in the turbine/generator, a cylinder gate, and a draft tube extension module that extends 10' downstream.

The design efforts to improve the generation and passage modules from this baseline focused on reducing the cost of the designs to meet the project objective cost goals. The design efforts for the foundation module focused on transitioning the modular rebar cage and cast-in-place concrete foundation that existed at the start of the project into a truly precast, standard modular concrete foundation.

FOUNDATION MODULE – The definition and purpose of a foundation are eloquently provided by Jumikis (1971):

Definition of foundation:

"A structure usually consists of two major parts, the upper, known as the super structure (a truss of a bridge, for example), and the lower, known as the substructure (piers, abutments, and their supporting bases), known in a broad sense as the foundation, to hold the superstructure in place and to transmit all loads of the superstructure to the underlying supporting soil or rock.

A foundation is a connecting link between the structure proper and the soil. It is not visible to the public eye. The true value of a foundation lies out of sight in the substructure below the ground surface."

Purpose of foundation:

"The foundation is a special, important, artificially built constituent part of a structure having for its purpose:

- To receive and transmit structural loads and loads (wind, vibration) externally applied to the substructure to the soil (rock) at a given depth below the ground (water) surface, whichever is the case.
- To distribute stresses at the base of the footing of the foundation to an intensity allowable on the soil (rock)."

In addition, the foundation for h-Modulor needs to:

- Provide appropriate and level surfaces for the assembly of stacked modular units.
- Prevent excessive total and differential settlement.
- Create a water impermeable barrier which prevents the flow of water under downstream water retaining bulkhead.
- Control seepage to reduce loss of water and exit gradients to an acceptable level for soil foundations.
- Protect foundation against scour due to discharge and overtopping.

The initial modular foundation design uses a concrete pad integral to the bottom of each modular stack, after analysis, this transformed into an external precast concrete slab with embedded wire flange beams and to the final conceptual design for a two-way, two-layer, precast concrete grade beam foundation system. From this point, LPS further investigated the possibility of contouring the bottom planks to match the riverbed contour for further cost reduction.

The initial concept (see Figure 10) is a reinforced concrete pad foundation that is integral to the bottom frame of a module stack. It incorporates welded rebar connections and shear studs. The issues with this concept are that it is very heavy, over 24 tons, which does not fit with the easy-to-transport philosophy of h-Modulor. It also impairs the replaceability of the bottom module, which goes against the indefinite lifetime philosophy of h-Modulor. Of technical concern is that since it is incorporated into a single stack, it is prone to differential settlement, and there is potential for cracking around the steel frame members. It is also quite complex, and thus expensive, to fabricate.

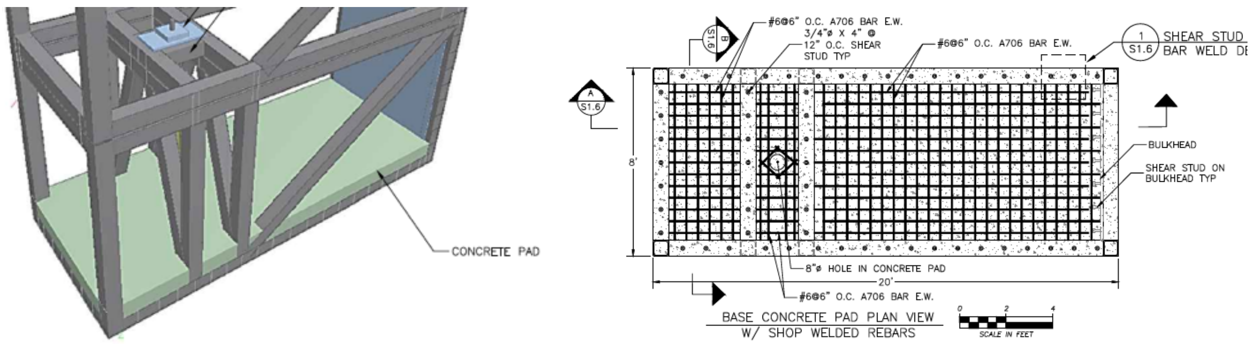


Figure 10: Initial concept for a modular foundation – integral to the bottom frame of each module stack.

The second concept for a modular foundation is shown in Figure 11. It is a pre-cast concrete slab with embedded wide flange beams. The issues with this approach are that it has poor transverse stiffness, is subject to damage from edge loading, and is only in one stack, so it has the same concerns related to differential settlement as the first concept, and it is also very heavy over 23 tons.

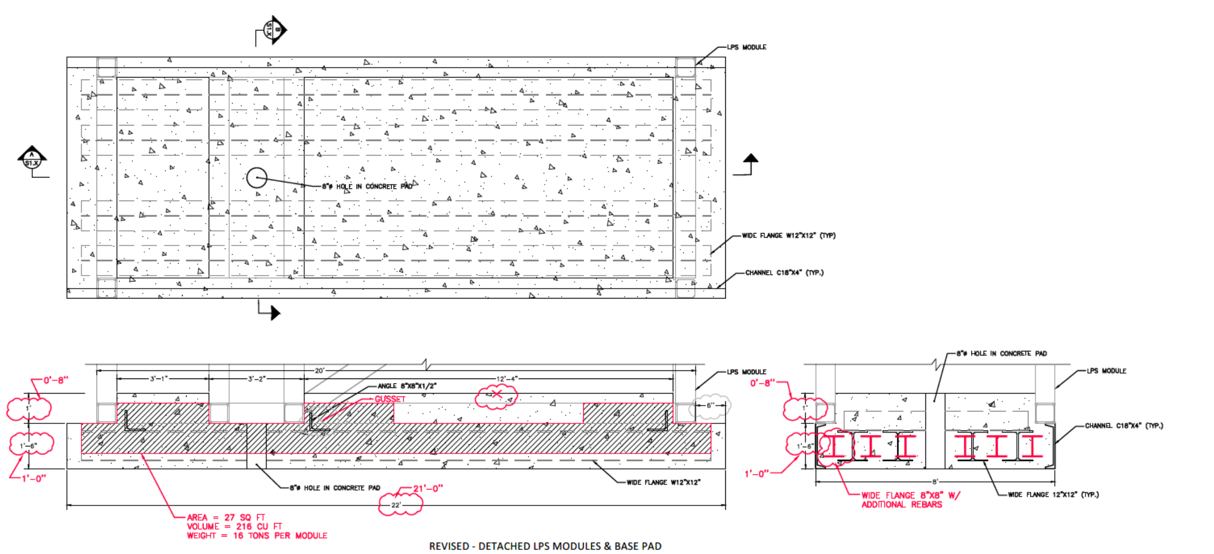


Figure 11: Second concept for a modular foundation – precast concrete slab with embedded steel flanges.

Overcoming these issues led to the final concept design, which is a two-way, two-layer precast concrete grade beam foundation system that is secured to the river bottom with ground anchors (Figures 12 - 15). The elements of the foundation system include the bottom and top beams, reinforcement, and connections. Bottom grade beams are 16 in square cross-section and reinforced with embedded HHS square tubing. They are 35 ft long and weigh 6 tons. They are laid next to each other and key into each other with alternating raised and recessed bosses. The top-grade beams are $1\ ft - 4\ in$ thick, $5\ ft$ wide, and $8\ ft$ long. They are laid across the bottom-grade beams and tied into them with connector bars.

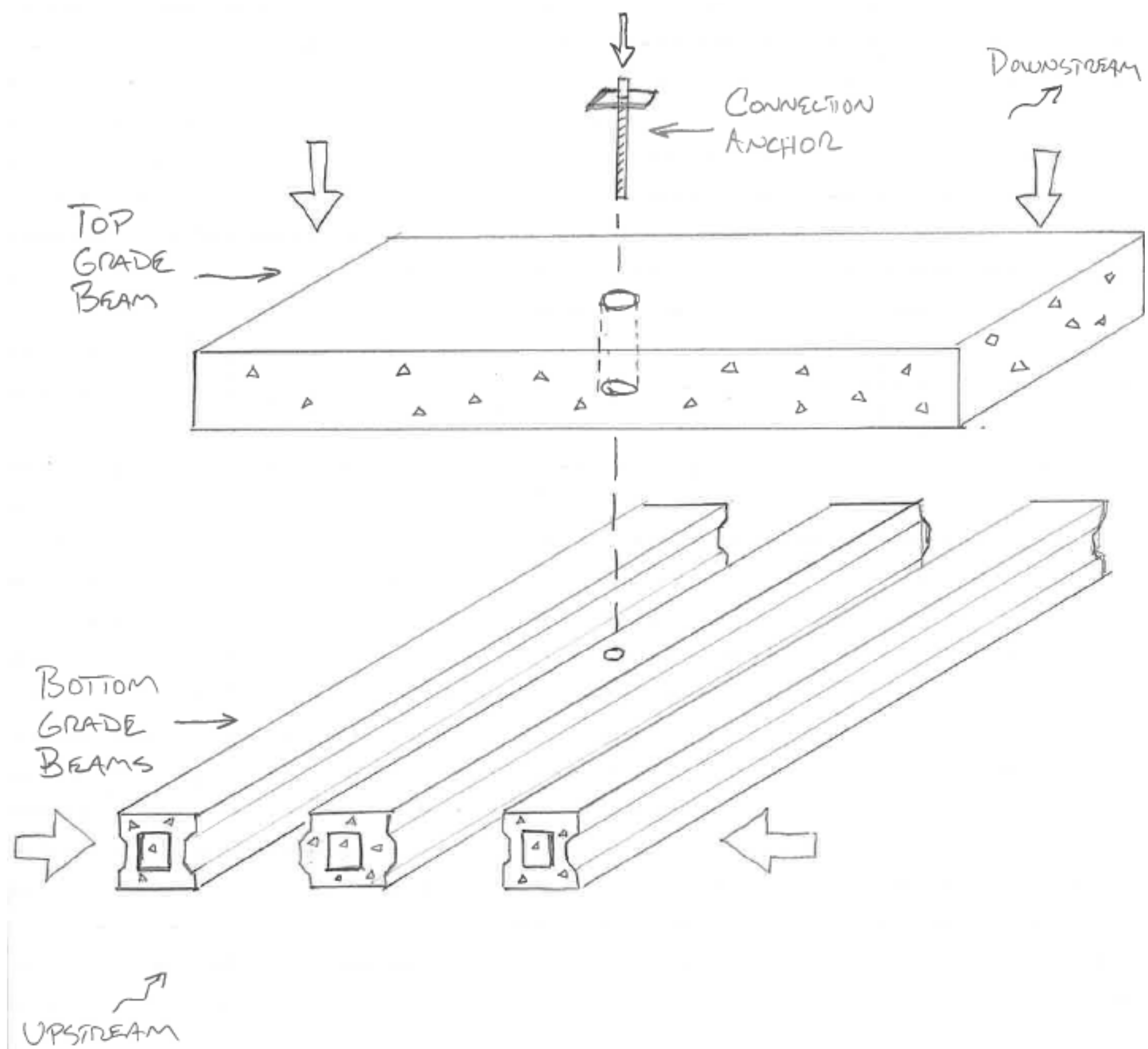


Figure 12: Concept sketch of the two-way, two-layer precast concrete grade beam foundation system.

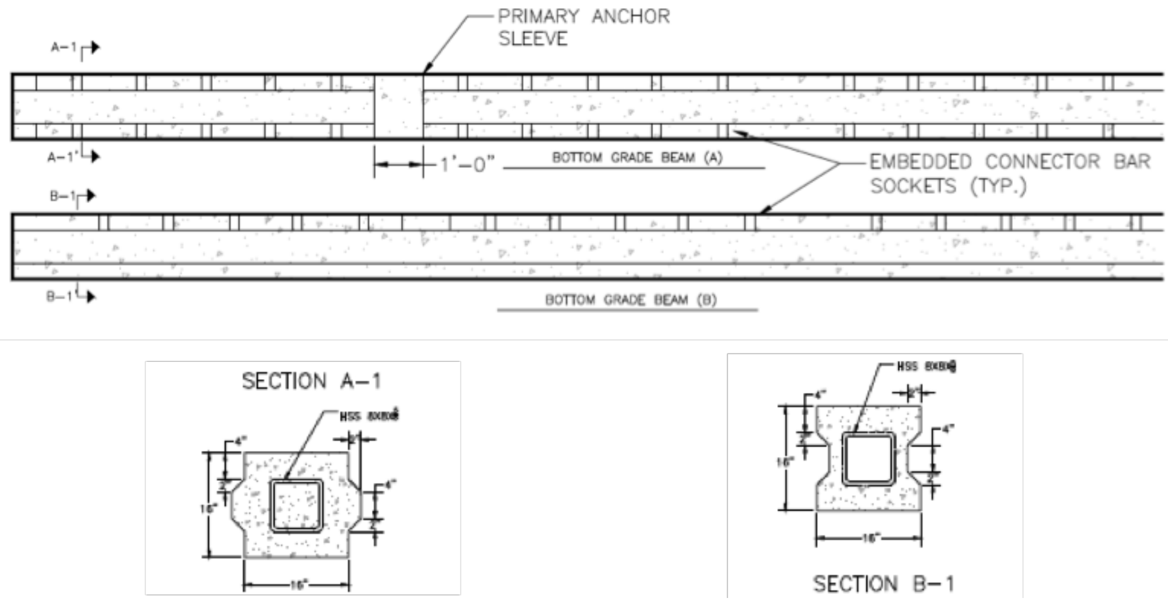


Figure 13: Bottom grade beam, weight equals 6 tons.

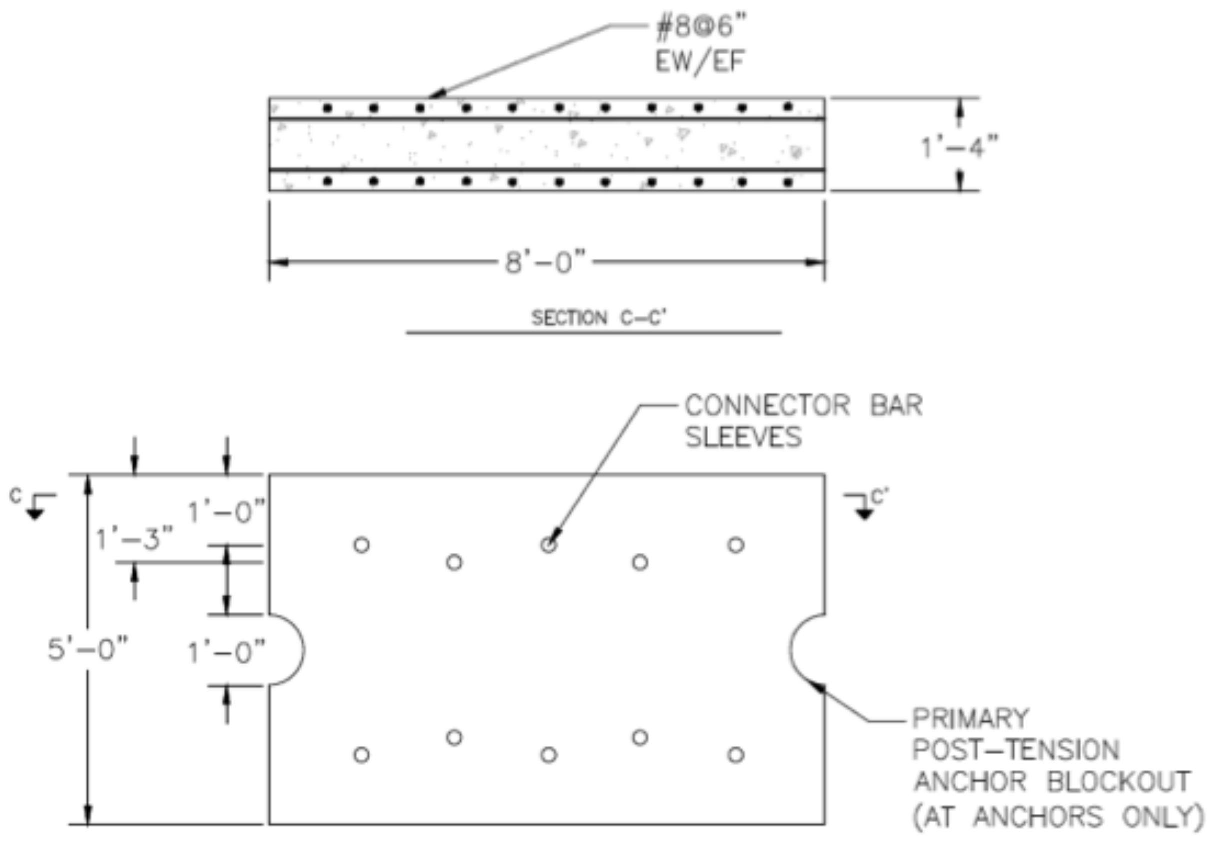


Figure 14: Top grade beam, weight equals 4 tons.

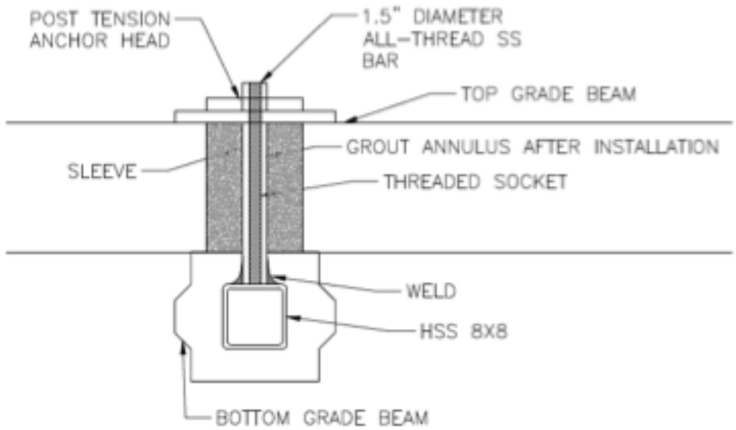


Figure 15: Grade beam connection detail.

<u>*SEDIMENT PASSAGE MODULE AND GENERATION MODULE*</u> – This section presents and discusses the design modification to the sediment module stack and generation module stack together because the sediment module stack is the framework that houses the turbine/generator and the draft tube that becomes the generation module stack.

To address the daunting task of cost reduction, LPS interviewed multiple manufacturers to obtain manufacturing quotes and recommendations, interviewed professional civil engineers, hired an engineer from the air and space industry to bring a new perspective, brought in seasoned professional engineers with decades of hydropower experience, and eventually hired an expert in small hydropower to become part of the leadership team. The evolution of the design is discussed in the context of Figure 15, which compares the redesigned generation module stack with the initial one.

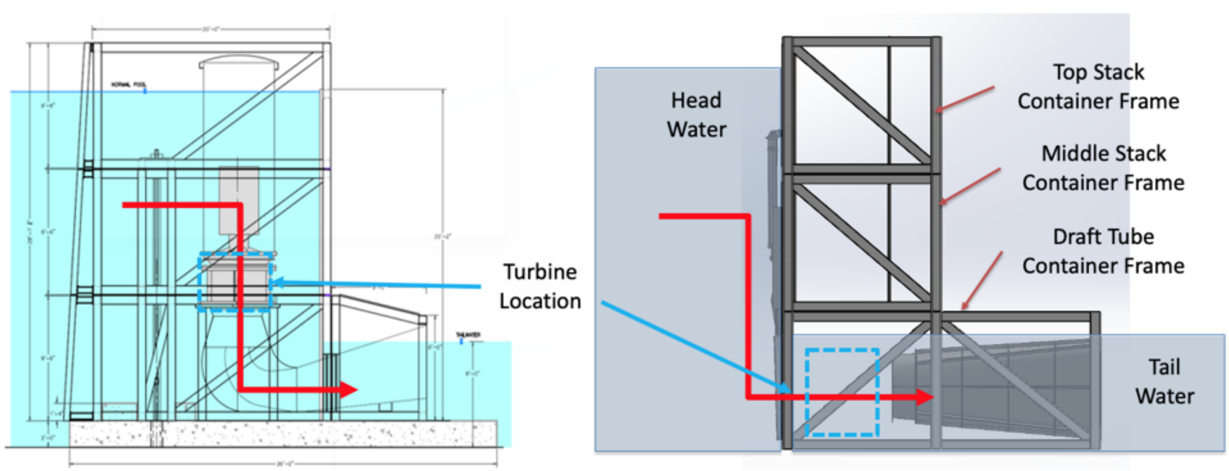


Figure 16: Design modifications to generation module stack. Original design on left, redesign on right.

The shipping container philosophy constrains the size of the frames to $8\ ft$ wide by $9.5\ ft$ high to either $10\ ft$, $20\ ft$, or $40\ ft$ long. One path to reduce costs is to use $10\ ft$ long frames as the basic building block of the modules rather than the baseline 20 ft length. Reducing the length of the bottom frame reduces the stability of the stacks against overturning, but the middle and top frames are prime candidates for this cost-reduction move.

This change requires getting rid of the elements that fill that space in the original design. The first element to move is the tie-down anchor, which opens space for the turbine/generator to move up closer to the upstream face. The tie-down anchors in the redesign are located inside the vertical members (see Figure 16). The original, single tie-down rod was replaced with four small diameter tie-down rods. This move adds some cost but makes room to allow the shorter frames and adds redundancy to the most critical dam safety element of the design. The tie-down anchors were also extended to emerge from and lock off at the top of the stack making them easier to install and maintain than when they locked off below the water surface in the original design.

The next substantial change is to reconfigure the turbine from having a vertical axis of rotation to having a horizontal axis of rotation and locating the intake closer to the river bottom which expands its use to lower head sites. At the same time, keeping the generator located vertically above the turbine while moving the bulkheads to the upstream face so the generator is no longer submerged, reduces both initial generator purchase costs and maintenance costs. The turbine and generator are combined into a single cassette that can be installed into the stack on slide rails on the inside of the stack using an installation/retraction plate and crane, e.g., gantry or davit crane (see Figure 17).

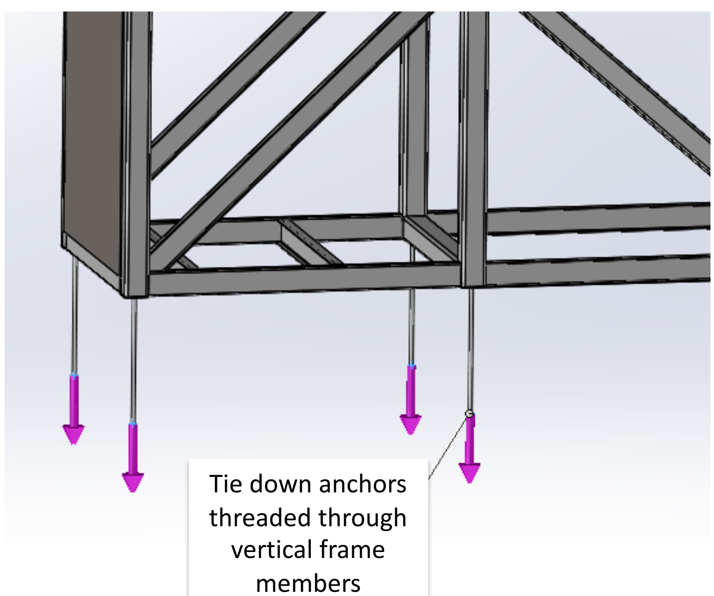


Figure 17: Tie-down anchors thread through the open cavity in the vertical members.

Reorienting the turbine to a horizontal axis of rotation yields another cost reduction by supporting a shorter straight draft tube rather than the original curved one. The original design specified a relatively thick wall casting for the draft tube; the design for the straight draft tube specifies a light weight waffle-like ribbed draft tube that uses less material and is specified to be fabricated from thin gage material using a low-cost robotic laser cutting and welding process (Figure 18).

Finally, the redesigned gate for the sediment module is also light weight using the same waffle-like design and fabrication approach as the draft tube, which supports using a lower-cost hydraulic cylinder to raise and lower the gate. This knife gate serves as the intake gate for the generation module stack.

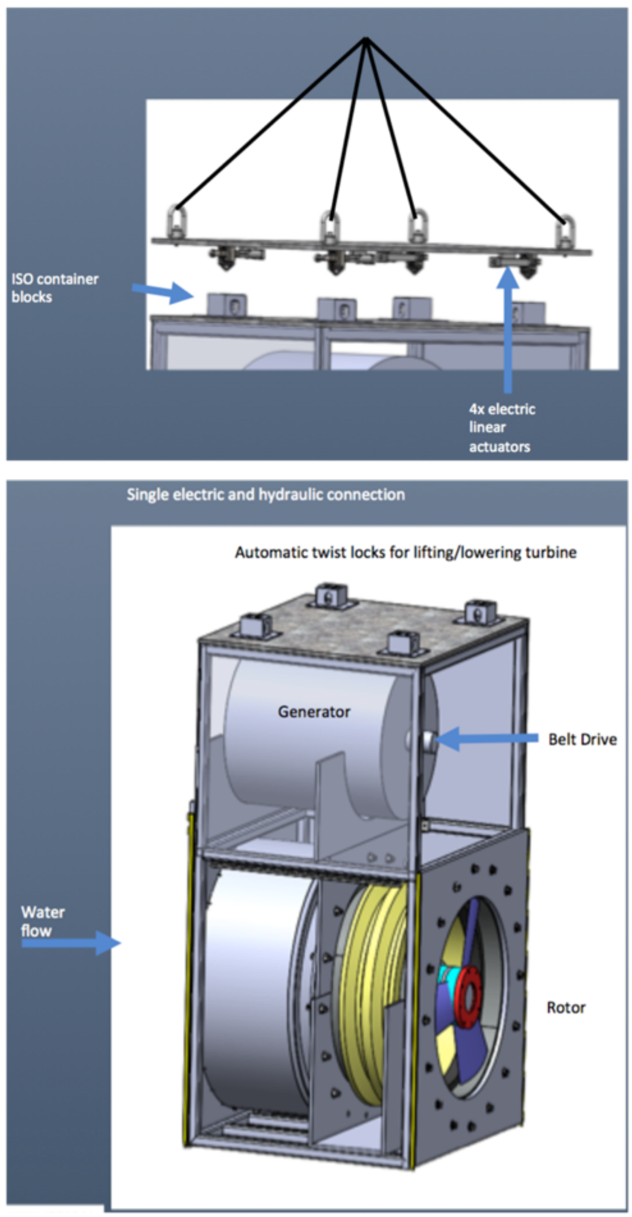


Figure 18: Turbine cassette and installation/retraction plate.

The results of these changes are presented in Table 5. The design changes reduce the weight of the frame components and gate by 34% to 68%, and reduce the draft tube length by 31%, which combined are expected to reduce the cost of the generation module stack (without the turbine/generator) by $45-56\%$. In addition, the redesign reduces the number of truck loads to deliver the modules by 33%, since the frames are so much shorter.

Table 5: Impact of redesign on cost reduction elements.

Assembly	Previous	Modified	Unit	% Reduction
Top Container Frame	6,991	4,634	lbs.	34%
Middle Container Frame	13,296	4,634	lbs.	65%
Draft Tube Container Frame	29,726	13,403	lbs.	55%
Flow Gate	4,588	1,481	lbs.	68%
Draft Tube Center Length	19	13	ft	31%
Generation Module Stack (excludes turbine/generator & draft tube)	54,600	24,152	lbs.	56%
	100 - 130	45 - 70	$ (normalized)	45% - 56%

The design modifications not only reduced cost but are also expected to reduce the environmental impact for the following reasons: 1) lower weight and smaller footprint translate to smaller lay down area and less time on site, and 2) less transportation and less material translate to lower carbon emissions.

PASSAGE MODULE (WATER AND DOWNSTREAM FISH) – Figure 19 compares the baseline water passage module stack design to the design that was modified for cost reduction. The cost reduction design changes to the water passage module stack, which also serves as a downstream fish bypass, follow those described above and include:

- replacing the middle 20 ft long fame with a 10 ft frame,
- replacing a single tie-down anchor with four smaller ones and running inside the vertical members,
- moving the water retaining bulk heads to the upstream side,
- moving the crest gate hinge to the upstream edge,
- retaining the 20 ft long bottom frame and replacing the top of the downstream half of it with an ogee.

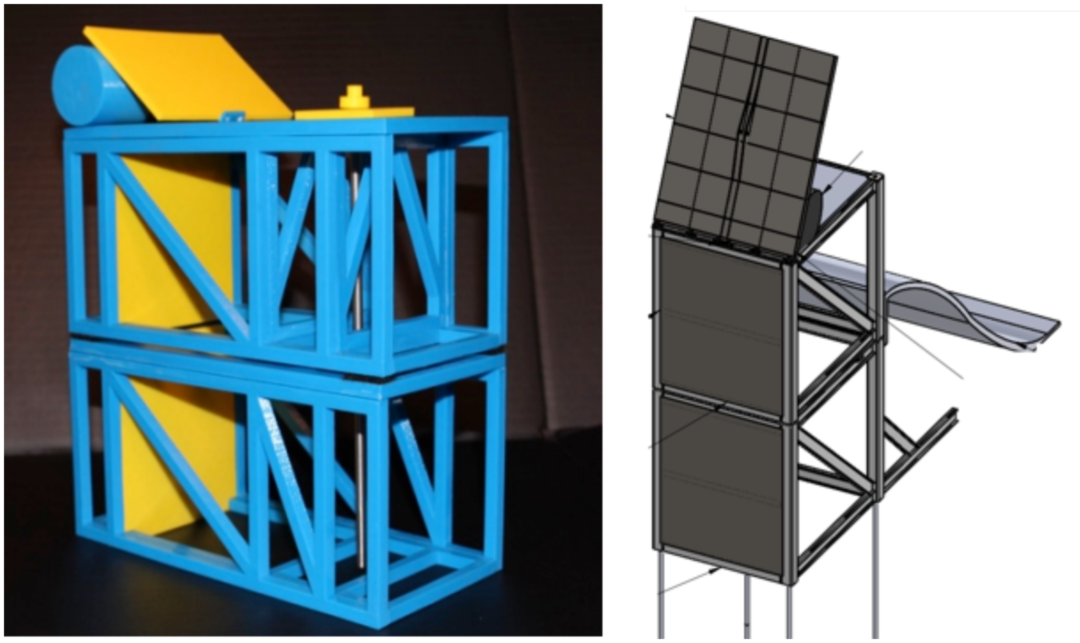


Figure 19: Water passage module – a 3D printed model of the base line design on the left and the redesign for cost reduction on the right.

<u>PASSAGE MODULE (UPSTREAM FISH)</u> – Because of the proximity of the Balcony Falls site and the LPS 566 site to downstream dams, it is unlikely that upstream fish passage will be necessary, however, at sites where upstream fish passage is required or if upstream fish passage would become a requirement in the future, it could be added to the h-Modulor facility in several ways.

Whooshh Innovation's Passage Portal™ has been designed with a modular approach in mind. Depending on the target species present at a particular facility, appropriately sized transport tubes and entry components can be selected. The safe passage has been successfully demonstrated for adult fish of a range of species from $12\ oz$ to $40\ lbs.$ in weight. Infrastructure requirements are extremely low when compared with conventional upstream fish passage technologies. Placement of fish entry and exit components and transport tube routing and fixturing can be integrated into the h-Modulor design, with most of the system pre-assembled or prefabricated. All component pieces are container or pallet shippable. Studies have proven that upstream migrating fish on the Columbia River can be safely moved at a lower cost, reaching their upstream spawning destinations sooner with the Whooshh technology than via other fish passage approaches, and can sort adult salmonids [Garvelli et. al. (2019)]. According to Whooshh's website, the transport technology has been demonstrated on the Frasier River in Canada, and the full suite of volitional entry, scanning & sorting, and transport has been demonstrated at Chief Joseph Dam. Studies on the Saco River in Maine have shown safe transport of American shad (HDR Engineering, 2017) which are complimented by studies on the Illinois River that have shown entry by thousands of Gizzard shad per Whooshh's website.

One attractive solution would be to include the Zero Ascend Omnispecies fish passage attraction system (ZAO-Attractor), which is being developed under a separate DOE grant (DE-EE0008969). ZAO-Attractor adds American shad and river herring attraction capabilities to the Whooshh Fish Transport System and extends its modularity to the form factor of a shipping container making it easier to transport the system to a site and install it once it is at the site.

Another approach to consider is to build a fish lock or fish lift into the h-Modulor form factor using either a $20\ ft$ long or $40\ ft$ long stack following the design philosophy of an open version of the Borland fish lock for low-head sites [Travade and Larinier (2002)]. In this approach, it would be incorporated into an h-Modulor stack. Considering a $40\ ft$ long form, a central vertical bulkhead, and a horizontal panel on the upstream side of the middle stack could define and separate an upstream chamber at normal pool elevation and a downstream chamber. There would be a down steam sluice gate in the bottom frame and an upstream sluice gate in the top frame. The fish lock module stack could be placed between two generation module stacks to take advantage of the turbine flow for attraction. During the attraction phase, both gates would be open, and the upstream sluice would control the flow through the lock. After a certain period of attraction time, the downstream sluice would be closed, and the water level would rise to a normal pool. At this point, the fish could be encouraged to exit into the headpond by opening a bypass in the lower chamber creating an upstream-to-downstream flow. Once the fish exited, the upstream gate would be closed, and the bypass gate could remain open until the water elevation reached a specified level at which time the downstream sluice gate could be opened allowing flow to exit downstream at a safe velocity. This whole cycle takes between one and four hours [Travade and Larinier (2002)].

PASSAGE MODULE (RECREATION) – Recreation passage for the h-Modulor facility needs to: i) be flexible so it fits a variety of sites, ii) function safely by following the best practices for drops and slopes, and iii) support the cost goals of the program. LPS interviewed a handful of companies headquartered in the U.S. with decades of experience providing engineering design for such paddled watercraft recreation. Examples of companies include the McLaughlin Whitewater Design Group of Merrick & Company; S2O Design; Recreational Engineering and Planning; and River Restoration. Some standard design schemes include a stepped chute from McLaughlin Whitewater Design Group (MWDG), a smooth chute from Recreation Engineering and Planning, an adjustable chute such as that used in the Boise White Water Park, and repositionable blocks.

These types of chutes may be able to be designed to provide fun and safe passage for a variety of river users: swimmers, boogie-boarders, tubers, kayakers, canoeists, rafters, fish, etc. Alternatively, chutes may be able to create river features that have the potential to attract visitors and potentially boost economic development for the local community.

Concerning cost, however, in the early stages of any small hydropower project the financial implications of adding a recreation passage are significant. All the existing approaches are in the range of millions of dollars. Fully appreciating the cost challenges for small hydropower, LPS brainstormed approaches that are inexpensive, prebuilt, and available in a variety of shapes to accommodate a variety of sites. Precast concrete culvert structures arose as a good approach. Standard culverts, bases, and foundations are of the size and shapes that seem suitable to be arranged to make a chute for safe kayaking and passage through the standard modular facility that includes drops, pools, and spills (see Figure 20).

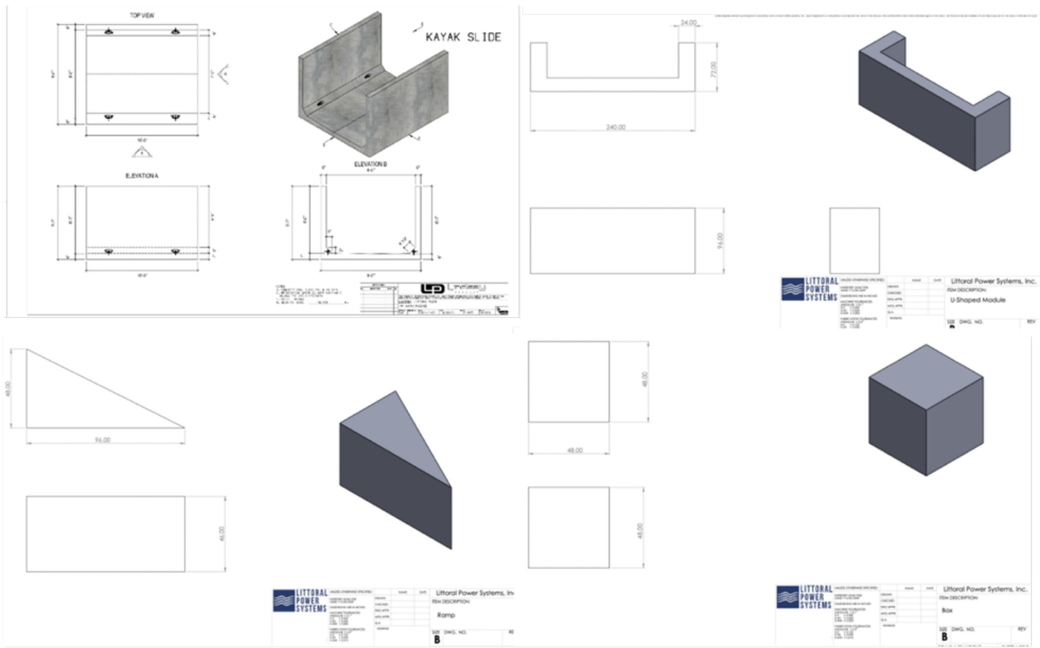


Figure 20: Kayak slide form Lindsey Precast and other simple precast shapes to make a safe passage for small, e.g., kayak, water craft.

A resulting conceptual design for a recreation passage chute using a few building block shapes in addition to culvert shapes is shown in Figure 21.

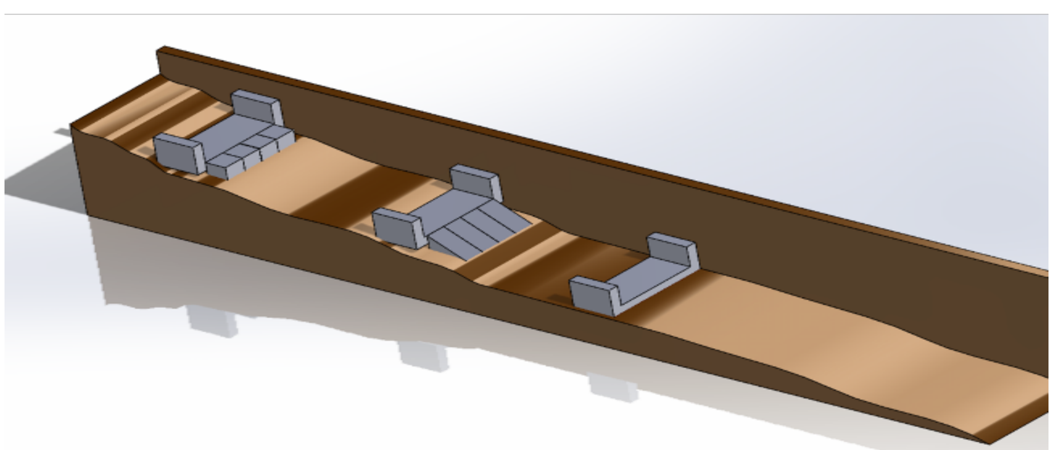


Figure 21: Conceptual design for a watercraft passage chute through an h-Modulor facility using prebuilt modules.

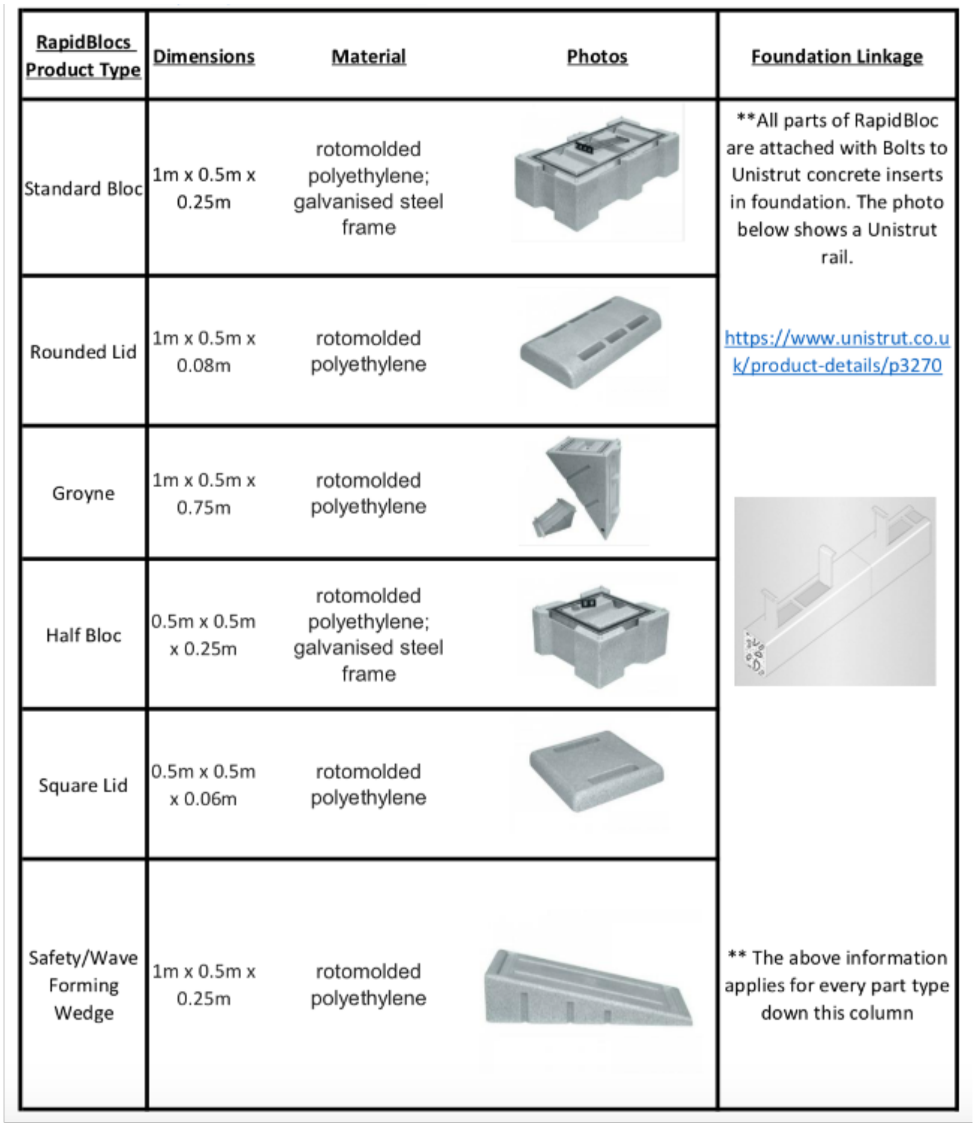
Rapid Blocs[4] obstacles for white water parks are off-the-shelf components (Figure 22) used to expand design options.

ABUTMENTS – Abutments are made up of the basic 20 ft or 10 ft frames that are used in the other modules. The frames are stacked 1-, 2-, 3- or 4- high depending on the site, and the bank topography. This approach is used in the rest of the facility design activities included in this report.

As an alternative to consider, abutments could be precast modular concrete retaining wall elements that provide vertical faces to interface with the ends of the module stacks on the inboard side and tie into the existing streambank topography on the outboard sides. A system using modular concrete units consisting of a vertical concrete face panel attached to a single or double counterfort stem can create upstream, downstream, and channel sides of abutments on both sides of the watercourse. The wall units could be stacked to create a tapered cross-section with the longest stems at the bottom to develop a monolithic gravity block with a wide base for stability. Backfill between the stems could provide the mass for the wall and interlock with the stems. Commercially available precast concrete wall systems of this type, such as the T-Wall from the Reinforced Earth Company may be suitable for this application.[5]

[4] http://rapidblocs.com/features/

[5] Commercially available T-Walls: https://reinforcedearth.com/products/retaining-walls/gravity-retaining-wall/t-wall/ and https://reinforcedearth.com/content/uploads/2018/07/Brochure_T-Wall_2.pdf.



RapidBlocs Product Type	Dimensions	Material	Photos	Foundation Linkage
Standard Bloc	1m x 0.5m x 0.25m	rotomolded polyethylene; galvanised steel frame		**All parts of RapidBloc are attached with Bolts to Unistrut concrete inserts in foundation. The photo below shows a Unistrut rail. https://www.unistrut.co.uk/product-details/p3270
Rounded Lid	1m x 0.5m x 0.08m	rotomolded polyethylene		
Groyne	1m x 0.5m x 0.75m	rotomolded polyethylene		
Half Bloc	0.5m x 0.5m x 0.25m	rotomolded polyethylene; galvanised steel frame		
Square Lid	0.5m x 0.5m x 0.06m	rotomolded polyethylene		
Safety/Wave Forming Wedge	1m x 0.5m x 0.25m	rotomolded polyethylene		** The above information applies for every part type down this column

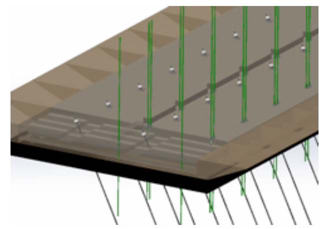
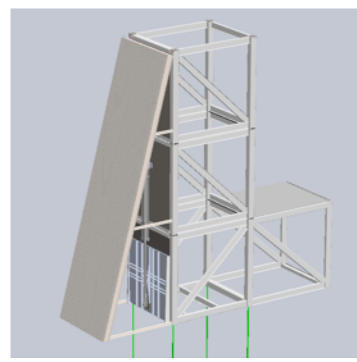
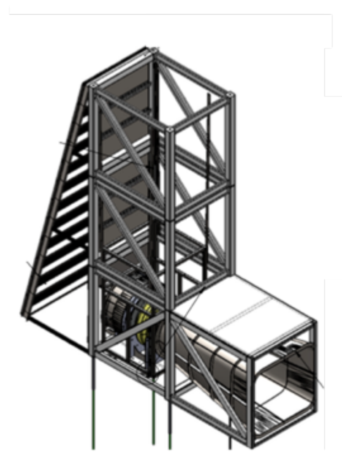
Figure 22: RapidBloc shapes that could be used to expand recreation passage capabilities for enhanced recreation experiences beyond basic passage through the SMH facility.

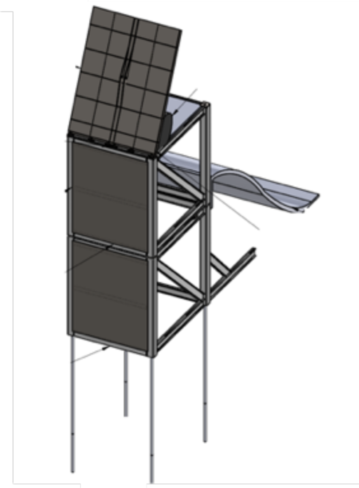
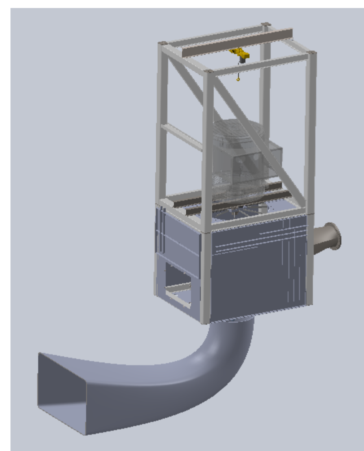
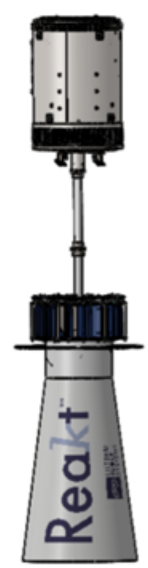
3.2.3 Results & Outcomes

The designs for the foundation, generation, and passage module stacks along with relevant equipment are presented in Table 6. These results reflect generalized designs and specifications for the modules for both the Balcony Falls and LPS 566 sites. Equipment such as the turbine and auxiliary equipment are presented.

The h-Modulor system can be effective from $0.5 - 40\ MW$. The typical modules are sized for between $300 - 500\ cfs$ based on operating head and fisheries regulations. Module stacks can operate economically from a range of $12 - 35\ ft$ while alpine sites (those using a penstock) can operate up to any head range. A practical limitation becomes the unit size of the generator, when the unit generator exceeds $2\ MW$, then the associated infrastructure becomes a limiting factor on the benefits of the modular approach. These modules serve as the basic building units that can be selected and assembled to form the SMH facility as described in Section 3.3. for Facility Development.

Table 6: Types of modules and major equipment that comprise the h-modular system.

Module type	Description and specification	Image of SolidWorks model
Foundation Module	The modular foundation connects the various container frame modules to a competent substrate to ensure stability. It is reinforced precast concrete modules.	
Sediment Module	LPS h-Modulor Sediment Stack is a three-frame high stack including 120 cfs design flow bar screens at 1.0 fps approach velocity (module 01160), and a modular frame and knife gate (module 01114). The Sediment Stack sub-assembly includes penstock connections. The h-Modulor 01150 is factory assembled, welded, and evaluated.	
Generation module	The general purpose of the generation stack module is to provide clear, debris-free passage of water to the turbine assembly housed in the module stack. This stack is meant to function as a drop-in generation module with a turbine, generator, knife gate, bar screen, and draft tube assembly.	

Water / Fish Passage Module	The purpose of the water passage module is to serve as a modular spillway. This unit can be used between other stacks as a surface bypass for downstream fish passage and debris passage.	
Pressure Box Module	LPS h-Modulor Pressure Box was designed to connect to the turbine foundation ring and discharge tube, anchor to adjacent rock, and support access for turbine maintenance. Pressure box connection points will be suitable for a 40" Reakt-type turbine.	
Turbine Equipment (Reakt AST40)	A turbine-generator consists of a propeller runner, turbine shaft, gate housing with precision contoured wickets, head cone with integral modular bearing holder, generator coupler, connection shaft, and linkage with 385 rpm synchronous generator. The turbine design flow is 175 cfs at a design range of 42 ft head.	

Switchgear Module	Modular container with integral switchgear including synchronization for at least one Reakt turbine and variable speed controls for at least one other Reakt turbine. The system includes pre-set, wired, and factory-evaluated modules: 1) Main disconnect panel includes a switch type breaker with 2400 A Pringle type bolted pressure contact switch, the non-magnetic switch mechanism, UL 977 standard, quick action front face lever, and fault protector in a National Electrical Manufacturers Association (NEMA) 3R enclosure. 2) Distribution breaker panel, QED Switchboard Class 612/661I-Line, copper bus bars, molded case breaker style attachment, NEMA 3R, 8 M One breaker for each generator rated nominal 1200 A @ 550 kW. 3) Generator contactor and excitation system in NEMA 3R Enclosure. Includes contactor, Powertronics digital exciter, resistive load power cut-off/under voltage/ overload protection. International Electrotechnical Commission (IEC) 60947-4-1, rated breaking capacity of 6400 A, overvoltage category III, rated impulse withstand voltage of 8 kV, fuse rating of 1200 A. 4) Generator contactor with ABB ACS880 permanent magnet generator (PMG) configured drive.
Modular Hydraulic Pressure Unit (HPU)	HPU regulates and delivers hydraulic fluid to actuate electromechanical and hydromechanical equipment on site. It consists of a hydraulic pump, hydraulic receiver, and valve manifold for control of flow delivery. Delivered as a prefabricated, factory-tested unit.
Control Panel Equipment Module	Turbine control system including input/output (I/O), ExOR remote access modem, and headless human-machine interface (HMI) panel. The system includes digital or analog inputs for system condition monitoring, supervisory control, and diagnostics. Data is transmitted via a data line to the HMI panel for operation near the plant’s control station in town.
Automation system instrumentation Module	Programable logic controller (PLC): Automation Direct Productivity 3000 RPM encoder: Koyo TRD-MX500VD

	Current transformer: Schneider Electric Line reactor: MTERL5002 Head water pond sensor: Global Water WL400 Impoundment level sensor: Global Water WL400 Temperature sensor: Global Water 270-WQ101 submersible temperature sensor Dissolved oxygen (DO) sensor: Rosemount Analytical 499 Series DO Sensor Tailwater pond sensor: Global Water WL400 Tailwater level sensor: Global Water WL400 Pressure transducer: Global Water WL16

3.2.4 Module design specifications support project goals

The design of these modules serves as the basic building unit for an SMH facility. The design specifications for the modules and equipment satisfy the project goals and metrics as summarized in Table 7 below.

Table 7: Module designs support the project goals and metrics.

Goal Characteristic	Goal Metric	How module designs support the goal metrics
Nameplate capacity (flow and hydraulic head)	≤ 10 MW (e.g., up to 5,000 cfs and up to 30 ft. hydraulic head)	The generation module and equipment are designed to construct a facility of up to 10 MW. The generation and passage modules design support the safe and cumulative passage of flows up to 5,000 cfs and up to 30 ft heads when assembled.
Modeled installed capital cost per nameplate capacity	< $3,500/kW Stretch goal <$2,000/kW	The module designs were specifically redesigned to reduce cost, for example by approximately 45% or more (see Table 5).
Estimated construction timeline	< 2 yrs. site prep. to commissioning	The size and standardization of the modules lend themselves to easily being constructed in a period commensurate with supporting the development of a facility in under 2 years.
Replication – the same type of modules	Multiple U.S. sites (2 or more)	The standardization and modularity aspects associated with the ability to stack, and a fixed shape form factor lend themselves to easy

		applicability to different sites enhancing the replicability of the h-Modular system to SMH facility development across the U.S.
Passage – water, fish, recreation craft, sediment	Safe and timely	Module stacks are designed for 10 ft of overtopping for safety even in high floods. Module stacks include bar screens to exclude fish from entering the turbines. Water passage modules also serve as a surface bypass for fish. Recreation passage modules have a low slope for safety. Sediment Module Stacks include a sediment sluice.
Water quality	No degradation	Supports ROR facility. Moving the intake for the turbine in the generation module to a lower elevation where temperatures will be lower supports water quality.
Co-Development Opportunity	At least one	The fact module stacks are designed to be structurally independent, which allows them to be removed, supports potential future replacement with upstream fish passage modules, recreation modules, or future improved stacks that could increase the facility's safe and effective passage as well as contribute to the community.

3.2.5 Lessons Learned

Two main challenges faced in the design/redesign process relate to i) connecting the foundation modules to the stream bed and connecting the generation, sediment, and water passage modules to the foundation, and more generally ii) thinking through configurations that might be needed to support a variety of site conditions through an engineered product. In addition, the recreation module is still awfully expensive, and this section recommends that future work address an alternative concept that may be less costly.

CONNECTING MODULES TO THE FOUNDATION – The module designs existing at the beginning of this project relied on a post-tension tie-down anchor that was topped off on the bottom frame of the top module and passed through the cast-in-place concrete foundation into the stream bed at an orientation perpendicular to the top surface of the foundation concert slab. As described above the re-designed module stacks include four tie-down anchors: one threaded through each vertical member. At first, these four tie-down anchors were specified to pass perpendicularly through the concrete foundation into the stream bed like the incoming design.

Professional engineers at Schnabel Engineering reviewed this approach and recommended exploring an approach that separately locks off the post-tensioned tie-down of the concrete slab independently from the module stack, which they pointed out may reduce or eliminate the post-tension force on the downstream tie-down and thereby reduce column member size, and may aid stack replacement by providing enough stability that an upstream bulkhead could safely span the stack to be replaced. Furthermore, they suggested it should be possible to design an anchor plate assembly on top of the foundation slab to transfer the load between the foundation anchor and the module anchors with the rock anchor located clear of the module columns. This approach allows module installation to continue independently of tensioning the foundation. The resulting connection design ties the foundation modules to the streambed with two tiebacks per modular stack installed at a 20° batter angel. A representation of this design is shown in Figure 23.

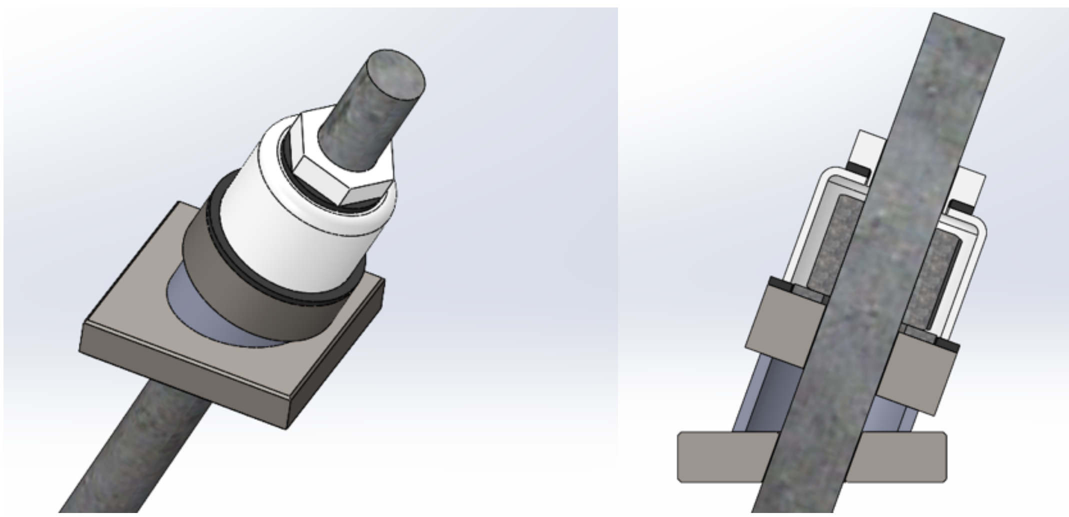


Figure 23: Representative image of the battered tiebacks for securing the modular foundation to the streambed.

As illustrated in Figure 24, there are separate, smaller tie-downs through the vertical members of the module stacks that connect the module stacks to the concrete foundation. The end caps on the bottom of the vertical members on the bottom frame align with the concrete pad. Tie-down rods are coupled to the concrete inserts.

This design progression results in the load on each tie-down anchor through the module stacks changing from 840 thousand pounds force (kips) for the original design using one tie-down anchor per module stack that ran through the concrete foundation into the streambed, to $350\ kips$ for four tie-downs per stack also running through the concrete foundation and into the stream bed, and finally to $75\ kips$ for the design approach that separates the tie-downs for the foundation from the those that secure the module stacks to the concrete foundation. This reduction in load on the frame members in the stack allows some of the frame members to be specified as less costly I-beams as compared to hollow structural sections. Additionally, these changes simplify corrosion control for these members. Figure 25 shows the results of the finite analysis for the loading case with ten feet of overtopping that supports this design change. This analysis was performed using the finite element module in SolidWorks. The frame material is ASTM A500 steel, Grade C with a specified yield strength of $50{,}000\ psi$. With a $1.5 *$ factor of safety, the design stress is $33{,}000\ psi$.

ENGINEERED PRODUCT IMPLICATIONS – Traditional hydropower facility design is developed by studying a site and then applying a stepwise process of site-specific design. The major civil, hydromechanical, electromechanical, and ancillary equipment are primarily specified from bespoke equipment. Construction firms with hydropower expertise bid to perform the work to build the project. The successful bidder manages the project in some project fulfillment approach.

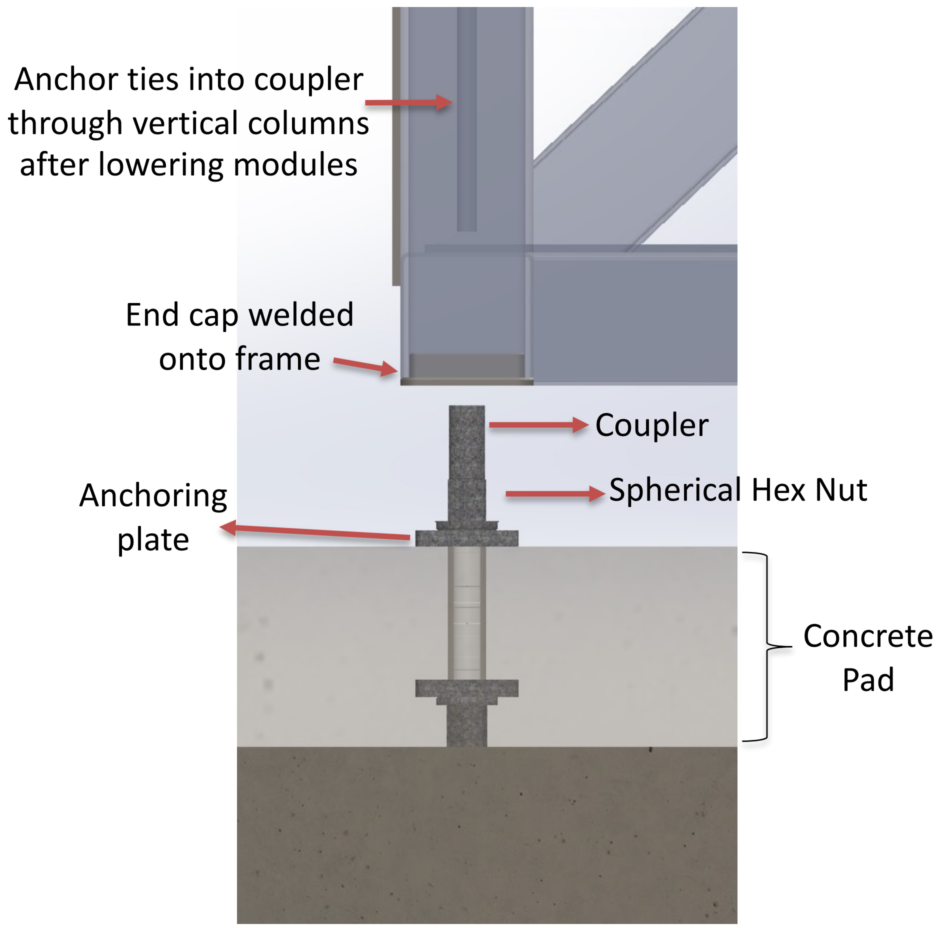


Figure 24: Connection of modules to the concrete foundation.

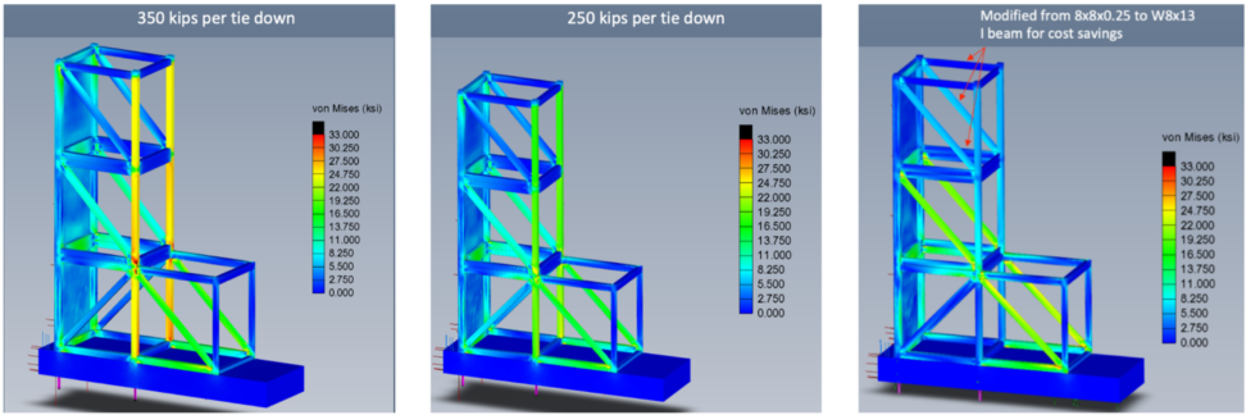


Figure 25: Separating the frame connection to the concrete slab from the tie-back of the concrete to the riverbed decreased the design loads in the tie-down anchors to 75 kips per tie allowing the specification of less costly steel members.

In contrast, the h-Modulor approach replaces the bespoke equipment with prefabricated, modular components tuned to the essential stream functions. The initial phases of designing the modules viewed them as a standard kit of parts that could be brought in once the site was prepared; thereby relegating the site-specific constraints to the site preparation phase. A more accurate way to think about the h-Modulor approach is as a complement of engineered products that can be selected, sized, and configured to fit a site. This approach affords the required diversity to apply the design to multiple sites with different design constraints while allowing for the use of standard equipment and standardized design, specification, and installation processes. Some examples of the modules being configured for specific site conditions are discussed next.

While the module stacks discussed above are made up of three box frames stacked on top of each other, there are sites with lower heads where only two box frames could be used and would make more sense for cost reasons, and there are sites with higher head where a four-box-frame-stack would make sense. Two-box-frame-high stacks are nominally 19 ft tall, three-box-frame-high stacks are nominally 29.5 ft tall, and four-box-frame-high stacks are nominally 38 ft high. For higher head sites, or depending on the topography of a site, the sediment module stacks may be reconfigured as intakes with a penstock exiting the downstream side of the stacks and conveying water to downstream generation modules.

In addition to the number of box frames, the water passage modules can be configured with longer crest gates to increase their hydraulic conveyance by pushing the hinge down into the lower box frame, which may increase the conveyance by a factor of approximately 3.6 times [Winchell (2018)]. Another important example of the engineered product approach that applies the h-Modulor system to multiple sites with different design constraints is that the turbine may be selected from a family of turbines across a range of operating conditions, as shown for the Reakt turbine in Figure 26.

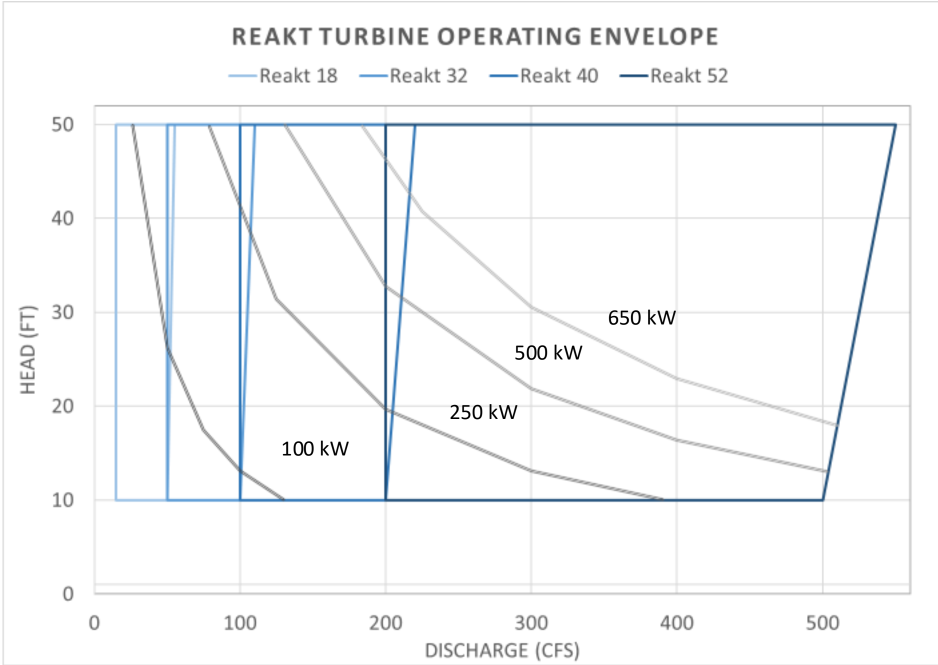


Figure 26: Reakt turbine operating envelope.

ALTERNATIVE RECREATION MODULE – Passing recreation water craft through an h-Modulor facility using the approach described above would provide safety and enjoyment; the passage could be part of the ride. However, this approach is expensive. An alternative to consider is to use a lock, combining it with the fish lock described above. A concept for a recreation passage guillotine-style lock provided by Doug Hartsock is presented in Figure 27.

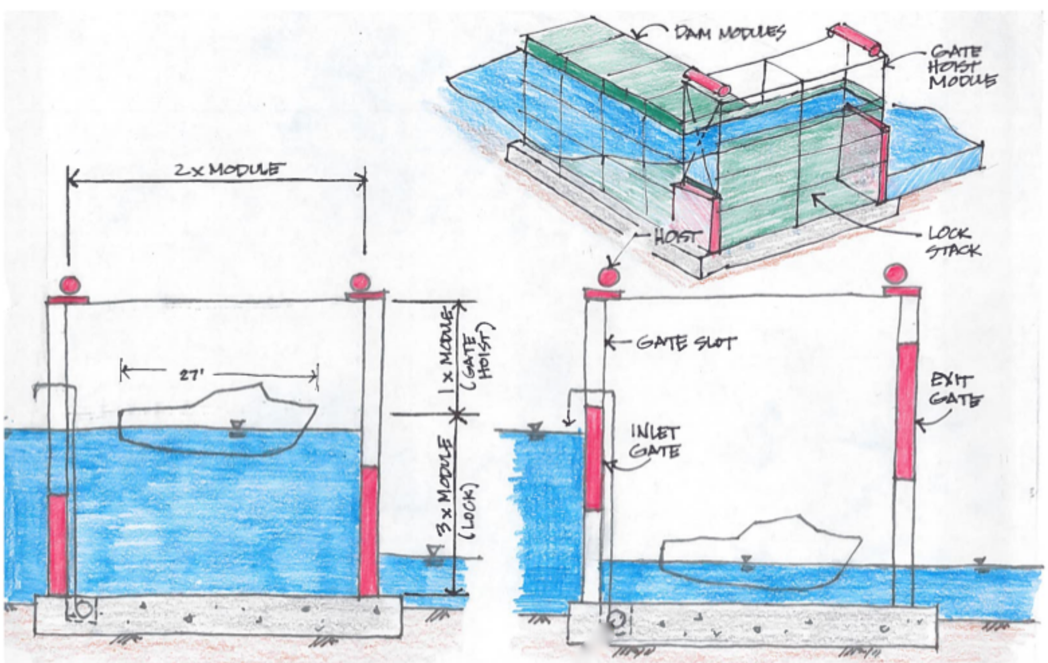


Figure 27: Concept for a guillotine-style modular recreation passage lock.

3.3 Task 3: Facility Development

3.3.1 Task Objective

The objective for Facility Development is to develop detailed conceptual facility designs for the two hydropower project locations selected above and to establish plans for construction and assembly using standardized modules for generation, passage, and foundations that meet the facility goals presented in Table 1. According to EDES, modularity within a facility pertains to the use of different module types to construct an entire facility. The collective design of the modules acknowledges the alignment of stream functionalities of renewable energy, water flow, sediment passage, fish movement, and recreation with the generation, passage, and foundation modules (Witt et.al. 2017).

3.3.2 Approach and Methodology

DESIGN APPROACH – Repeating what was said in 3.2.5 above, a traditional hydropower facility design is developed by studying a site and then applying a stepwise process of site-specific design. The major civil, hydromechanical, electromechanical, and ancillary equipment are primarily specified from bespoke equipment. Construction firms with hydropower expertise bid to perform the work to build the project. The successful bidder manages the project in some project fulfillment approach. In contrast, the h-Modulor approach replaces the bespoke equipment with prefabricated, modular components tuned to the essential stream functions.

To take advantage of (and demonstrate) the impact of this major shift on a hydropower project design requires new tools and processes. This section explains these tools and processes, which define the method that was used to develop the facility designs and construction plans. The h-Modulor facility concept design process is shown in Figure 28.

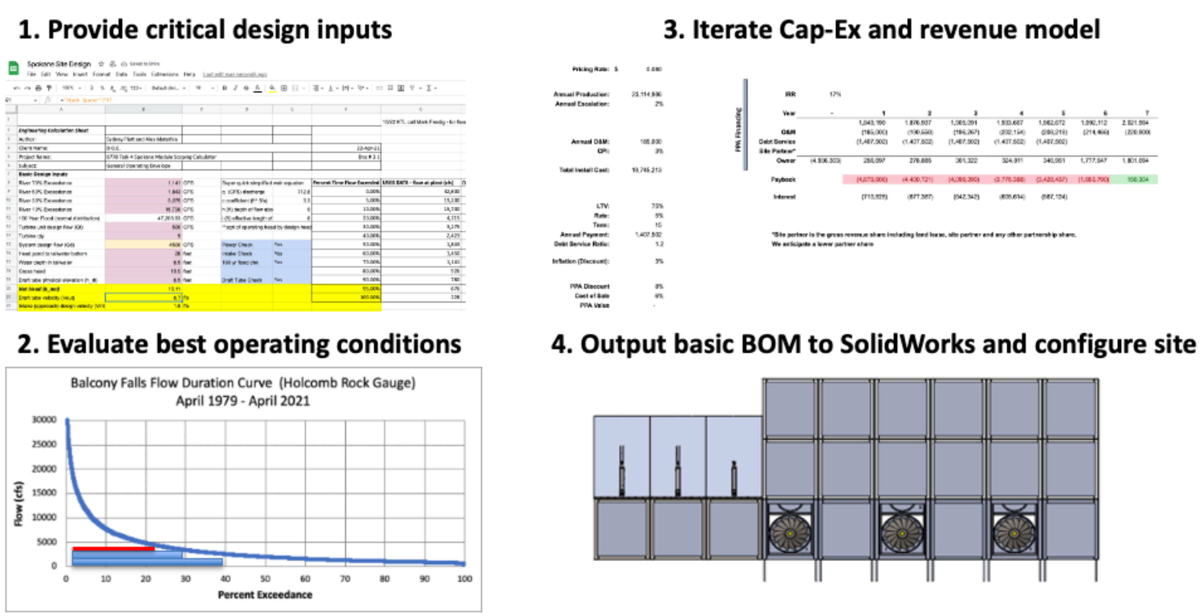


Figure 28: Conceptual design process for an h-Modulor facility.

It starts with using a low-resolution technical and financial model built as a multi-tab Excel workbook. The user puts in site characteristics such as i) streamflow data from a nearby USGS stream gage, ii) site elevations from Google Earth or Maps, and iii) stream width from Google Earth or Google Maps. Then the user picks a specific flow exceedance value from the model-constructed flow duration curve and sets it as the plant design hydraulic capacity. The model performs a set of rules-based configuration steps that select the type and quantity of modules. For example, the sediment module stack bar screen is sized and positioned based on intake and sweeping velocities. The model feeds these into a bill of materials with associated standard costs and constructs a rudimentary project revenue model outputting capital cost (CapEx) per nameplate capacity and annual payback. The model also provides outputs in terms of safety checks for flood conveyance and approach velocity into the bar screens. The inputs are iterated with the CapEx and revenue outputs to achieve an acceptable payback period, accepted as seven years or less. The project engineer uses the model-specified number of the various modules to quickly construct a SolidWorks model of the facility by using pre-existing 3D models of the module stacks and placing them where they need to go.

If the outputs of this model look good, then the conceptual facility design goes through i) an environmental assessment (see Section 3.4), ii) a robust analysis of energy generation based on historical daily flows and turbine characteristics curves (see Section 3.5), and iii) a detailed cost breakdown (see Section 3.6) that details module costs down to the cost of individual frame members, and includes field labor costs based on local rates for the relevant construction trades. The result is a detailed conceptual design as a 3D SolidWorks model of the facility. Figure 29 shows an example of an iso-metric view of a 3D SolidWorks model of a small facility with explanatory notes.

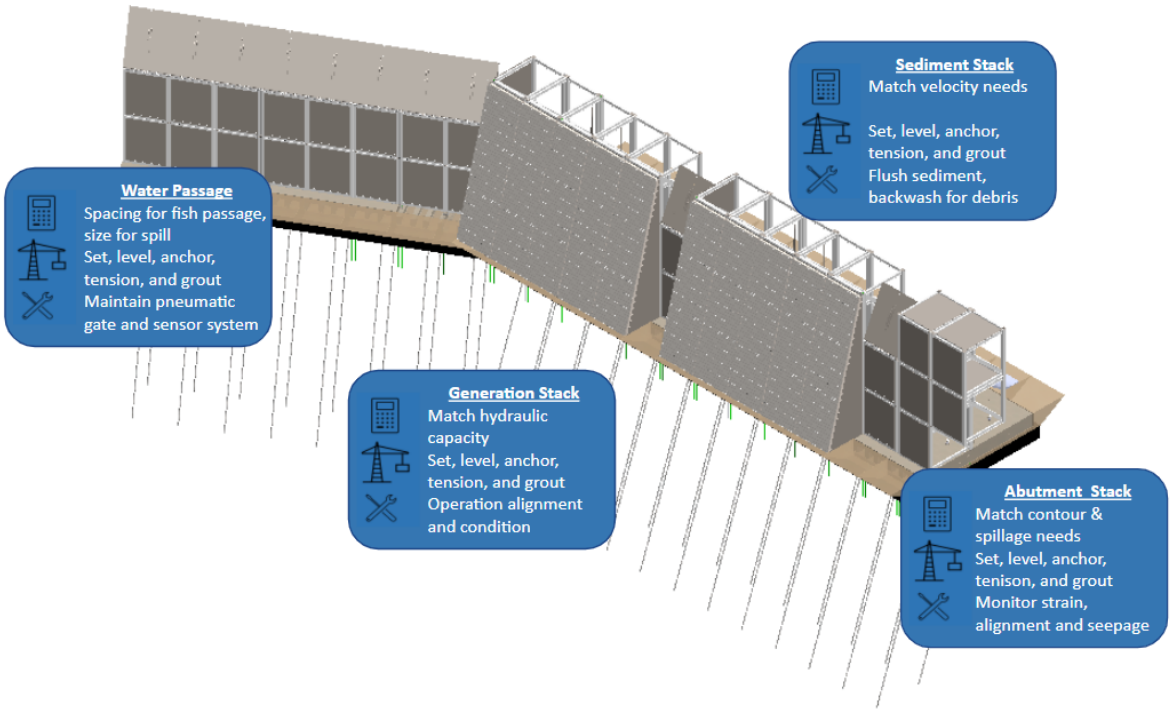


Figure 29: Iso-metric view of a 3D SolidWorks model of a small h-Modulor facility showing the primary module types along with notes related to the sizing parameters, installation steps, and operation & maintenance considerations for each type.

The resulting h-Modulor hydropower facilities are primarily comprised of a suite of modules described in the previous section and consist of foundation modules, generation modules that contain a Reakt turbine with generator, sediment (or low water) passage module stacks, abutment modules, water passage module stacks, which also provide a surface bypass for fish traveling downstream and modular ancillary equipment like switchgear and control boxes. Figure 30 shows a plan view overview of a typical h-Modulor facility.

Because of the inherent modularity in the assemblies, a plant can look different based on the user and requirements of the facility. A design using only stacks might look something like the image in Figure 31, which shows a plan view of Figure 29. It has eight water passage modules (left-hand side) that are oriented at an angle to the main power wall. The power wall, oriented perpendicular to the river flow, is made up of alternating generation module stacks and sediment passage stacks with a water passage (aka downstream fish passage stack) located approximately every $40\ ft$.

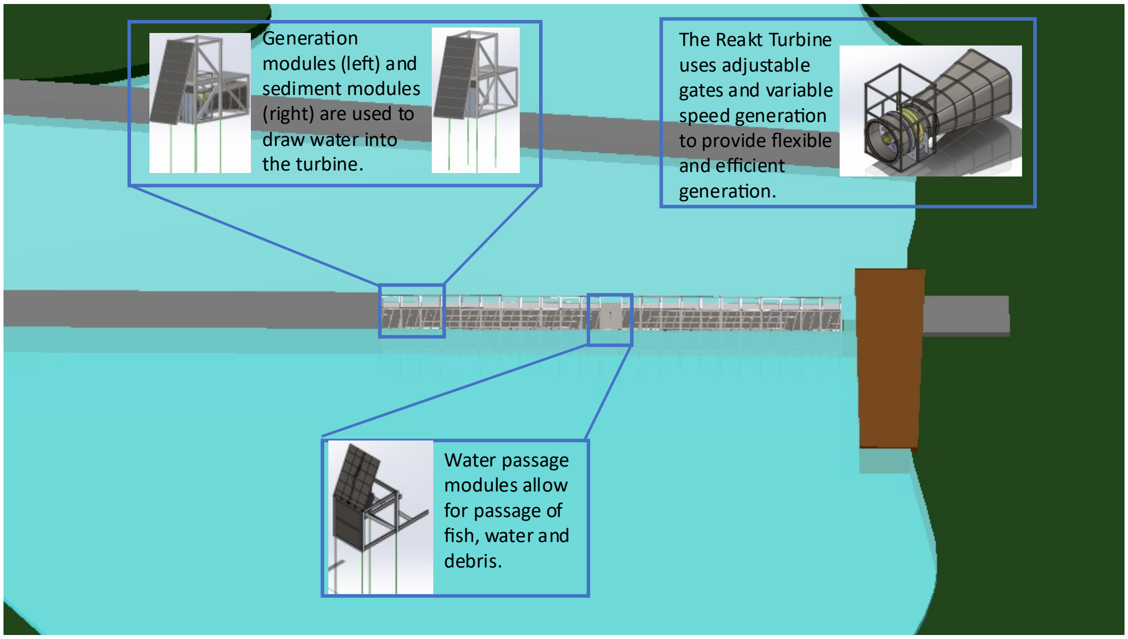


Figure 30: Plan view of a typical h-Modulor SMH facility.

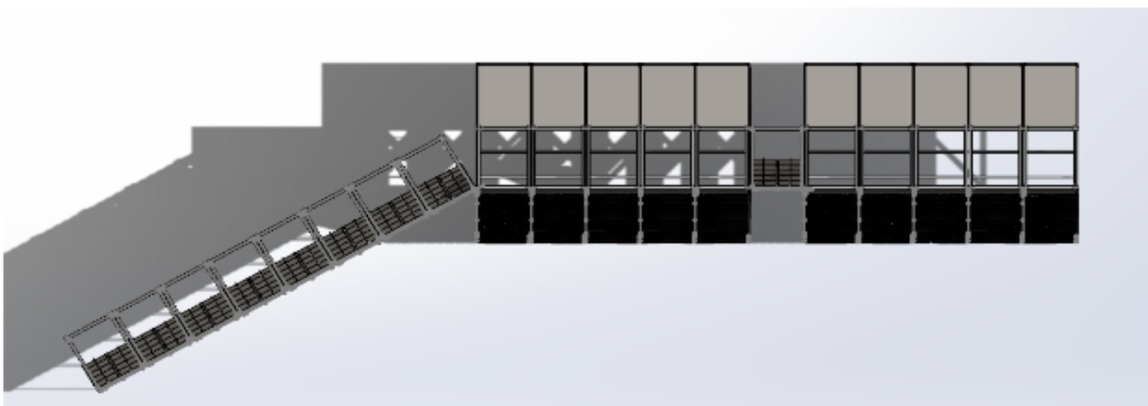


Figure 31: Indicative site layout is shown as a plan view of Figure 28.

The modules can also be integrated into a penstock orientation as shown in Figure 32. This facility configuration uses the sediment module stacks as intakes structures set at the top of a small waterfall. Penstocks connect to the gate opening through the bottom frame and slope downstream to feed two Pressure Box Module turbine- generators. This approach allows for application in medium or high-head sites or sites with significant naturally occurring variability in the local head. Each module set is selected, configured, and sized based on a few governing inputs.

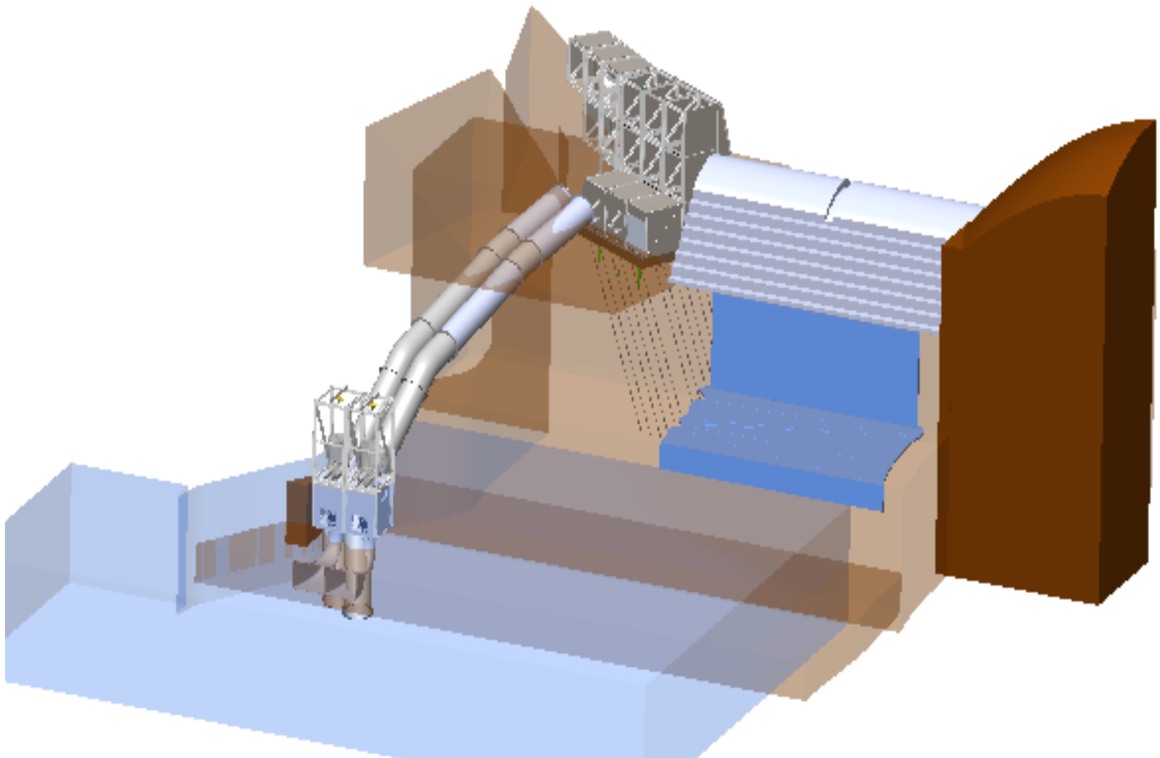


Figure 32: Penstock integration at an h-Modulor site uses two.

<u>CONSTRUCTION PLANNING APPROACH</u> – The paragraphs above describe the tools and processes used to develop the h-Modulor facility designs. Just as the design of the facility requires new tools and processes, so does the construction planning. Traditionally, a hydropower project plan set includes civil engineering drawings and specifications that mature along a path with completion phases, such as $30\%, 60\%, 65\%, 90\%, and\ 100\%$ as defined by the US Army Corps of Engineers (USACE) -2009. Construction specifications typically follow the 50 divisions of construction information as defined by the Construction Specifications Institute. One of these, Division 11, is related to equipment. The rest are primarily related to onsite work.

The biggest difference in the way construction planning is done with the h-Modulor facility as compared to a traditional approach stems from the fact that an h-Modulor facility is mostly equipment installation of engineered products, whereas the traditional approach is mostly onsite construction. The modules are a product; each one comes with its standard IO&M manual (Figure 33). The construction plan for a given h-Modulor facility consists of a product specification and IO&M manual for each type of module selected for the facility and the appropriate construction specifications for local sub-trades (see Figure 34).

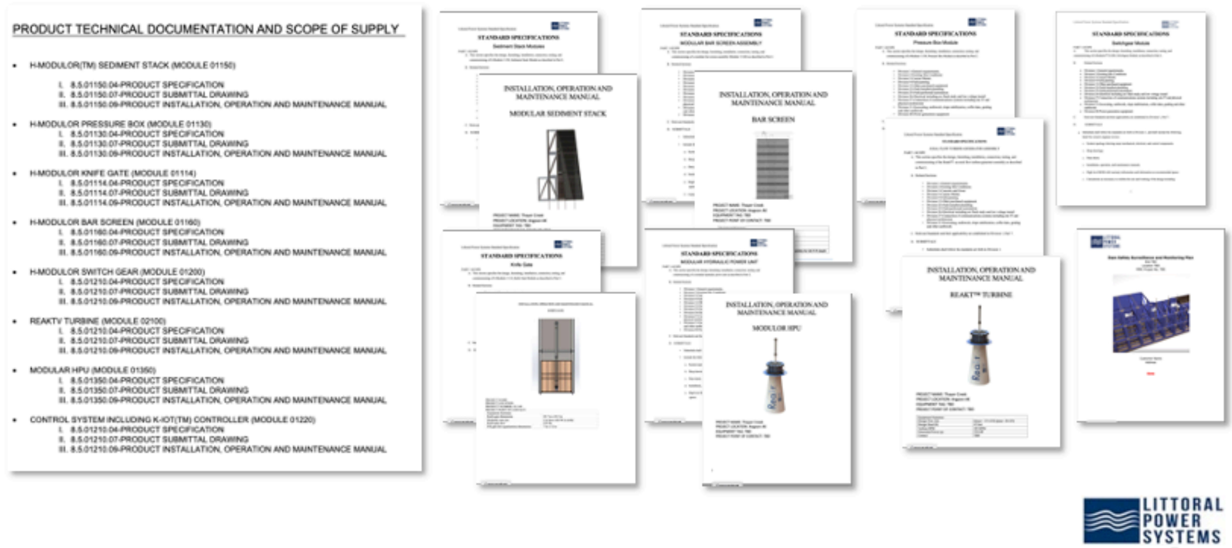


Figure 33: Standard specifications, submittal drawings, and IO&M manuals for an h-Modulor facility.

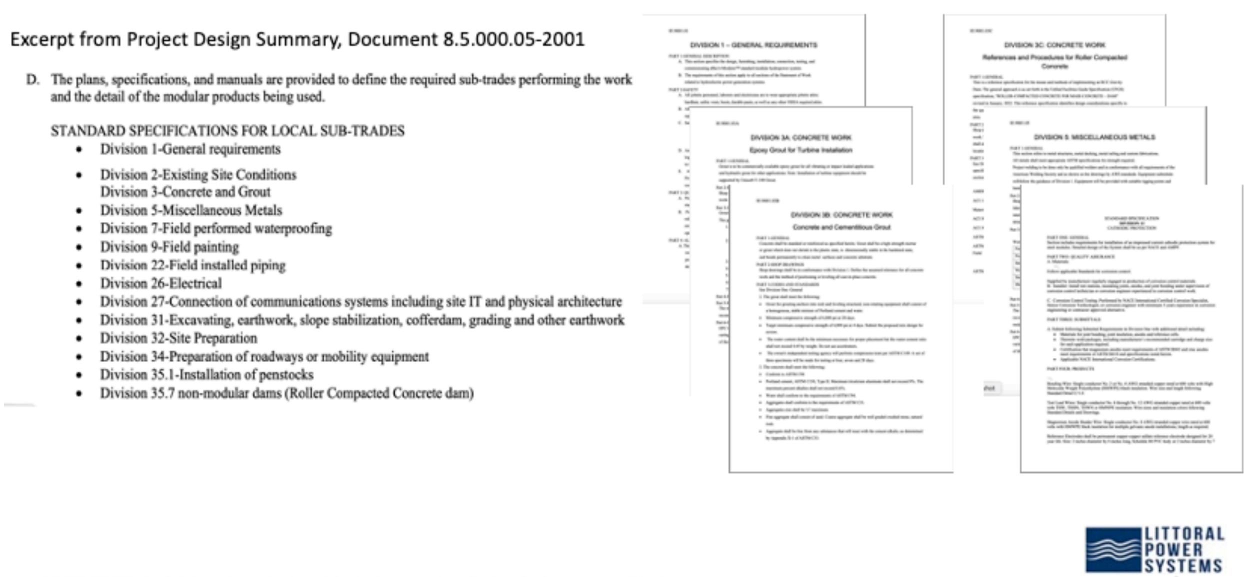


Figure 34: Subtrade specifications for an h-Modulor facility.

3.3.3 Results & Outcomes

FACILITY DESIGN – Utilizing the modules presented in 3.2.3 and the approach described in 3.3.2 facility designs are developed for the Balcony Falls site and for the LPS 566 site. The facility design for Balcony Falls is depicted in Figure 35 and Figure 36. Figure 35 is the iso-metric view of the 3D SolidWorks model for the facility. In Figure 36, this 3D model overlays a Google Maps image of the project location on the James River depicting the placement of the generation and sediment passage module stacks on the left side (looking downstream) and the water passage module stacks on the right side of the facility, with the recreation passage kayak chute in the middle of the water passage module stacks.

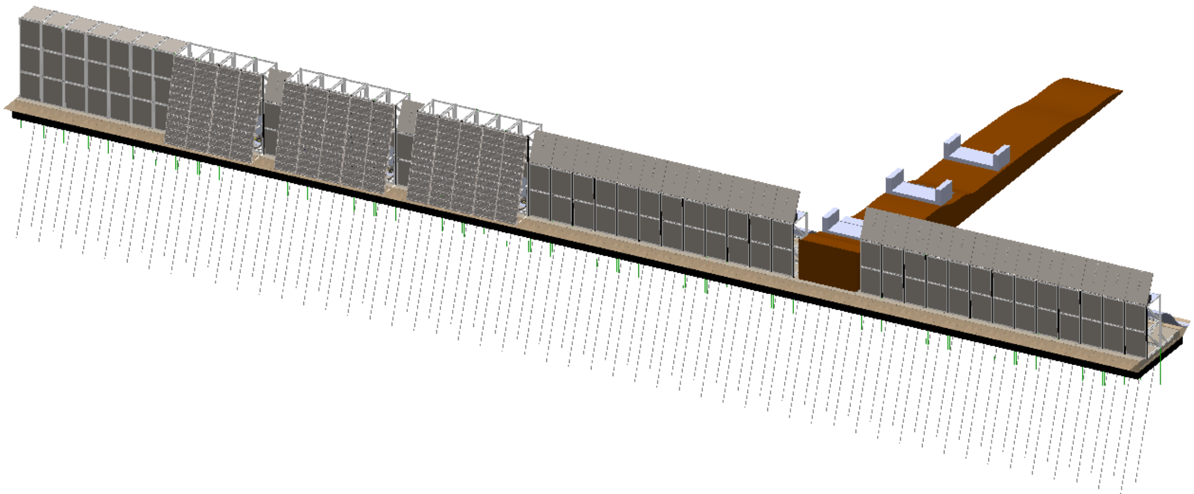
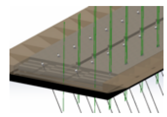
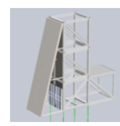
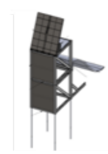
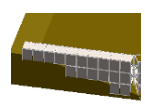


Figure 35: 3D SolidWorks model of the h-Modulor Balcony Falls facility. The flow direction is from the bottom left to the upper right.

Figure 36: Plan view of 3D SolidWorks model of the Balcony Falls facility situated in the James River. Flow from upper left to lower right.

The design includes a total of 8 axial flow neo-Kaplan turbines, which use a combination of adjustable guide vanes and variable speed (frequency) drives (VFD) to optimize power production in changing flows. Six units are Reakt FIT52, which have variable speed drives for regulation with no guide vane adjustment. Two units are Reakt AIT52 turbines with both adjustable guide vanes and a variable speed drive. The capacity of each machine is $500\ cfs$. The bill of material (BOM) is presented in Table 8.

Table 8: BOM for the conceptual h-Modulor facility design at Balcony Falls.

Major equipment type and model	Model or description	Quantity
Modular foundation		51
h -Modulor Sediment Stack	**h-Modulor 01150** 	6
h-Modulor Generation Stack	**h-Modulor 01100-500** 	8
h-Modulor Water Passage	**h-Modulor 01120-500** 	30
Abutment frame		21
h-Modulor Switchgear	**h-Modulor 01200**	2
Modular Hydraulic Pressure Unit (HPU)	HPU is delivered as a prefabricated, factory-tested unit.	1
Control Panel	**h-Modulor 01220**	1
Automation system instrumentation	Programable logic controller (PLC)	1
Trash Rack Cleaning Device	AirBurst™	1
Gantry Crane		1
Walkway		1
Pneumatics for Crest Gate		1

The facility design for LPS 566 is depicted in Figure 37 and Figure 38. Figure 37 is the iso-metric view of the 3D SolidWorks model for the facility. In Figure 38, this 3D model overlays a Google Earth image of the project location on the Spokane River. As shown in these figures the wall with the generation modules (power wall) is oriented at an angle whereas, in the Balcony Falls facility, the power wall is straight across the river. The Spokane River in this location is about $185\ ft$ wide, whereas at Balcony Falls the James River is about 352 feet wide; the power wall for LPS 566 is angled to fit all the modules in that narrow width.

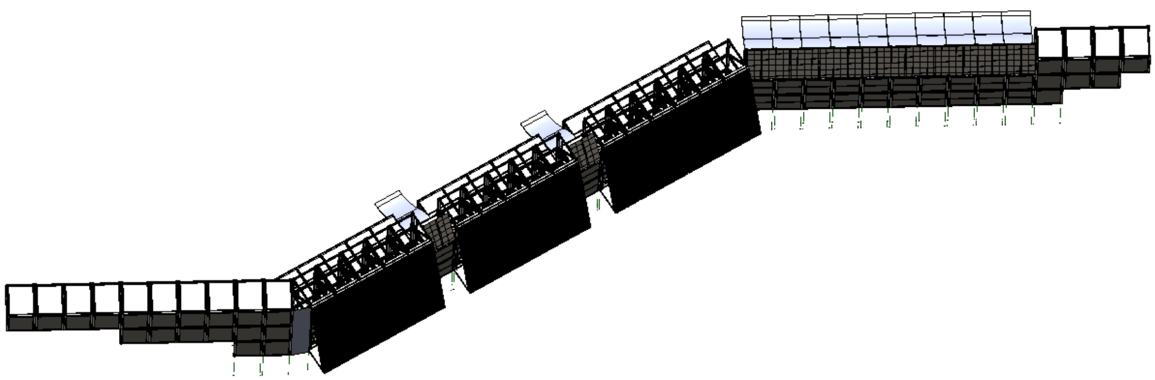
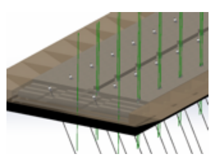
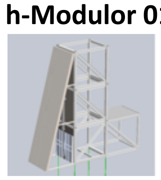


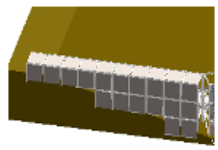
Figure 37: Isometric view of 3D SolidWorks model of the LPS 566 h-Modulor facility. Water flows from the lower right to the upper left.

The design includes a total of 9 axial flow neo-Kaplan turbines, which use a combination of adjustable guide vanes and variable speed (frequency) drives (VFD) to optimize power production in changing flows. Seven units are Reakt FIT52, which have variable speed drives for regulation with no guide vane adjustment. Two units are Reakt AIT52 turbines with both adjustable guide vanes and a variable speed drive. The capacity of each machine is 500 CFS. The BOM for the conceptual h-Modulor facility design LPS 566 is presented in Table 9. Since kayaking is not as critical at the LPS 566 site as at the Balcony Falls site, recreation modules were excluded.

Figure 38: Plan view of the 3D SolidWorks model of the LPS 566 facility overlaying a Google Map image of the site location on the Spokane River. Flow is from right to left.

Table 9: BOM for the conceptual h-Modulor facility design LPS 566.

Major equipment type and model	Model or description	Quantity
Modular foundation		42
h -Modulor Sediment Stack	**h-Modulor 01150** 	7
h-Modulor Generation Stack	**h-Modulor 01100-500**	9

		
h-Modulor Water Passage	**h-Modulor 01120-500** 	12
Abutment frame		23
h-Modulor Switchgear	**h-Modulor 01200**	2
Modular Hydraulic Pressure Unit (HPU)	HPU is delivered as a prefabricated, factory-tested unit.	1
Control Panel	**h-Modulor 01220**	1
Automation system instrumentation	Programable logic controller (PLC)	1
Trash Rack Cleaning Device	AirBurst™	1
Gantry Crane		1
Walkway		1
Pneumatics for Crest Gate		1

CONSTRUCTION SEQUENCE AND SCHEDULE – For minimal risk, and safe installation the subbase area is dewatered and prepared to receive the modular foundation slabs. Dewatering half the stream course at a time allows the preparation of one-half of the subbase in the dry and continuous stream flow around the dewatered half. For the first half of the river, the abutment stacks on the dewatered bank are installed, then the sediment, generation, and water passage module stacks are installed. Once this section is complete, the knife gates in the bottom of the stacks, and the crest gates on the water passage module are kept open so water can flow through them, while the other half of the river is dewatered, and the installation steps repeated for that side.

Since both locations are likely to be bedrock underlayment, dewatering is accomplished as follows: 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 plates can be sandwiched between the FIBCS to provide additional seepage control. Ideally, construction takes place during the low water season and alternative cofferdams that may be able to be used are the Portadam or the Dam-It bladder-type cofferdam. The cofferdam is removed following the placement of the first phase of modules and the process is repeated on the opposite bank. This construction process ensures continuous flow of the stream course during construction and should have minimal environmental impacts.

Once dewatering is complete for half of the stream, the bedrock is drilled at a 20°batter to accept $2 - 1/4$ in tiebacks. The modular foundation slabs are scheduled for delivery to minimize on-site storage and lay-down area needs. Then the modular foundation is installed following the steps in the figure below and secured to the bedrock with the tiebacks. Following the dewatering process and subgrade preparation, the foundation module is constructed according to the sequence shown in Figure 39.

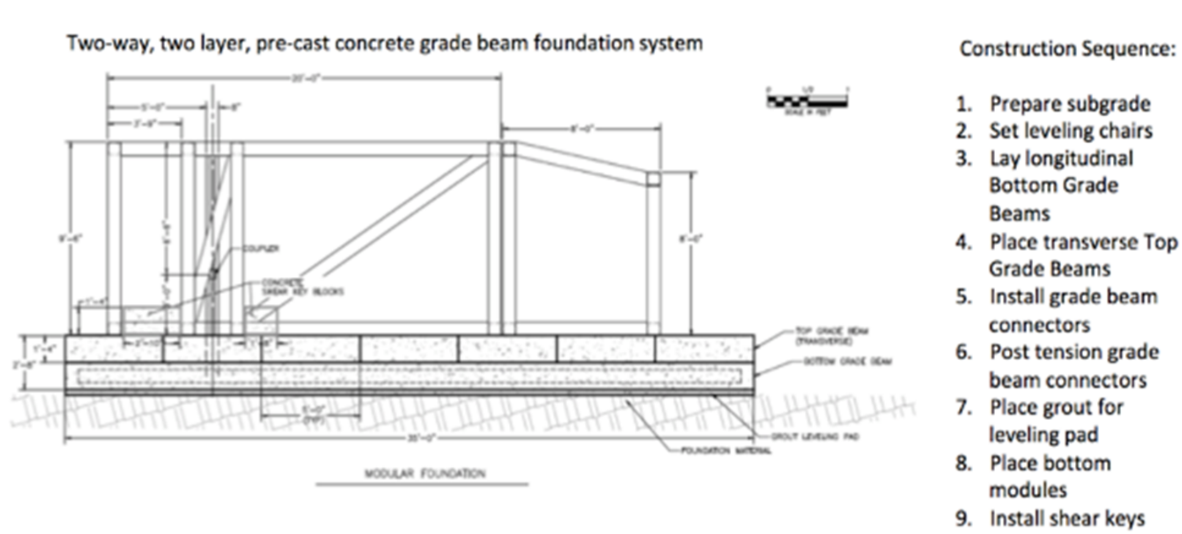


Figure 39: Drawing and construction sequence of the two-way, two-layer precast foundation system.

Then the modules are installed on top of the foundation in the following sequence:

- Transport modules to the site according to a schedule that minimizes storage and laydown area;
- Install abutment on one bank, then start from the abutment;
- Place the base frame (one with a draft tube, then one without) so that the four upstream vertical columns are positioned over the concrete connectors (foundation slabs are delivered with concrete connectors embedded in them);

- Snug the base frame against shear keys with grout filled bag so that the grout does not touch and bond to the frame (so the stack can be removed later as needed);
- Place horizontal seal, then place middle frame so that the corner blocks on the four vertical columns align and seat onto the base frame;
- Place horizontal seal, then place top frame so that the corner blocks on the four vertical columns align and seat onto the middle frame;
- Thread tie-down bars through each of the four vertical columns and screw them into the couplings, pre-tension them, and lock them off per specifications;
- Once the first stack is completed, secure it to the abutment;
- Place remaining stacks;
- Check hydraulic knife gates (they are pre-installed at the factory), and leave them open:
- Place the pneumatic crest gate top module (gates are pre-installed at the factory), and leave them open;
- Install vertical seals;
- Connect ancillary system lines (hydraulic, pneumatic) that were preinstalled on the modules at the factory, install coupling to connect to modules on the second half of the river;
- Install trash racks.
- Remove the coffer dam from the first side of the stream and let the water run through the open gates.
- Dewater the other side of the stream, and repeat the process;
- Once all stacks are in place, then install the turbine/generator cassette module into the generation module stacks;
- Connect electrical lines that were preinstalled at the factory on the modules and connect to turbine/generator units;
- Construct top-of-dam access ways and associated systems;
- Construct electrical interconnection;
- Commission turbines/generator systems and begin power production.

A detailed schedule to accomplish this installation for the LPS 566 site is presented in Table 10. It includes a 20% factor for capacity utilization and an additional 20% contingency. The duration (days and weeks) values for the level two tasks may overlap; the duration values for the level one task are for the overall duration of the sub-levels and the schedule was set up so that none of the level one tasks overlap. The total duration is 71 weeks (1.36 years). With a slightly more aggressive plan that includes staggering the installation crew to work weekends, i.e., 7 days per week, the schedule drops to 42 weeks (0.80) years. For Balcony Falls, which is a larger facility having a total length of 408 feet compared to the 344 ft for LPS 566, the estimated installation time is 98 weeks (1.88 $years$), and with a $7-day$ workweek is $58\ weeks\ (1.12\ years)$.

Table 10: Installation schedule for LPS 566 facility.

No.		DESCRIPTION	days	wks.
1		**Mobilize Team and Trailer**	**10**	**2.0**
		The first half of the stream (left side looking downstream)		
2		**Furnish & install PortaDam Cofferdam**	**15**	**3.0**
3		**Prepare first half**	**12.5**	**2.5**
3.1		Excavate for precast foundation (152' x 40' x 4')	2.5	0.5
3.2		Drill bedrock (38 holes, 20º batter, 2-1/4" dia.)	10	2.0
4		**Install precast foundation modules**	**37.5**	**7.5**
4.1		Set leveling chairs	2	0.4
4.2		Lay longitudinal bottom grade beams (6/stack = 114 picks, 6 tons ea.)	5	1.0
4.3		Place transverse top-grade beams (4/stack = 76 picks, 4-tons ea.)	4	0.8
4.4		Anchors - furnish, install, connect, torque, align, confirm	15	3.0
4.5		Pump in grout for leveling and anchors, cure	4	3.0
4.6		Tension anchors	10	2.0
5		**Install modules on top of the foundation**	**17.5**	**3.5**
5.1		Furnish, and place module frames (pick, place 53 frames, 2 crest gates)	4	0.8
5.2		Set-up scaffolding	5	1.0
5.3		Thread tie-down bars and attach them to couplings (36 bars)	10	2.0
5.4		hydraulic knife gates preinstalled	0	0.0
5.5		Install vertical seals (10 abutments, 13 stacks)	2.9	0.6
5.6		Connect preinstalled hydraulic and pneumatic lines (338 quick connects)	3.5	0.7
5.7		Install trash racks (13)	1	0.2
6		**Completion of the first side**	**22.5**	**4.5**
6.1		Confirm all work complete requiring "in the dry"	10	2.0
6.2		Upon "release to water up" fill the cofferdam	10	2.0
6.3		Remove the cofferdam, set it up on the other side	15	3.0
		The second half of the stream (right side looking downstream))		
7		**Prepare second half**	**12.5**	**2.5**
7.1		Excavate for precast foundation (152' x 40' x 4')	2.5	0.5
7.2		Drill bedrock (38 holes, 20º batter, 2-1/4" dia.)	10	2.0
8		**Install precast foundation modules**	**37.5**	**7.5**
8.1		Set leveling chairs	2	0.4
8.2		Lay longitudinal bottom grade beams (6/stack = 114 picks, 6 tons ea.)	5	1.0

8.3		Place transverse top-grade beams (4/stack = 76 picks, 4-tons ea.)	4	0.8
8.4		Anchors - furnish, install, connect, torque, align, confirm	15	3.0
8.5		Pump in grout for leveling and anchors, cure	4	3.0
8.5		Tension anchors	10	2.0
9		**Install modules on top of the foundation**	**20**	**4.0**
9.1		Furnish, and place module frames (pick, place 40 frames, 11 crest gates)	5	1.0
9.2		Set-up scaffolding	5	1.0
9.3		Thread tie-down bars and attach them to couplings (36 bars)		2.0
9.4		hydraulic knife gates preinstalled	0	0.0
9.5		Install vertical seals (10 abutments, 8 stacks)	2.3	0.5
9.6		Connect preinstalled hydraulic and pneumatic lines (338 quick connects)	3.5	0.7
9.7		Install trash racks (8)	0.4	0.1
10		**Completion of the second side**	**20**	**4.0**
10.1		Confirm all work complete requiring "in the dry"	10	2.0
10.2		Upon "release to water up" fill the cofferdam	10	2.0
10.3		Remove cofferdam	5	1.0
11		**Turbine, generator, and electrical hook up**	**20**	**4.0**
11.1		Connect the top of the dam crane rails	10	2.0
11.2		Install top of dam gantry crane	10	2.0
11.3		Furnish, and install (9) turbine/generator cassettes w/ gantry	4.5	0.9
11.4		Connect preinstalled electrical lines (162 quick connects)	1.7	0.3
12		**Completion, testing, commissioning**	**20**	**4.0**
13		**Utilization capacity (20%)**	**49**	**9.8**
14		**Contingency (20%)**	**58.8**	**11.8**
		TOTAL DURATION with 5 days/week	**294**	**71**
		TOTAL DURATION with 7 days/week	**294**	**42**

PLANT OPERATION – The combined set of turbines and the overall management of the Balcony Falls plant and the LPS 566 plant would be controlled against a carefully constructed water management plan factoring in environmental, water quality, recreational, and power generation factors. In simple summary the plan is:

- Water required for purposes other than a generation is routed accordingly to the environmental, aesthetic, water quality, or recreational needs via central plant control.
- Generation flow is controlled through the plant via an optimization stair-climber function. This function integrates the available generating flow to turn on the right number of turbines based on the available flow. Since the Reakt turbines with fixed vanes (FIT) are regulated only by the variable speed (frequency) drive (VFD), which provides limited flexibility to changing flow (analogous to a semi-Kaplan) additional

regulation comes from throttling the operating point of the two fully regulated Reakt turbines with adjustable vanes (AIT) stepper units.

- At a given flow the system is further optimized by following an onboard algorithm in the control system that adjusts operating speed and power to find the best relationship at a given flow and head.
- Each turbine is paired with a $315\ rpm$, $750\ kW$ induction generator.
- There are multiple gates for flow control including a knife gate in the bottom of the dam stack, otherwise known as a Sediment Stack, for low water outlet and sediment sluice.
- The control and automation system devices are listed in the bill of materials.

3.3.4 Facility Metrics

The design and construction of the h-Modulor facility for Balcony Falls and the LPS 566 site described in this section support the goals outlined in Table 1 as described below and shown in Table 11. Salient features for Balcony Falls:

Station Name: Balcony Falls TBD Hydroelectric

Owner: TBD

Operator: TBD

FERC Project. No: N/A

DAM No: N/A

Station Location: Glasgow, VA

Longitude & Latitude: N37.62118, W79.44123

Name of River: James River

Watershed size: 3,050 square miles

Plant maximum flow: 83,115 cfs (Assumed all 30 crest gates open and 10’ of overtopping along the full length of the dam; assumed knife gates closed.)

Site Head: 19.1 ft Head

Type of Dam: h-Modulor

Height: approx. 28.5 ft (stacks are three frames high, each frame is 9.5’ tall)

Length: approx. 408 ft (includes 8 generation module stacks, 6 sediment passage module stacks, 30 water passage module stacks, and 7 three-frame high abutment stacks, each stack is approximately 8 ft wide)

Site Capacity: 6.0 MW, 4,000 cfs

Transformer: Step up from 480 V to 13.47 kV

Generator: 315 RPM, 750 kW variable speed generation with PMG and VFD with related power electronics

Number of units: 8 x 500 cfs (52" Reakt) - 6 Reakt FIT52 (FIT means fixed vane, induction generator, direct drive) and 2 Reakt AIT52 (AIT means adjustable vane, induction generator, direct drive)

Est. Annual Energy Production: 27.8 GWh estimated from monthly flow analysis (see Section 3.5)

Salient features for LPS 566:

Station Name: LPS 566 TBD Hydroelectric

Owner: TBD

Operator: TBD

FERC Project. No: N/A

DAM No: N/A

Station Location: Spokane WA

Longitude & Latitude: N47.680749, W117.466138
Name of River: Spokane River

Watershed size: 4,290 square miles

Plant maximum flow: 51,282 cfs (Assumes crest gates are open and there is 10' of overtopping along the full dam length but does not include flow through the knife gates)

Site Head: 19.1 ft Head

Type of Dam: h-Modulor

Height: approx. 28.5 ft (stacks are three frames high, each frame is 9.5' tall)

Length: approx. 344 ft (includes 9 generation module stacks, 7 sediment passage module stacks, and 12 water passage module stacks, each stack is 8 ft wide, and 80 ft of abutments on the left-hand side and 40 ft of abutments on the right-hand side)

Site Capacity: 6.75 MW, 4,500 cfs

Transformer: Step up from 480 to 13.47 kV

Generator: 315 RPM, 750 kW variable speed generation with PMG and VFD and related power electronics

Number of units: 9 x 500 cfs (52" Reakt) - 7 Reakt FIT52 (FIT means fixed vane, induction generator, direct drive) and 2 Reakt AIT52 (AIT means adjustable vane, induction generator, direct drive)

Est. Annual Energy Production: 32.9 GWh; based on analysis with the daily flow in Section 3.5.5.

Table 11: Facility designs support goal metrics.

Goal Characteristic	Goal Metric	Facility design supports the goal metrics
Nameplate capacity (flow and hydraulic head)	≤ 10 MW (e.g., up to 5,000 cfs and up to 30 ft. hydraulic head)	Balcony Falls: Capacity is 5.95 MW, 19.5 ft head, 4,000 cfs. LPS 566: Capacity is 7.44 MW, 19.5 ft head, 4,500 cfs
Modeled installed capital cost per nameplate capacity	< $3,500/kW Stretch goal <$2,000/kW	Balcony Falls: $3,798/kW $3,449/kW (with lock-type recreation module and fixed weir water passage modules) LPS 566: $1,928/kW (See Section 3.6)
Estimated construction timeline	< 2 yrs. site prep. to commissioning	Balcony Falls: 1.12 years LPS 566: 0.80 years
Replication – the same type of modules	Multiple U.S. sites (2 or more)	Designs reflect the ability to replicate standardized and modular development at two different sites within the U.S. – Balcony Falls and LPS 566.
Passage – water, fish, recreation craft, sediment	Safe and timely	Crest gates and overtopping capability support passing flood flows that exceed the estimated 1000 yr. flood per Tables 3 and 4. Balcony Falls: 83,115 cfs maximum plant flow LPS 566: 51,282 cfs maximum plant flow Downstream fish passage safety is supported by: Approach flow velocity less than 2 ft/s, bar spacing 0.75" or power wall angled at 30°, surface bypass

		every fifth stack (approx. every 40 ft), downstream plunge pool. Recreation passage modules for water craft have a gentle slope (< 10º). The knife gate passes sediment and low water.
Water quality	No degradation	No degradation, see Section 3.4
Co-Development Opportunity	At least one	Balcony Falls – Paddler safety, head pond recreation Spokane River – Head Pond recreation, irrigate the golf course, sediment control for downstream hydro plant

3.3.5 Lessons Learned

Surprisingly, the biggest challenge with developing the facility designs and specifications was not technology, equipment design, or integration related but process related. Initial attempts to fit the modules into the traditional construction specification document process failed, in that it was complicated, unclear, and time-consuming – just the opposite of what should be able to be achieved with a standardized modular facility. Achieving the promise of reduced risk, time, and cost via prefabricated standard modules required re-thinking the hydropower project engineering process and workflow. LPS considered a variety of process flows revolving around thinking of the facility as a kit of parts like LEGO® or Ikea®, or a library of parts like standard fasteners, gears, and bearings in mechanical design CAD software. What finally made the process clear was coming to an understanding that the modules are engineered products, much like water processing equipment (pumps, filter cabinets, hydraulic units, etc.,) where each module is accompanied by a standard specification and an IO&M manual.

The standard process steps to go from site inputs, through design to an h-Modulor hydropower project construction plan (i.e., work instructions) is shown in Figure 40.

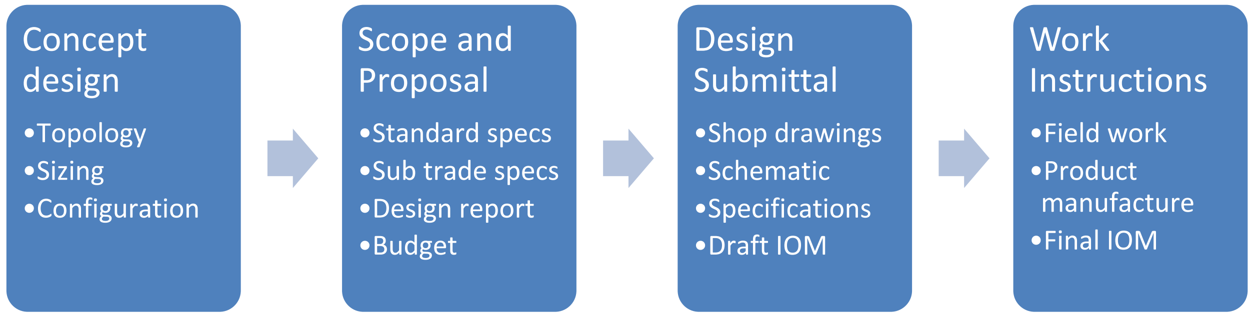


Figure 40: h-Modulor hydropower project design and construction specification process.

The key elements of the process include:

- The standardized set of calculations for site evaluation,
- The complete product set,
  - Data sheets
  - Sizing Tools
  - Specifications
  - Design Definition, Models, BOM, Cut-Sheets, Supporting Calcs
  - Testing Regime
  - Commissioning Regime
  - IO&M, and
- Support and realization of reference documents by product and process.

The full process to get an h-Modulor facility designed, installed, and commissioned, from initial customer inquiry through commissioning, is designed around prefabricated products. It includes sizing the overall plant, specifying major components, making submittals, and realizing plant installation and commissioning. This process is integrated into a workflow compliant with ISO 9001:2015 as illustrated in Figure 41. Note: the xxxx's in the document icons, e.g., 8.5.xxxx, are a place holder for a specific project number.

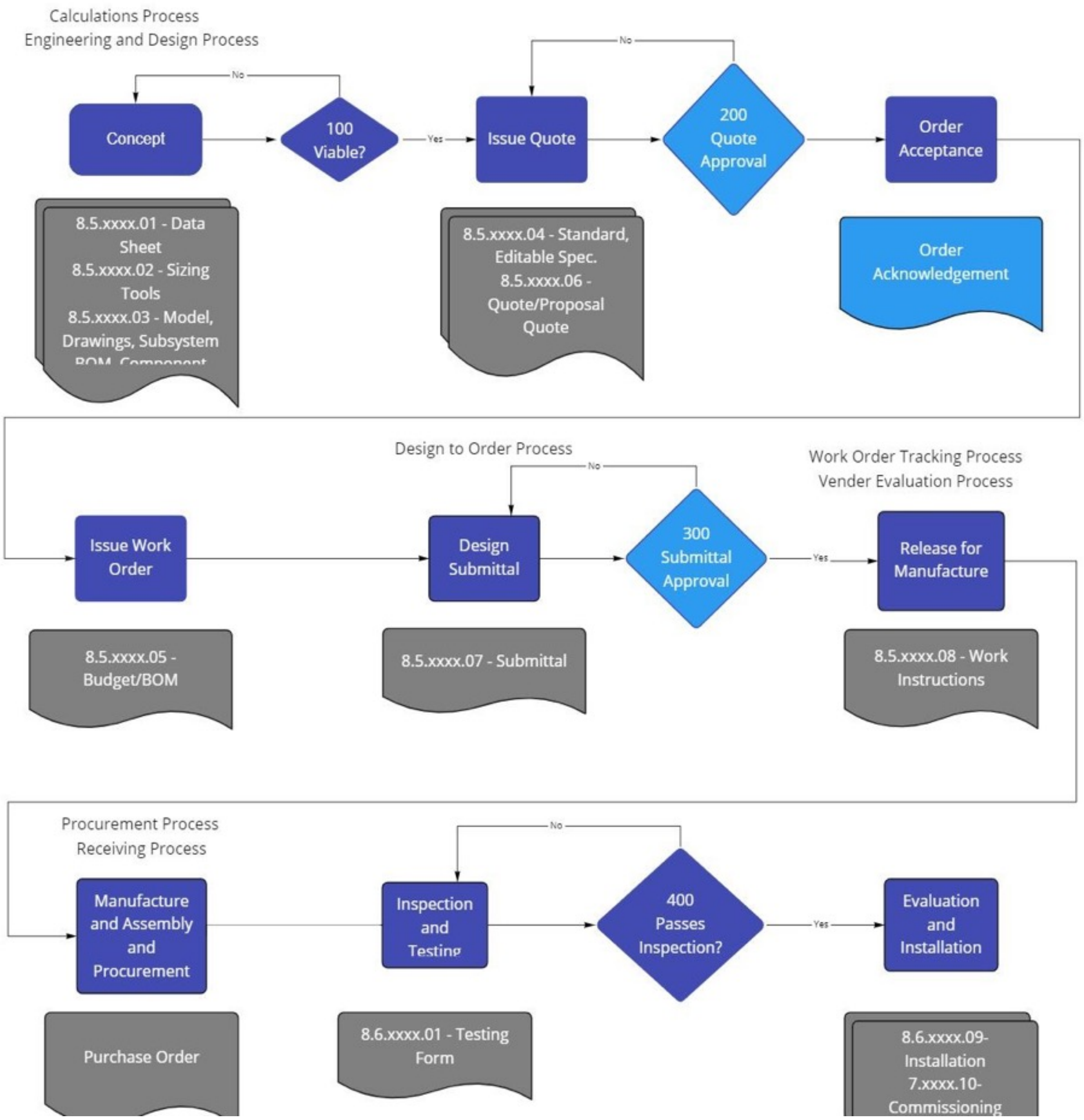


Figure 41: Workflow process diagram for realizing an h-Modular hydropower facility from customer inquiry to plant commissioning.

3.4 Task 4: Environmental Assessment

3.4.1 Task Objective

The objective of Environment Assessment is to establish an understanding of the potential impacts and mitigation measures concerning water quality, greenhouse gas (GHG) emissions, sediment transport, fish passage, and recreation. The assessment outlines environmental benefits and enhancements associated with the SMH facility developments. The environmental assessment provides insight into the developments' performance for the safe and timely passage of constituents such as water, fish, sediment, and recreational as outlined in the facility goals presented in Table 11.

3.4.2 Efforts & Method

For both developments, Balcony Falls and the LPS 566, a desktop-type approach and the use of an empirical model for analysis are taken. Analysis is limited to using readily available existing information from relevant sources. For each site, the project setting and existing resources are examined. The environmental evaluation examines potential impact and mitigation measures for water quality, greenhouse gas (GHG) emissions, sediment transport, fish passage, and recreation (see *Appendix I* for detailed methodologies and analysis). For each of these elements, the overall study constitutes a scoping-level analysis. Environmental benefits and enhancements are discussed.

To assess the effectiveness of downstream fish passage, experts at Alden Research Laboratory (Alden) reviewed the following rules-based approach based on the governing velocity and rack spacing for various fish species:

- Bar screen spacing, velocity, and bypass channel spacing based on the most restrictive relevant target species;
- $V_{approach} < 1.5\ ft/s$;
- Bar spacing: 1 in if Alosine fish are present, $0.75\ in$ for eels, $1.5\ in$ otherwise;
- Downstream Fish Passage Module Stack every fifth stack ($\sim 40\ ft$) so fish do not need to traverse a long bar screen surface.

3.4.3 Results & Outcomes

The details of the environmental assessment are provided in *Appendix I*. Neither site is expected to require upstream fish passage due to blockage by downstream dams. If that were to change then Balcony Falls may see American shad, river herring and American eel and LPS 566 may see anadromous salmon and steelhead (see details in *Appendix I*).

In summary, the environmental assessment for the facility at Balcony Falls finds the project offers renewable electricity generation potentially displacing combustion-based generation that would produce GHG emissions and other air pollutants. The location of the project above existing barriers to diadromous fish migration means that the Balcony Falls project will not interfere with the population recovery of these species, at least as long as the existing barriers downstream of Balcony Falls remain unmitigated. If conditions develop that warrant it, fishways can be retrofitted to the Balcony Falls project. The inclusion of a sediment module stack will support sustainable sediment management at the dam. The project is not expected to adversely affect water quality above or below the dam. This conclusion derives from an examination of the project and environmental characteristics and water quality conditions at existing similar projects downstream of Balcony Falls.

The potentially most significant adverse impacts of this project are inundation and loss of the recreationally important Balcony Falls Rapid and blockage of recreational craft by the dam. Downstream boat passage can be mitigated by the inclusion of a recreational passage module in the series of water passage modules to provide a pathway for downstream boat movement; however, the impact of inundation of the Balcony Falls Rapid on whitewater boating cannot be mitigated. The impoundment creates a flat-/slack-water boating opportunity near a heavily used hand-carry launching site. This launch site could be upgraded to support the use of trailered boats suitable for the newly created impoundment.

The LPS 566 hydropower project has positive and negative attributes. It is located within a $110 - mile$ reach that is regulated for hydropower production. Located upstream of a high-head dam that blocks anadromous salmon and steelhead migrations, it will create a new facility for renewable energy production without impacting anadromous fish migration. If fishways are developed at downstream barriers, fish passage facilities can be retrofitted to this project. The project has both positive and negative effects regarding recreational boating. Sediment loading and sediment management will be a challenge at this site; if managed poorly there is a potential for the creation of undesirable conditions including localized flooding. Managed effectively the project may improve sediment-related conditions downstream of the project. Effective management of sediment will benefit from detailed sediment transport modeling. The project is unlikely to have adverse effects on GHG emissions, DO concentrations, or water temperature.

Concerning downstream fish passage, Alden reviewed and commented on the approach providing the following key takeaways (full memo report available in *Appendix II*):

- The downstream passage concept developed by LPS for modular hydropower applications uses design standards that are consistent with current recommendations for fish guidance structures installed at hydropower projects (i.e., bar racks and louvers).
- LPS should carefully consider site conditions and potential debris loading in evaluating head loss.
- The target approach flow velocity of $1.5\ ft/s$ or less for silver eels may be overly conservative based on available research. In general, a target of $2\ ft/s$ or less should be sufficient for silver eels, as well as all species and life stages of anadromous fish species found in east coast rivers.
- The angle of a guidance structure to approaching flow should be between 15° to 45°. Guidance efficiency increases with decreasing angles.
- Target bar spacings are appropriate for the diadromous and resident fish species being considered. However, if a clear bar spacing of $0.75\ in$ is selected because American eel is present, an intake structure does not need to be angled because all silver eels will be physically excluded from entrainment, and a high percentage of other species will be either physically or behaviorally excluded. In the absence of an angled structure,

additional bypasses will need to be located along the length of an intake to allow discovery and downstream passage on time.

- Downstream bypass systems will also need to be designed following current resource agency guidelines.
- The overall biological performance of downstream passage facilities should be determined to total downstream passage survival at any given project. This will allow LPS to determine if a proposed design will meet fishery management goals for migratory or resident species populations. Total project survival can be estimated for a defined migration season or over a year by determining route-specific passage and survival rates (i.e., spillway, fish bypasses, turbines) over the range of expected river discharges for a specified time. If a large proportion of fish passes over a dam or through gates during periods of a spill, and/or turbine survival is relatively high, total project survival could reach levels considered appropriate for target species even if guidance efficiencies are at the low end of the expected range (e.g., 50%).

3.4.4 Environmental Assessments Compared to Facility Metrics

The results of the environmental assessment vs. goal environmental and social metrics for Balcony Falls are:

- *Safe and timely fish passage* – Seven of the 11 dams down-stream have no fish passage; a need for fish passage seems unlikely given the number and diadromous fish passage ranking assigned to the dams upriver of Scotts Mill.
- *Safe and timely sediment passage* - Shoreline erosion along the banks of the impoundment is a potential mechanism for enhanced erosion; however, run-of-river operation of the Balcony Falls project will minimize water level fluctuations and sediment trapping by the impoundment will be transitory and offset by reservoir sediment trapping. Furthermore, the LPS modular project design includes a sediment module stack with a gate installed at the base of the dam. This module allows for controlled passage of bedload and other sediments via density current venting and flushing during periods of high flow and via sluicing during periods of impoundment drawdown as needed to manage sediment accumulation in the reservoir.
- *The safe and timely passage of recreation craft* - Recreational water craft passage can be included in the facility to provide a pathway for downstream passage of canoes, kayaks, and small rafts which partially mitigates the loss of the Balcony Falls rapidly. The Glasgow Boat Ramp could be upgraded to accommodate the launch of heavier boats suitable for the newly created impoundment.
- *No degradation to water quality* - Limnological characteristics of the reservoir are such that adverse temperature and dissolved oxygen conditions are not to be expected and mitigation measures are not warranted.

- *At least one co-development opportunity* - The principal environmental benefits of the Balcony Falls hydropower project are renewable electricity generation yielding a net reduction of GHG emissions, and the creation of new opportunities for flat-/slack-water recreation in the project impoundment. These opportunities include fishing, boating, and swimming.

The results of the environmental assessment vs. goal environmental and social metrics for LPS 566 are:

- *Safe and timely fish passage* - The Spokane River hydropower project lies within the historic range of anadromous salmon and steelhead; however, the closure of the Grand Coulee hydropower dam 80 years ago blocked anadromous salmon and steelhead from reaching the Spokane River. License terms for the project certainly would not include a fishway prescription; however, a fishway could be prescribed later under a license amendment if circumstances change (i.e., the fish passage becomes a reality at Chief Joseph and Grand Coulee dams). No mitigation is warranted under current conditions; however, fishway retrofit could be required in the future. The modularity of the project design facilitates fishway retrofit if it becomes necessary.
- *Safe and timely sediment passage* - Sediment management will be critically important to the long-term operation of the hydropower project. Detailed modeling of sediment transport will be valuable for predicting patterns of sediment deposition and mobilization and for devising management and mitigation measures. A full suite of sediment management methods should be considered, including routing, sluicing, flushing, bypass, and drawdown. Inclusion of sediment passage modules near the bottom of the stack will provide flexibility for managing sediment at the project. Appropriately designed hydraulic structures at the Hangman Creek – Spokane River confluence may be useful for discouraging delta formation and riverbed aggradation and routing sediment toward the dam where it can be passed downstream.
- *The safe and timely passage of recreation craft* - Mitigation of recreation-related impacts may include the construction of new or improved small boat access points and the inclusion of one or more recreational boat passage modules in the stack to facilitate downstream movement of small boats at the dam.
- *No degradation to water quality* - While induction of water quality exceedances by the impoundment is unlikely, sediment management can reduce the potential for developing in-reservoir conditions conducive to water temperature elevation and oxygen depletion. Specifically, sediment deposition can be managed, primarily through sediment routing to prevent sediment deposition patterns that promote expanses of relatively shallow static water that would promote microbial decomposition of accumulated organic matter. The inclusion of Sediment passage modules near the bottom of the stack will provide flexibility for managing sediment at the project.

- *At least one co-development opportunity* - The project produces environmental benefits and enhancements to recreational boating and sediment management. The slack water in the impoundment provides an area of a few acres or less suitable for flatwater watercraft use and improved access to this reach. Storage (both short-term and long-term) of incoming sediment allows for improved sediment management downstream of the impoundment.

3.4.5 Lessons Learned

As a result of the environmental assessment process, it is clear that a real challenge to any hydropower facility, not only the two cases studied here, is that environmental and social conditions can change, and the facility may be required to change.

The fish passage may be required in the future at a site where it wasn't initially required. The U.S. Fish and Wildlife Service (USFWS) - for eel, and National Oceanic and Atmospheric Administration (NOAA) - for anadromous species, have the authority to prescribe fish passage facilities within the FERC regulatory regime. At the time a hydropower facility is licensed, these agencies may preserve their authority to prescribe fish passage in the future. For example, the Cushaw Hydroelectric Project (FERC-P-906), which is just downstream of Balcony Falls, was relicensed in 2008; USFWS and NOAA declined to prescribe fishways at that project but reserved their authority to do so in the future (FERC 2008).

The hydrology at a site may change. Section 9505 of the SECURE Water Act of 2009 requests that the DOE assess the effects of, and risks from, global climate change associated with the water supplies for federal hydroelectric power generation and marketing practice. The results of the assessment reported in 2017 are that "the most important climate change effect impacting future hydropower generation is likely to the earlier snowmelt, change of runoff seasonality, and increasing frequency of extremely high- and low-runoff events." (DOE 2017)

Community and social priorities can change with each new election and generation.

The h-Modulor facility designs contemplate changes in conditions and community-driven opportunities. As described in Section 3.2.2, one way to add upstream fish passage to an h-Modulor facility, or any existing site, with minor facility modifications is to use the ZAO-Attractor which includes the passage capabilities of the Whooshh Fish Transport System. Changes in demands for generation, water passage, sediment management, and community requirements for recreation, among others can be addressed by removing and replacing a given module stack with a different type or an upgraded model.

The sequence to replace a stack with a future fish passage module, recreation passage, or any other module is described below for the most difficult stack, the generation module stack.

1. Bring crane and replacement modules to the site.
2. Close the knife gate.

3. Remove the turbine cassette.
4. Remove the trash racks from the stack to be replaced and from the two adjacent stacks (the trash racks "hang" on the upstream side of the stack and can be removed by the top of the dam access). This step can be accomplished with a crane and top dam access.
5. Place a bridge plate that spans the front of the stack that needs to be removed and sealed against the two adjacent stacks. This step can be accomplished with a crane and top dam access.
6. Enter the turbine cavity and break out the grout bags so the stack is not restricted by the shear keys. This step may require water work or creating a dewatered area depending on the tailwater level at the time.
7. Remove the four tie-rods.
8. Lift-out module stack to be replaced.
9. Install the new module stack as described in Section 3.3.3, except install the knife gate elements on the upstream bulkheads first.
10. Re-install tie-rods or install new tie-rods depending on their condition.
11. Refill grout bags to snug up against shear keys.
12. Slide the vertical seals into place.
13. Remove the bridge plate.
14. Hang the trash racks on the three stacks.
15. Install turbine/generator cassette module.
16. Connect hydraulics and electrical.
17. Operate using replaced stack.

3.5 Task 5: Performance Analysis

3.5.1 Task Objective

The objective of Performance Analysis is to develop energy generation performance predictions and assess dam safety. While it was not a specific objective of FOA-0001836 to assess the cost of energy, of course, that is a critical characteristic to evaluate for any standard approach to a hydropower facility to find commercial success. Energy generation supports the overall goal of the FOA-1836 to support the development of technologies that contribute to the growth of small hydropower. In addition, these objectives support the goal of safety as outlined in the facility goals presented in Table 1 as the facility must *safely* pass water, sediment, fish, and recreation.

3.5.2 Approach and Methodology

ENERGY GENERATION - The analysis uses site hydraulic characteristics and flow duration curves combined with the generation characteristics from an array of turbines. One of the turbines in the array is a single adjustable-vane stepper, while the others are fixed vane. This approach increases the turndown ratio and the overall performance of the array.

For a run-of-the-river plant such as Balcony Falls or LPS 566 to be economically viable, 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[6] needs to be extremely 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 (Q) drops below about 80% of the maximum. By contrast, a fully regulated unit has a turndown ratio of about 5. This means that a turbine that is designed to handle 500 cfs of flow can go down to $Q = 100\ cfs$ with no appreciable loss in efficiency. Traditionally, this is accomplished through a mechanical adjustment to the guide vanes and blade pitch. Recent innovations, however, allow the use of a combination of adjustable guide vanes and a VFD to monitor and adjust the operating peak and deliver the performance of a fully regulated turbine without mechanical complexity and at a lower cost.

The mechanical control of the adjustable inlet guide vanes is critical to maximizing the turndown ratio, but it adds about 35% to the cost of an unregulated unit. The h-Modulor facility designs only use a single adjustable-vane "stepper" generation module, whereas the other generation modules 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 an array can efficiently span a flow band from $100\ cfs$ to $4{,}500\ cfs$, with water-to-wire efficiency at all times of approximately $80 - 83\%$.

For each of the developments, annual energy production (AEP) is determined using an array of efficiency. The AEP reflects the amount of generation that the facility can produce based on its operation and flow capacity. Flow duration curves were developed using data from USGS gauge stations nearest the sites; the Holcomb Rock Gauge for Balcony Falls (Figure 5) and Gauge No. 12422500 for LPS 566 (Figure 6). The Balcony Falls facility is designed for a maximum operating flow of $4{,}000\ cfs$ which corresponds to a 24% exceedance flow. LPS 566 is designed for $4{,}500\ cfs$ maximum operating flow, which corresponds to 43% exceedance flow.

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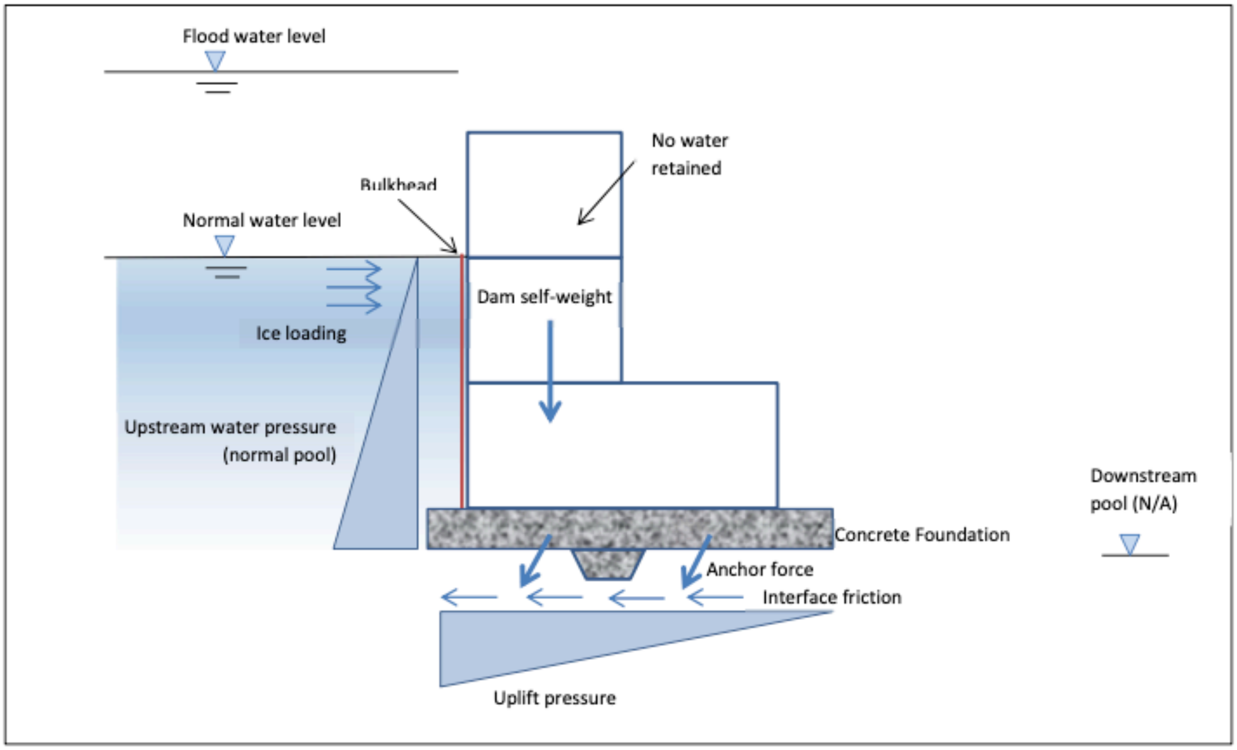
[6] Turndown ratio refers to the width of the operational range of a device and is defined as the ratio of the maximum capacity to minimum capacity.

Predicted energy (kWh) is modeled for each site based upon the following factors: i) the corresponding exceedance flows, ii) the average monthly flows, iii) respective facility design flows, and iv) turbine array efficiency of 83% for the array as described above multiplied by 0.9 to equal 75% to be conservative.

DAM SAFETY - Global stability is analyzed using the standard methodology and guidance primarily described in the FERC's "Engineering Guidelines for the Evaluation of Hydropower Projects," and USACE's "Gravity Dam Design."

The foundation material was assumed to be intact competent bedrock. Figure 42 presents a simplified free-body diagram of a typical/generic modular stack used for the stability analysis. The stability analysis calculates three aspects of the global stability of the h-Modulor system: sliding, overturning (i.e., rotational stability represented by the location of the resultant force), and flotation.

The analysis covers the topic of global stability of a single h-Modulor stack that is assumed to act monolithically and independently from adjacent stacks and adjacent concrete structures. The water-retaining feature of the module stacks, i.e., bulkhead plates, is installed at the upstream side of the stacks, therefore, no weight of water was used for the dam self-weight. Recommended minimum factors of safety for use in this analysis are based on Table 2A in Chapter 3 of the FERC Engineering Guidelines for the Evaluation of Hydropower Projects (March 4, 2016). These recommended factors of safety are appropriate when a "no cohesion" assumption has been applied, as is the case for these analyses. For seismic loading, the h-Modulor system is analyzed using the "pseudo-static" method by which a horizontal driving force is applied to the structure in response to a seismic acceleration. A more detailed analysis (such as finite element modeling) should be performed for the final design of the dam at any specific location per FERC guidance. Dynamic earthquake analysis should be performed for the h-Modulor hydropower structure. Current FERC dam safety guidelines mandate the use of analysis for post-earthquake conditions, which account for potential changes resulting from the earthquake, such as increased uplift, decreased cohesion bond, loss of soil strength, etc. For this analysis, the pseudo-static method was judged to be acceptable which conforms with USACE methodologies for analyzing similar concrete and steel structures. No dam-foundation interface cohesion has been assumed, so a loss of bond will not be an issue. The structure framing appears robust, so damage to the section (and potential loss of weight from the section which would reduce sliding resistance) is not expected. Therefore, the post-earthquake stability evaluation did not modify the foundation parameters or the section properties. Loading conditions (I, II, II-A, and III) are summarized in Table 12 shown below.



Notes:
1. Sketch not to scale. Modules are 10 (middle and top) and 20 (bottom) feet long and 9.5 feet tall each.
2. No silt or fill on the upstream side is shown on this figure. Silt loading ignored.
3. Module self-weight negligible. Dam self-weight includes weight of concrete foundation pad. Two anchors used.
4. Earthquake loading not shown.
5. Sliding resistance from the shear key not considered for conservatism.

Figure 42: Simplified free body diagram of a typical/generic modular stack used for stability analysis.

Two interface friction coefficient values were used to describe the shear behavior between the concrete base pad and foundation bedrock. Sliding friction angles of 25° and 35° were used to represent the lower and upper bound of the concrete-bedrock friction types, respectively. A shear key in the foundation pad was proposed. For this analysis, sliding resistance from the shear key was not considered, for conservatism. Additionally, no cohesion effects have been considered. Both assumptions are considered conservative for bedrock foundation conditions. Additional resistance to sliding would be provided by both the shear key and cohesion between the concrete and bedrock (though different minimum safety factors would need to be applied if cohesion were considered.).

Table 12: Loading conditions for dam safety analysis.

Interface Friction Angle	Case ID	Headwater (above bottom of base pad)	Tailwater (above bottom of base pad)	Other Loads
25° (lower bound concrete on bedrock)	I (normal pool)	21.5	--	n/a
	II (flood pool)	31.5	--	n/a
	IIA (normal pool plus ice)	21.5	--	2' of Ice
	III (normal pool plus earthquake)	21.5	--	0.32 g (PGA)
35° (upper bound concrete on bedrock)	I (normal pool)	21.5	--	n/a
	II (flood pool)	31.5	--	n/a
	IIA (normal pool plus ice)	21.5	--	2' of Ice
	III (normal pool plus earthquake)	21.5	--	0.32 g (PGA)

Note: n/a denotes "not applicable". "--" denotes no tailwater.

- *Case I, Static Case*: Normal water at top of the middle cell (i.e., $19\ ft$ above the top of the foundation pad or $21.5\ ft$ above the bottom of the foundation pad).
- *Case II, Flood Case*: No flood flow data has been provided; therefore, it was assumed that an additional $10\ ft$ of water above the normal pool represents the maximum water surface elevation for the Spillway Design Flood load case.
- *Case II-A*, Static Case Plus Ice: An ice thickness of $2\ ft$ was used per USACE guidance for lakes/reservoirs in North America, which is judged conservative for Thayer Creek. Note that active ice mitigation measures may be incorporated into the final design.
- *Case III*: The design Peak Ground Acceleration was estimated to be $0.32g$.
- "Post-Earthquake" conditions are assumed to be the same as "Normal pool" conditions because no cohesion has been assumed in the analyses and therefore any potential loss of cohesion due to earthquake-induced cracking will not result in reduced stability.
- No tailwater was used. No reduction in uplift was considered.

- Post-tensioned anchor bars have an inclination angle of 20° from the vertical direction (towards the upstream side).
- The weight of other accessories (such as the access deck and crane) was not considered in the global stability analysis.
- Horizontal sliding resistance from both anchors was used; overturning resistance from the upstream anchor was only used for simplicity.
- Eccentricity was computed and checked per FERC-2016. Cracked base analysis was not performed if eccentricity requirements were met.

3.5.3 Results & Outcomes

ENERGY GENERATION - Monthly generation was calculated based on the monthly variability of flows and is shown in Figures 43 & 44 for Balcony Falls and Figure 45 & 46 for LPS 566. The sum of the monthly energy production over a year result in annual energy production of 27.8 GWh and 32.9 GWh for Balcony Falls and LPS 566, respectively.

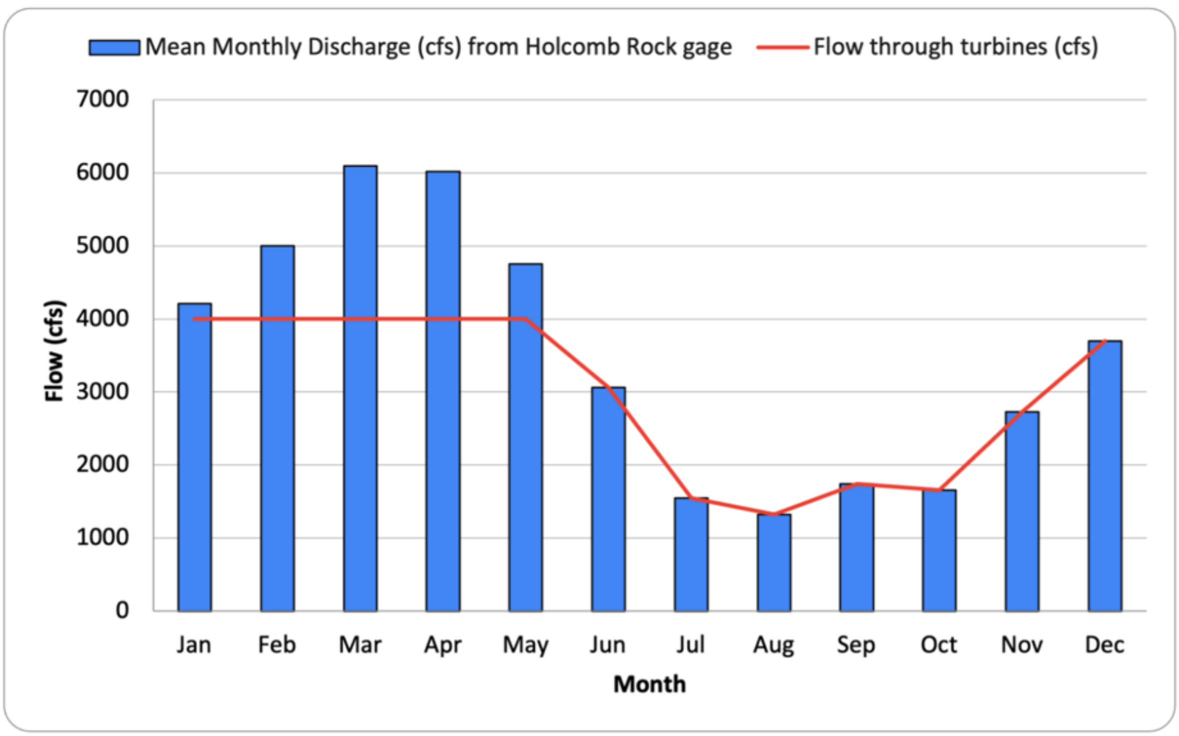


Figure 43: Mean monthly discharge vs. flow through turbines.

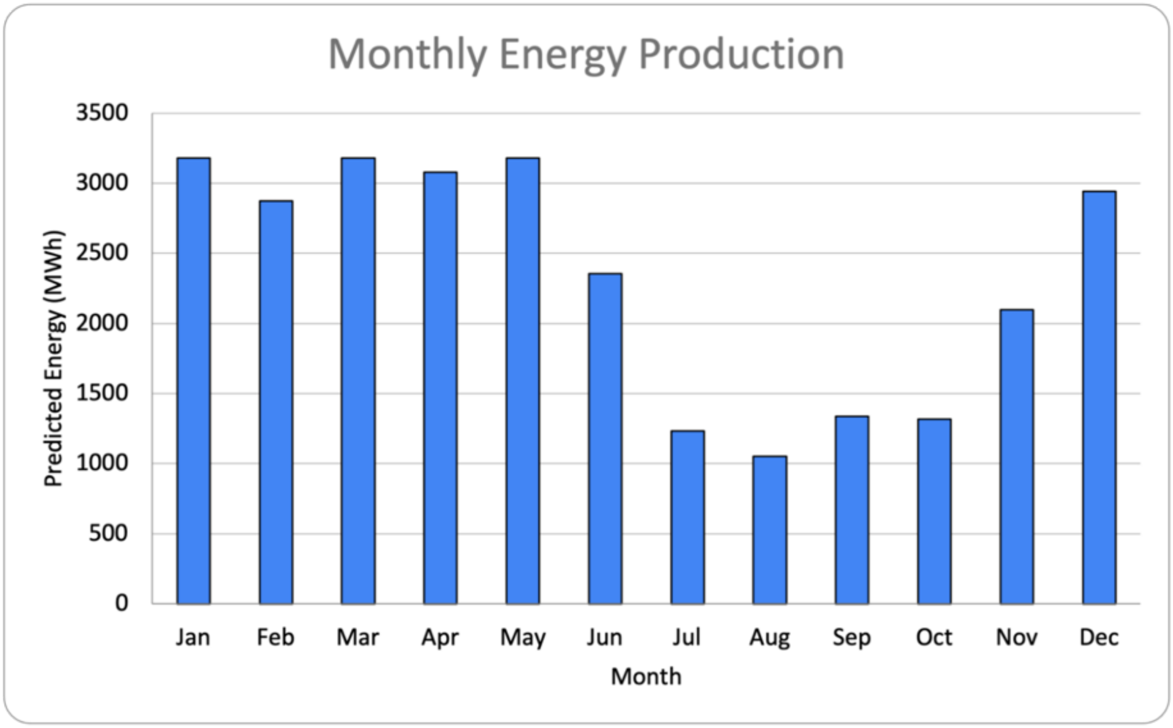


Figure 44: Monthly flow analysis and predicted monthly generation at the Balcony Falls site.

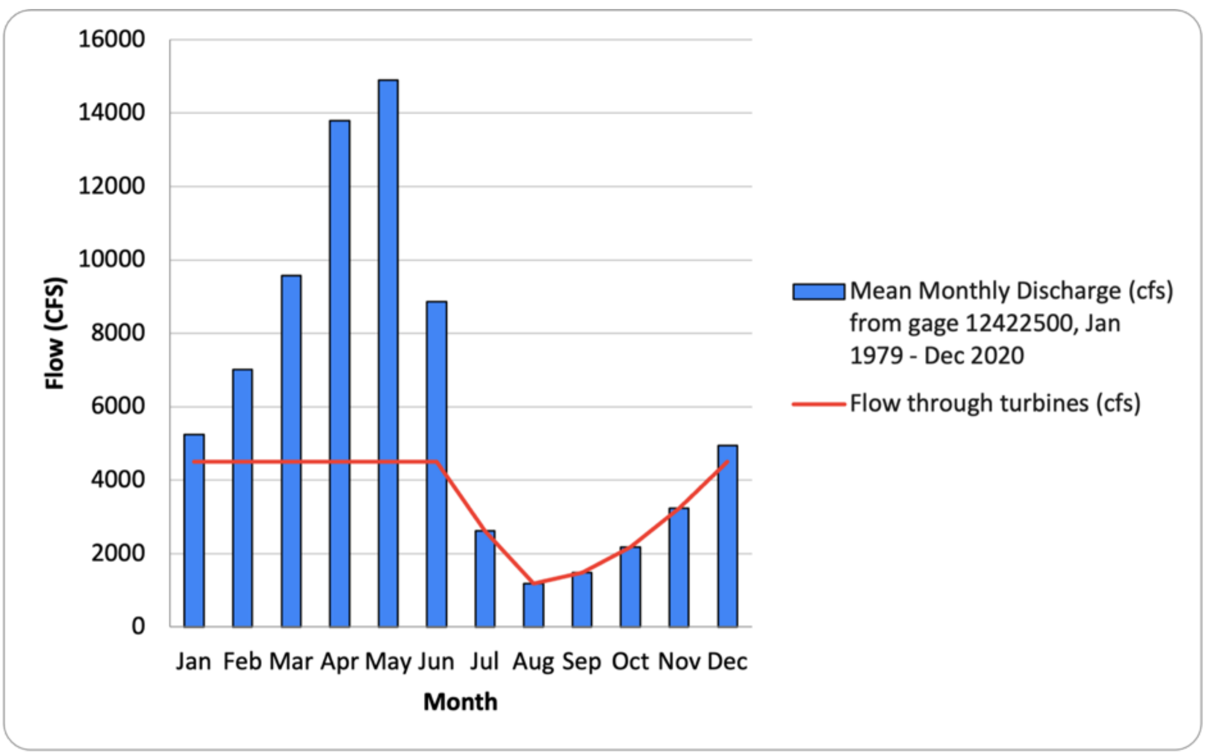


Figure 45: Mean monthly discharge (CFS) vs. flow through turbines (CFS)

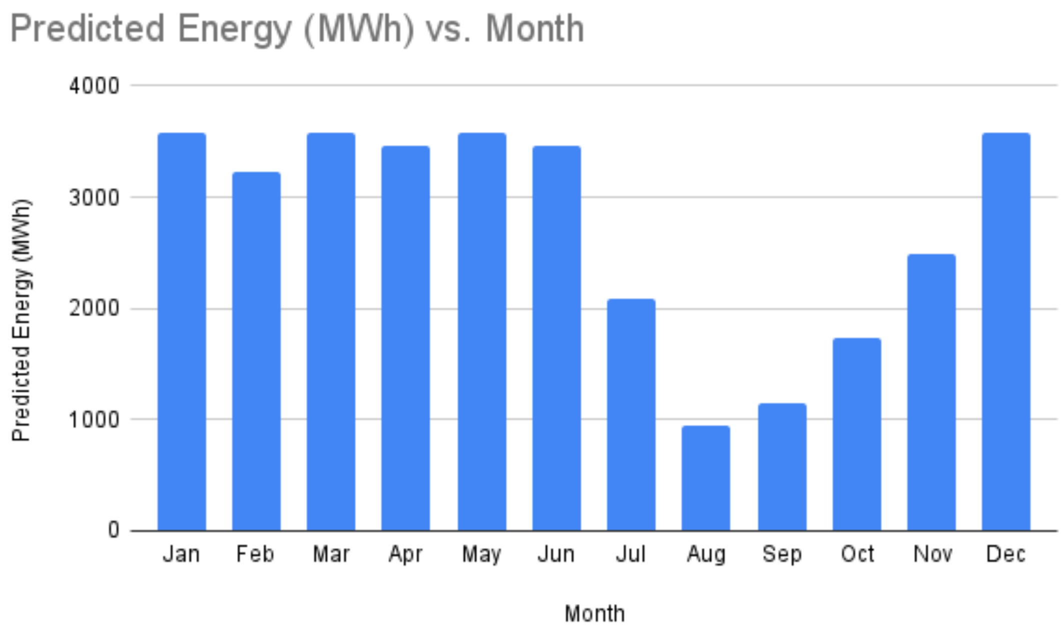


Figure 46: Monthly flow analysis and predicted monthly generation at Spokane River site.

DAM SAFETY - The analysis described above including calculations performed using spreadsheets developed in MathCAD ($v. 15.0$), confirmed that the global stability design criteria can be met for the developed loads given:

- Interface frictional angles of $25°$ and $35°$;
- Two (2) $2 - 1/4$" diameter 150 ksi all-thread post-tensioned ground anchors with an ultimate tensile strength of 490 $kips$, and
- A design capacity of 368 $kips$ (60% of the ultimate value) for each h-Modulor stack.

The MathCAD global stability analysis results are summarized in Table 13 (for an interface frictional angle of $25°$) and Table 14 (for an interface frictional angle of $35°$).

Table 13: Calculate Global Stability Analysis Results for Frictional Angle of 25°

Load Case ID	No Anchor			Proposed 150-ksi Anchor Bar Diameter x 2	W/ Anchor		
	Calculated FOS Against Sliding	Calculated Resultant Location	Calculated FOS Against Flotation		Calculated FOS Against Sliding	Calculated Resultant Location	Calculated FOS Against Flotation
Load Case I (Normal Pool at 19' above base)	-0.2	Outside Middle 1/3	0.6	2 1/4"	4.8 (≥ 1.5)	Middle 1/3	> 2
Load Case II (Flood Pool at 29' above base)	0.0	Outside Middle 1/2	1.1	2 1/4"	2.6 (≥ 1.5)	Middle 1/2	> 2
Load Case IIA (Normal Pool + 2' Ice thickness)	-0.1	Outside Middle 1/2	0.6	2 1/4"	2.8 (≥ 1.5)	Middle 1/2	> 2
Load Case III (Normal Pool + Earthquake acceleration of 0.32g)	-0.1	Outside Base	0.6	2 1/4"	3.2 (≥ 1.3)	Within base	> 2

Note: Assumed two 2-1/4" (#18) 150-ksi all-thread bars inclined 20° upstream and a foundation interface frictional angle of 25°.

Table 14: Calculate Global Stability Analysis Results for Frictional Angle of 35°

Load Case ID	No Anchor			Proposed 150-ksi Anchor Bar Diameter x 2	With Anchor		
	Calculated FOS Against Sliding	Calculated Resultant Location	Calculated FOS Against Flotation		Calculated FOS Against Sliding	Calculated Resultant Location	Calculated FOS Against Flotation
Load Case I (Normal Pool at 19' above base)	-0.2	Outside Middle 1/3	0.6	2 1/4"	6.1 (≥ 1.5)	Middle 1/3	> 2
Load Case II (Flood Pool at 29' above base)	0.0	Outside Middle 1/2	1.1	2 1/4"	3.3 (≥ 1.5)	Middle 1/2	> 2
Load Case IIA (Normal Pool + 2' Ice thickness)	-0.1	Outside Middle 1/2	0.6	2 1/4"	3.6 (≥ 1.5)	Middle 1/2	> 2
Load Case III (Normal Pool + Earthquake acceleration of 0.32g)	-0.2	Outside Base	0.6	2 1/4"	4.0 (≥ 1.3)	Within base	> 2

Note: Assumed two 2-1/4" (#18) 150-ksi all-thread bars inclined 20° upstream and a foundation interface frictional angle of 35°.

3.5.4 Facility Metrics

The results presented above show that the h-Modulor facilities support the dam safety objectives of the program. Energy generation will be discussed in the context of the levelized cost of energy in Section 3.6.

3.5.5 Lessons Learned

While reviewing the energy calculations with Avista Corp. and with ORNL, the annual energy calculations were adjusted to daily flows and energy estimates for the LPS 566 site for more precision. This analysis also integrated: i) the turbine characteristic curve (Figure 47), ii) a tailwater rating curve, a bar screen loss of 0.25, and other system losses resulting in a net head of $16.6\ ft$ to $18.1\ ft$, and iii) subtracted environmental flows, taken as 10% of the plant flows for the day, from the flows available for energy generation.

This analysis showed a daily predicted available flow ranging from $426\ cfs$ to $38{,}340\ cfs$ and daily energy generation ranging from $7{,}982\ kWh$ to $146{,}100\ kWh$. Using data from 32 years, which represents $11{,}688$ days accounting for leap years, the AEP is $36.6\ gigawatt-hours\ (GWh)$ and the average daily energy production is $0.1\ GWh$. Whereas using the monthly energy analysis described in Section 3.5.3 for LPS 566 the estimated AEP is $32.9\ GWh$; approximately 10% less than when the daily data was used for the analysis.

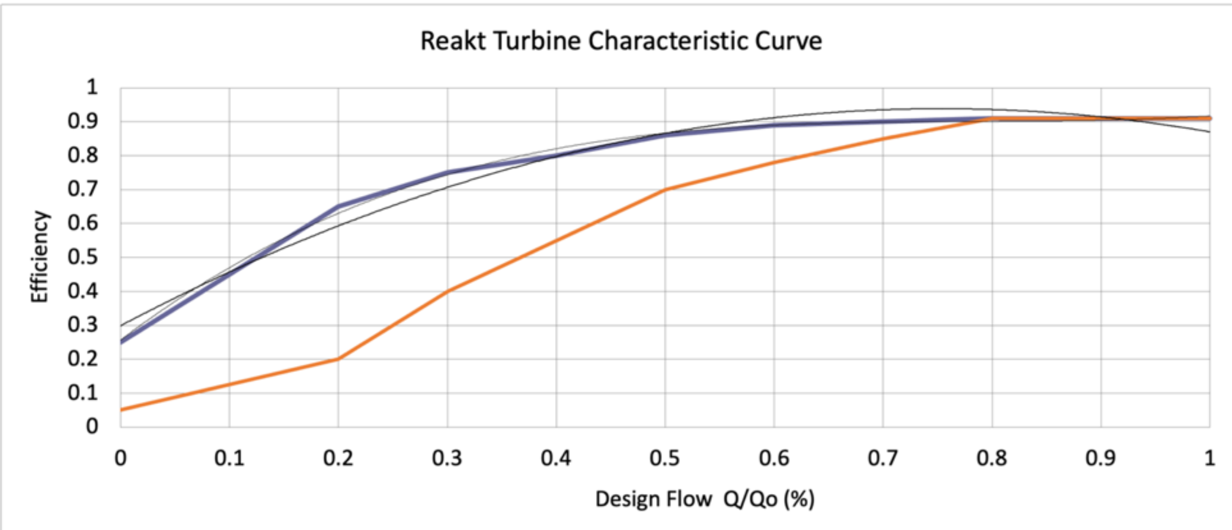


Figure 47: Characteristic curve for Reakt AIT (upper curve in blue) and Reakt FIT (lower curve in red) with curve fit to the Reakt AIT of $y=1.1265x^2+1.6974x+0.299$.

3.6 Task 6: Techno-Economic Analysis

3.6.1 Task Objective

As stated in the FOA-1836, a specific objective of the research is to better understand and disseminate insight into cost reduction potential and stakeholder acceptance of SMH technology, of which h-Modulor is a type. This task addresses that objective as well as the objective cost and performance metrics shown in Table 1.

3.6.2 Approach and Methodology

Three approaches are used to analyze the techno-economic characteristics and impacts of an h-Modulor facility: 1) An Association for the Advancement of Cost Engineering International (AACEI) Class 4 project cost estimate is combined with estimates of plant operating costs and a plant profit and loss (P&L) financial model for each of the two sites, 2) ORNL Small Hydropower Integrated Design and Economic Analysis (smHIDEA) tool (Oladosu 2021) is used to evaluate the LPS 566 site, and 3) a third h-Modulor facility design is developed for a remote Alaskan location and the project costs and performance are compared to a traditional small hydropower facility at the same location. In the first approach, the installed costs are estimated down to five levels of specificity (see Table 15). Operating cost estimates include costs for operators, maintenance, plant insurance premiums, loan-guarantee premium, property taxes, water rights, plant utilities (electricity and water), overhead, and management. Table 16 shows these cost estimates for the first year of the facility operation, which increase at a rate of 4% per year for subsequent years. Revenue inputs into the P&L model are estimated to include: i) firm capacity at $\$5/MWh$, ii) energy sales at $\$30/MWh$, iii) Section 242 or other benefits at $\$10/MWh$, and iv) renewable energy credit (REC) sales at $\$18/MWh$.

Table 15: Cost breakdown structure for estimating installation costs.

Level	CBS	CBS Item
1	1	Initial Capital Costs (ICC)
2	1.1	Civil Works (Including Modular Civil Work)
3	**1.1.1**	**Site Preparation**
4	1.1.1.1	Site Preparation including clearing, leveling, erosion
4	1.1.1.2	Site Access
4	1.1.1.7	Cofferdams
3	**1.1.2**	**Dams and Reservoirs**
4	1.1.2.1	Dam Stack
4	1.1.2.2	Abutment Stack
5	1.1.2.2.1	Container frame
5	1.1.2.2.3	Foundation Assembly
5	1.1.2.2.5	Concrete Works
4	1.1.2.4	Foundation preparation
5	1.1.2.4.1	Modular foundation equipment
5	1.1.2.4.2	Standard foundation Preparation
3	**1.1.3**	**Water Conveyances**
4	1.1.3.1	Sediment Stack
5	1.1.3.1.1	Knife gate
5	1.1.3.1.2	Container frame
5	1.1.3.1.3	Draft tube container frame
5	1.1.3.1.4	Foundation Assembly
5	1.1.3.1.5	Bar Screen Assembly
4	1.1.3.2	Water passage module
5	1.1.3.2.1	Crest Gate Assembly
5	1.1.3.2.2	Crest Gate Container Module Base
5	1.1.3.2.3	Top Container Frame
5	1.1.3.2.4	Foundation Assembly
4	1.1.3.3	Penstock

4	1.1.3.4	Thrust blocks
4	1.1.3.5	Concrete Works
5	1.1.3.5.1	Concrete Works and Labor (Stacks)
5	1.1.3.5.2	Concrete Works and Labor (Power Gen. Option)
4	1.1.3.6	Bulkhead Assemblies (1 qty per side)
3	**1.1.4**	**Power Generation**
4	1.1.4.1	Pressure Box
5	1.1.4.1.1	Pressure Box Casing
5	1.1.4.1.2	Draft Tube (Cost included in Electro-mechanical)
5	1.1.4.1.3	Turbine Assembly (Cost included in Electro-mechanical)
5	1.1.4.1.4	Container frame
5	1.1.4.1.5	Generator support structure
5	1.1.4.1.6	Gantry support
5	1.1.4.1.7	Circle to a square diffuser
4	1.1.4.2	Generation Stack Module
5	1.1.4.2.1	Knife Gate
5	1.1.4.2.2	Container Frame
5	1.1.4.2.3	Draft tube container frame
5	1.1.4.2.4	Cassette Assembly
5	1.1.4.2.5	Turbine Assembly (Cost included in Electro-mechanical)
5	1.1.4.2.5	Bulkhead Assembly
4	1.1.4.4	Recreation Module
2	**1.2**	**Electromechanical Equipment**
3	**1.2.1**	**Powertrain Equipment**
4	1.2.1.1	Reakt Turbine
5	1.2.1.1.2	Kaplan and Propeller Turbine
5	1.2.1.1.3	System Instruments
4	1.2.1.2	Control System (mechanical, analog, digital)
4	1.2.1.4	Generators /Motor-Generators
4	1.2.1.5	Generator Switchgear
4	1.2.2.2	Draft Tube and Foundation Assembly
5	1.2.2.2.1	Discharge tube and tolerance ring
5	1.2.2.2.2	Modulor or poured foundation
4	1.2.2.5	Communication Cable
4	1.2.3.5	Fire Protection
2	**1.3**	**Electrical Infrastructure**
3	**1.3.1**	**Switchyard**
4	1.3.1.1	Modular Switchgear box
4	1.3.1.2	Transformer and OVR Module
4	1.3.1.3	Switchgear Installation

2	**1.4**	**Engineering and Construction Management**
3	**1.4.1**	**Engineering and Management**
4	1.4.1.1	Detailed Design and Construction Engineering
4	1.4.1.2	Procurement Management
4	1.4.1.3	Construction Management
3	**1.4.2**	**Plant Commissioning**
4	1.4.4.1	Commissioning per Work Instruction
5	1.4.4.1.1	Electrical Testing per IEEE 1547
5	1.4.4.1.2	Hydromechanical Testing & Commissioning

Table 16: Estimated operating costs for the first year of operation of the h-Modulor facility; assumed the same at the Balcony Falls and LPS 566 facility.

Operating Expenses	
Operator	50,000
Operator fees	15,000
Maintenance	77,222
Plant insurance premium	10,000
Loan-guarantee premium	-
Property taxes	25,000
Water Rights	-
Utilities Electricity & Water	650
Management Fees	-
Overhead & Management expenses	25,000
Total Operating Expense	**$ 203,872**

In the second approach, ORNL performs a separate techno-economic analysis and determines the LCOE for the conceptual h-Modulor facility on the Spokane River using smHIDEA. smHIDEA is a bottom-up tool for simulating the performance and costs of potential facility configurations at small hydropower sites. Given site resources and infrastructure data, basic hydropower design features (turbine type, design flow, and head), facility component dimensions, and financial parameters, smHIDEA uses a combination of parametric and volumetric equations to design the facility and estimate capital costs. A performance optimization algorithm uses design information to evaluate the efficiency and generation profile of the plant over 200 half-percentiles of the daily water flow and head data for the site.

For inputs, the analysis uses:

- Same daily flow and head data as described in Section 5.3,
- Reakt turbine characteristic curves from the LPS website,[7] and
- Detailed capital cost data described above.

[7] https://littoralpower.com/ accessed June 2022

To assess the potential cost benefits of an h-Modulor SMH facility, the third approach develops a facility design and cost estimate for a remote Alaskan location and compares it to a facility design and cost estimate for a traditional small hydropower facility at the same location. The two design packages are evaluated by a third-party PE firm which reviews them against a set of 15 criteria as follows:

1. Appropriateness of the design for remote site conditions as defined by appropriate engineering standards.
2. Robustness (i.e., lack of vulnerability) of the system to the site conditions concerning seismic and environmental loading.
3. Reliability and fault tolerances of the system including system redundancy, minimum maintenance, and ease of maintenance (in consideration of the specific site setting).
4. Maintainability of the design including maintenance requirements, the complexity of tasks, labor requirements, availability of parts, and expected cost of maintenance efforts for the overall facility.
5. Reliability and availability of power generation from the proposed system.
6. Dam safety includes ease of surveillance and monitoring plan as well as potential failure modes.
7. Estimated LCOE integrating initial construction costs, lifecycle costs, and overall capital costs.
8. Overall schedule and variability of the schedule – manufacturing through construction.
9. Design attributes/features are consistent with dependable, low-cost/low-risk project delivery.
10. Scalability and responsiveness to environmental risks and considerations including impacts to a forest, wetland, water resources, fisheries, and wildlife.
11. Opportunities for local community members to be involved in construction.
12. Different opportunities for the community to be involved in operations.
13. Power and energy production comparison - design of system maximizes the output of the site hydrology and meets and exceeds energy demands of the target community.
14. Expected Life of the equipment.
15. Overall assessment of the suitability of design for meeting project requirements and needs of the region.

3.6.3 Results & Outcomes

Capital costs, excluding environmental and interconnection costs, are estimated to be $\$22.6\ million$ for Balcony Falls and $\$14.3\ million$ for LPS 566, respectively. These costs break down as shown in Tables 17 and 18.

Table 17: Cost breakdown for Balcony Falls.

Level	CBS	CBS Item	Definition	Project Totaled Cost
1	1	Initial Capital Costs (ICC)	All installed costs incurred prior to commercial operations date (COD), including hydropower generating plant, balance of station, and engineering.	$ 22,595,082
2	1.1	Civil Works (Including Modular Civil Work)	All direct costs to: 1) prepare the site, 2) purchase, construct, and install the modular and traditional features of the Civil Works of the hydropower station and station infrastructure including dams, intakes and conveyances	$ 19,011,713
3	1.1.1	Site Preparation	Preparation of a site for the construction of a hydropower plant	$ 480,701
3	1.1.2	Dams and Reservoirs	All materials, structures, equipment and labor necessary to create, enhance, or modify the impoundement structures for storing water and forming hydraulic head for power generation.	$ 5,826,451
3	1.1.3	Water Conveyances	Water conveyance system, starting from water intake, though turbine back to downstream river/waterway.	$ 6,089,712
3	1.1.4	Power Generation		$ 6,614,849
2	1.2	Electromechanical Equipment		$ 2,701,629
3	1.2.1	Powertrain Equipment	Supply and installation of the generating units and supporting electro-mechanical infrastructure	$ 2,701,629
2	1.3	Electrical Infrastructure	All electrical infrastructure to collect power from generators and deliver to the grid.	$ 505,740
3	1.3.1	Switchyard	The switching equipment, insulators, supports and protective devices between the high-voltage terminal of Step-up transformers and transmission line, providing the capability of connecting and disconnecting the generating plant from power grid system.	$ 505,740
2	1.4	Engineering and Construction Management	Engineering for selection, configuration and installation of the plant, project QC and site management.	$ 376,000
3	1.4.1	Engineering and Management	Owner or prime contractor engineering and management costs from financial close through commercial operation date.	$ 360,000
3	1.4.2	Plant Commissioning	Cost incurred by owner or prime contractor to test and commission the integrated power plant.	$ 16,000

Table 18: Cost breakdown for LPS 566.

Hydropower Project Cost Breakdown Structure (CBS)				
Level	CBS	CBS Item	Definition	Project Totaled Cost
1	1	Initial Capital Costs (ICC)	All installed costs incurred prior to commercial operations date (COD), including hydropower generating plant, balance of station, and engineering.	$ 14,338,519
2	1.1	Civil Works (Including Modular Civil Work)	All direct costs to: 1) prepare the site, 2) purchase, construct, and install the modular and traditional features of the Civil Works of the hydropower station and station infrastructure including dams, intakes and conveyances	$ 10,431,486
3	1.1.1	Site Preparation	Preparation of a site for the construction of a hydropower plant	$ 690,701
3	1.1.2	Dams and Reservoirs	All materials, structures, equipment and labor necessary to create, enhance, or modify the impoundement structures for storing water and forming hydraulic head for power generation.	$ 4,185,885
3	1.1.3	Water Conveyances	Water conveyance system, starting from water intake, though turbine back to downstream river/waterway.	$ 5,554,900
2	1.2	Electro-Mechanical Equipment	Supply and installation of the turbines generating units and supporting electro-mechanical infrastructure	$ 2,786,331
3	1.2.1	Powertrain Equipment	Supply and installation of the generating units and supporting electro-mechanical infrastructure	$ 2,786,331
2	1.3	Electrical Infrastructure	All electrical infrastructure to collect power from generators and deliver to the grid.	$ 748,702
3	1.3.1	Switchyard	The switching equipment, insulators, supports and protective devices between the high-voltage terminal of Step-up transformers and transmission line, providing the capability of connecting and disconnecting the generating plant from power grid system.	$ 748,702
2	1.4	Engineering and Construction Management	Engineering for selection, configuration and installation of the plant, project QC and site management.	$ 372,000
3	1.4.1	Engineering and Management	Owner or prime contractor engineering and management costs from financial close through commercial operation date.	$ 360,000
3	1.4.2	Plant Commissioning	Cost incurred by owner or prime contractor to test and commission the integrated power plant	$ 12,000

The estimated plant financial performance for Balcony Falls and LPS 566 are shown in Tables 19 and 20.

Table 19: Balcony Falls facility estimated financial performance.

power (kW)	6,000	revenue	$ 1,753,194	project equity (%)	20%
				equity ($)	4,519,016
job cost	$ 22,595,082	payback	13	project debt ($)	18,076,066
cost/installed kW	$ 3,766				
AEP (MWh)	27,828	est. LCOE	$ 0.068	debt service cov. ratio	1.32
est. CPI	0.04				
cost of capital	4.5%	term of loan, yrs.	25	A/R days on hand	45
	Input				
	Reference				

Table 20: LPS 566 facility estimated financial performance.

power (kW)	6,750	revenue	$ 2,071,207	project equity (%)	20%
				equity ($)	2,867,704
job cost	$ 14,338,519	payback	4	project debt ($)	11,470,816
cost/installed KW	$ 2,124.225				
AEP (MWh)	$ 32,876	est. LCOE	$ 0.041	debt service cov. ratio	2.43
est. CPI	4.0%				
cost of capital	4.5%	term of loan, yrs.	25	A/R days on hand	45
	Input				
	Reference				

The LCOE results for LPS 566 facility determined using the smHIDEA tool are shown in Figure 48. It ranges from $0.51 to $0.53 $per\ kWh$ as compared to the results in Table 20 showing an LCOE of $0.41/$kWh$.

LCOE results

Project Economics Summary		
Installed Generating Capacity	6.27	MW
Total Hydraulic Capacity	4,500.00	cfs
Average Annual Generation	34,833.88	MWh per year
Average Annual Capacity Factor	0.63	-
Average Summer Capacity Factor	0.51	-
Overnight CapEx	16,682,480.03	$2662/kW
Overnight Dev. Cost	344,781.17	$55/kW
Fixed O&M	412,262.00	$66/kW
IRR	0.20	-
NPV	6,540,358.04	-
LCOE (Overnight/Econ Life)	50.86	LCOE ($51/MWh)
LCOE (Cash Bal)	53.28	LCOE ($53/MWh)
Min PPA to meet ROE	Not Estimated	
Project Cost Details		
LCOE Components	**LCOE ($/MWh)**	**% Contribution**
ICC	38	75%
Annual O&M	12	23%
Licensing	1	2%
Total	**51**	**100%**

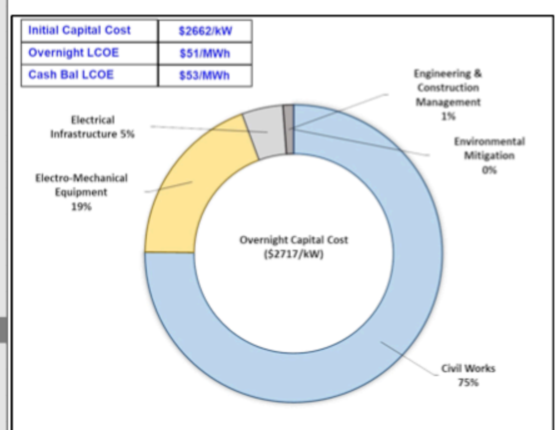


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Figure 48: LCOE results for the LPS 566 facility using the smHIDEA tool, cost supplied by LPS as shown in Table 18, and turbine characteristics from the LPS website.

The conclusions from this analysis are:

Overall, the design has favorable economics for the LPS 556 site.

- Estimated LCOE of about $53/$MWh$.

- Large available flow and 40% exceedance enable a capacity factor $> 60\%$
- The favorable economics of scale from multiple Reakt turbines using a single control system

Concerning LCOE comparisons between an h-Modulor facility and a traditional facility for a remote AK location, the h-Modulor approach scored 30 points whereas the traditional approach scored 18 points (higher is better). The other scores are shown in Table 21 below.

Table 21: Scoring results of the evaluation on 15 criteria of a traditional (T) facility and an h-Modulor (h-M) facility at a remote AK location.

No.	Review Criterion	Weighting Factor	Score		Points	
			T	h-M	T	h-M
1	Appropriateness of the Design with respect to Remote Site Conditions	3	9	7	27	21
2	Robustness of the System with respect to Seismic and Environmental Loading	3	7	7	21	21
3	Reliability and Fault Tolerance, Redundancy, and Ease of Maintenance	2	5	8	10	16
4	Maintainability of the Design	2	8	7	16	14
5	Reliability and Availability of Power Generation	2	7	9	14	18
6	Dam Safety, Ease of Surveillance and Monitoring Plan, Failure Modes	3	7	6	21	18
7	Estimated Levelized Cost of Energy	3	6	10	18	30
8	Overall Schedule	1	8	8	8	8
9	Reliability of Design Features, Low Cost, Low Risk	3	8	6	24	18
10	Scalability and Responsiveness to Environmental Risk; Environmental Impacts	3	8	8	24	24
11	Construction Opportunities for Local Community	1	7	7	7	7
12	Operations Opportunities for Local Community	1	7	7	7	7
13	Power and Energy Production	3	9	10	27	30
14	Expected Life of Equipment	2	9	8	18	16
15	Overall Assessment of Design	3	9	8	27	24
				Total Score	**269**	**272**

3.6.4 Facility Metrics

For Balcony Falls the model installed capital cost is $22.6 million and the estimated nameplate capacity is $6\ MW$ resulting in $\$3{,}767/kW$, which is 7.6% higher than the goal metric of

$\$3{,}500/kW$. The Balcony Falls facility includes a recreation passage for a small watercraft with an associated cost of approximately $2 million. If this approach were replaced with the guillotine lock concept to pass small watercraft as shown in Figure 26 the cost is estimated to be closer to four sediment module stacks, i.e., approximately $\$690{,}000$. This change would reduce the facility capital costs to $\$21.3\ million$ with an attendance of $\$3{,}550/kW$. In addition, the facility has adequate spillway capability for flood control, and some of the pneumatic crest gates on the water passage modules could be replaced with lower-cost fixed weirs. Eliminating half of the pneumatic crest gates would further reduce the facility cost down to $\$20.5$ million with an attendant value of $\$3{,}419/kW$ for the modeled installed capital cost per nameplate capacity metric, which is better than the goal value. Making these changes results in a lowering of the estimated LCOE to $\$0.063/kWh$ as compared to the $\$0.068$ shown in Table 19.

The LPS 566 facility has a model installed capital cost of $\$14.3$ million and the estimated nameplate capacity is $6.75\ MW$ resulting in $\$2{,}124/kW$, which is 39% lower than the FOA goal of $\$3{,}500$ and only 6% away from LPS's goal of $\$2{,}000/kW$.

3.6.5 Lessons Learned

Avista, the power utility in Spokane WA, reviewed the project design and cost estimates for LPS 566 and made the following comments.

- Given the pricing assumptions with tax credits, the hydro project could be competitive against other resource alternatives at the pricing and energy levels provided.
- Avista values the energy, capacity, and RECs at $\$53/MWh$ (levelized)
- Utility ownership increases the cost to approximately $\$60/MWh$ due to differences in financing methods.
- The Washington Utilities and Transportation Commission has suggested utilities include non-energy impacts in the financial analysis of resources, a project like this may earn up to an additional $\$12\ per\ MWh$ for economic benefits- but could be reduced depending on perceived environmental detriments.
- Tax credits, if available, contribute to making this project competitive with other projects.
- Capital costs are significantly lower than estimated for equivalent size hydro projects with existing dams.
- Environmental and interconnection costs were not included but could be a significant component of capital costs.

Washington State has an aggressive policy that electric generation and electricity from renewable resources supply one hundred percent of all sales of electricity to Washington retail electric customers by January 1, 2045. However, the Revised Code of Washington includes a clause 19.405.050(5)(a) that makes it clear that Hydroelectric generation used by an electric utility to satisfy those requirements, "may not include new diversions, new impoundments, new bypass reaches, or expansion of existing reservoirs constructed after May 7, 2019, unless the diversions, bypass reaches, or reservoir expansions are necessary for the operation of a pumped storage facility that: (i) Does not conflict with existing state or federal fish recovery plans; and (ii) complies with all local, state, and federal laws and regulations."

ORNL comments are that other potential facility costs that were not included and could impact overall costs and LCOE are:

- Environmental mitigation costs
- Connection and related infrastructure costs

Comparing Balcony Falls and LPS 566 it was more difficult to achieve the goal for the ICC per nameplate capacity for Balcony Falls. The Spokane River at the LPS 566 site is narrower than the James River at Balcony Falls and requires less infrastructure to be built. To keep the facility costs low on new hydropower at greenfield sites, select a site with a narrow river and steep banks with high flow.

4. 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, PI - concept leadership, commercialization focus, LCOE
Katherine Leighton - Project Manager
Wayne Dyok, PE, hydropower consultant – site selection leadership
Ryan Cook, technical leader, small hydro expert –facility performance analysis, construction plans, and economic analysis.
Ravi Challa, Ph.D. senior scientist – hydrology analysis pertaining to downstream fish passage
Sydney Platt, mechanical engineer – module design drawings
Henry Shuler, production engineer – production and installation specifications
Anthony Seabert, senior engineer – innovative concepts for cost reduction
Alexander Matathia, project engineer – concept designs for cost reduction

Kootznoowoo, Inc. (KI), born because of the Alaska Native Claims Settlement Act of 1971, is the corporation for the village of Angoon in Southeast Alaska. Angoon has a population of about 450 people. Most of the shareholders are Tlingit Indian and have strong family and cultural ties to Angoon. When translated to English, Kootznoowoo means "Fortress of the Bears" which reflects the large bear population on Admiralty Island, where Angoon is located. Unlike other for-profit corporations, shares in Kootznoowoo cannot be bought, sold, or traded; shares are passed on to the next generation of shareholders through gifting and inheritance. Kootznoowoo's vision is to improve shareholders' quality of life while operating profitably, upholding traditional values, and providing stewardship of ancestral lands. **KI generously supported the project with a significant cost-share contribution in the form of site data and traditional designs.** KI or Angoon community personnel that supported the Project are:

Hal Dreyer, President (former) – detailed site data, traditional design, and cost estimates
Ed Kookesh, Supervisor of Angoon Power Plant – provided boat transit for a site visit
Trevor Frederickson, Angoon resident – bear guard during the site visit
Devany Plentovitch, PE, Project Manager – lead KI effort to compare SMH to traditional design

Founded in 1972, the Electric Power Research Institute (EPRI) is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, dependable, affordable, and equitable access to electricity across the globe. **EPRI generously supported the project with a cost share.** EPRI personnel that supported the project are:

Paul Jacobson, Ph.D., Principal Technical Leader – author of *Appendix I*.

Avista Corporation is an energy company involved in the production, transmission, and distribution of energy as well as other energy-related businesses. Avista Utilities is the operating division that provides electric and natural gas services to customers across 30,000 square miles across four northwestern states. **Avista generously supported the project by contributing, at no cost to the federal government, to review, and comment on the techno-economic analysis of a conceptual h-Modulor facility design on the Spokane River.** Avista personnel that supported the project are:

Steve Wenke, PE, Chief Generation Engineer (retired)
Clint Kalich, Senior Manager, Resource Analysis – Energy Supply
James Gall, IRP Manager

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 most of its dams and hydropower staff, are in Norwood, MA. GZA personnel who supported the Project are:

Chad Cox, PE, technical and engineering leadership on the modular foundation
Bin Wang, PE, geotechnical and dam safety analysis of the facility

The Inside Passage Electric Cooperative (IPEC) is a non-profit, consumer electric utility serving over 1.300 members in the rural Southeast Alaska communities of Hoonah, Kake, Chilkat Valley, Angoon, and Klukwan. The head office is in Juneau AK.

Brandon Shaw, Operations Manager, reviewed and commented on h-Modulor for remote AK communities served by IPEC, which included visiting a small hydropower site in VA where h-Modulor equipment was being installed.

Schnabel Engineering helps develop the structures and systems that are crucial parts of modern life by engineering quality solutions, managing risk, and providing specialized expertise. Specializing in geotechnical, dam, and tunnel engineering services, Schnabel offers small-firm responsiveness and big-firm capabilities, partnering with clients throughout the life of a project. Designers, innovators, and industry experts have successfully tackled projects in remote locations, challenging environments, and for communities large and small across the U.S. and in over 150 countries.

Edward O'Connor, PE, Senior Consultant
Steven H. Fisher, PE, Senior Consultant
Ed and Steve worked together to review the h-Modulor module designs and analysis including integration with the foundation.

Flow science and engineering experts. Since 1894, Alden has been collaborating with clients across industries to solve their most complex flow-related engineering and environmental problems. Alden has specialized expertise in upstream and downstream fish passage issues at hydroelectric facilities. Alden personnel that supported the project are:

Steve Amaral, Principal Fisheries Biologist, consulted on fish safety.
Gregory Allen, PE, Director of Environmental and Engineering Services, consulted on intake flow modeling and design for fish safety. Authors of *Appendix II*.

Oak Ridge National Laboratory (ORNL) Energy Science and Technology Directorate's Water Power Program is supporting standardized, scalable technologies that match stream environments, lower cost, and speed deployment of new hydropower facilities. ORNL project support was directly funded by DOE. ORNL personnel that supported the project are:

Kevin Stewart, project lead for the SMH facility
Christopher DeRolph, Geospatial Scientist, aided site selection an interface with Explorer Tool
Paul Matson, Aquatic Ecologist, environmental assessments
Gbadebo Oladosu, Ph.D., senior research economist, reviewed techno-economic analysis.
Colin Sasthav, pursuing his Ph.D., framework for techno-economic analysis.
Scott DeNeale, program management

HydroDyne Energy has owned, built, and operated small hydropower plants since 1996 primarily in North Carolina but throughout the eastern U.S., This activity has included dam rehabilitation, as well as the canal, penstock intake gate, and trash rack work and refurbishment as well as complete turbine, generator and controls installation and upgrades. HydroDyne personnel that supported the project are:

Mike Rickly, PE, provided professional engineering review and contribution to module and facility designs.

Turbo Solutions Engineering, LLC (TSE) provides high-quality, efficient, effective solutions for turbo machinery. TSE has experience working with new equipment and aftermarket suppliers, government agencies, entrepreneurs, and aerospace, industrial, and process clients. TSE provided an expert review of the turbine design for the generation modules. TSE personnel that supported the project are:

Nicholas D'Orsi, Partner, Chief Engineer
Chip Hobson, PE, Partner, Mechanical Engineer

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Appendix – I

Environmental Analysis

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Introduction and Background

Background

Starting from 7000 sites in the Oak Ridge National Laboratory New Site Development database, LPS is developing a screening tool to narrow the list to 168 potential sites. The site list was further filtered using a cost model and expert inspection for technical constraints and commercialization potential. The selection process produced two sites suitable for design development and environmental analysis (this document). The two selected sites are:

- Balcony Falls, James River at Glasgow, Virginia
- Spokane River, Spokane Washington

Scope and Method of Analysis

For each of the three sites, this environmental analysis describes the project setting and existing resources; outlines the potential impacts and mitigation measures related to fish passage, sediment transport, greenhouse gas (GHG) emissions, water quality, and recreational resources; describes selected environmental benefits and enhancements; and summarizes the potential environmental effects of the project. For each topic examined, the analysis is limited to readily available existing information and simple desktop analyses, and in selected cases empirical models.

Balcony Falls

Project Setting and Existing Resources

Balcony Falls site is approximately 100 miles west of Richmond, Virginia, and 22 miles northwest of Lynchburg, Virginia within the George Washington National Forest, and Blue Ridge Mountains (Figure 49).

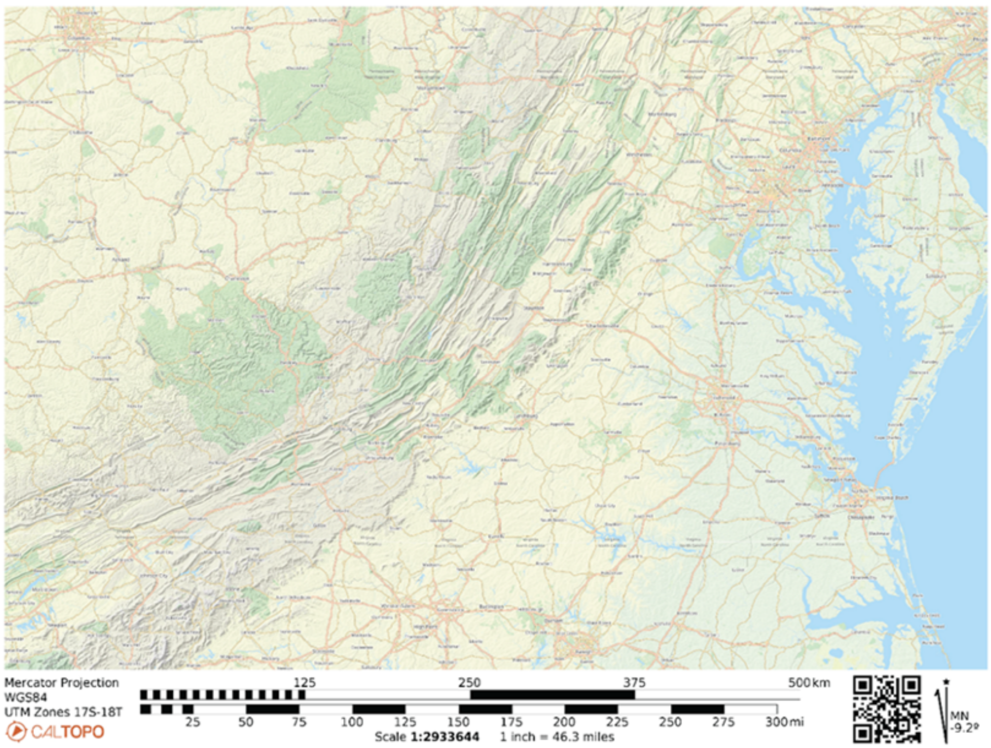

Figure 49: Location of Balcony Falls in west central Virginia, approximately 100 miles west of Richmond, Virginia, and 22 miles northwest of Lynchburg.

The dam site is located on the James River near Glasgow, Virginia, approximately $300m$ downstream of the Maury River confluence with the James River (Figure 50). The proposed dam site would coincide with the location of a dam previously built at this site and subsequently removed. The remains are visible as can be seen from US Hwy 501 overlooking the James River (Figure 51). The area is popular for recreational boating and fishing on the James and Maury rivers. The immediate area is served by two ramps for small boat access: the Glasgow boat launch on the James River just upstream of the mouth of the Maury River, and Locher Landing on the Maury River upriver of the railroad bridge crossing the Maury River and $100m$ from the river mouth. Hiking is a popular activity in the George Washington National Forest, and the Appalachian Trail crosses the James River approximately 3 miles downstream of Balcony Falls. Balcony Falls is approximately 185 river miles from Richmond and 287 river miles from the mouth of the James River at Fort Monroe.

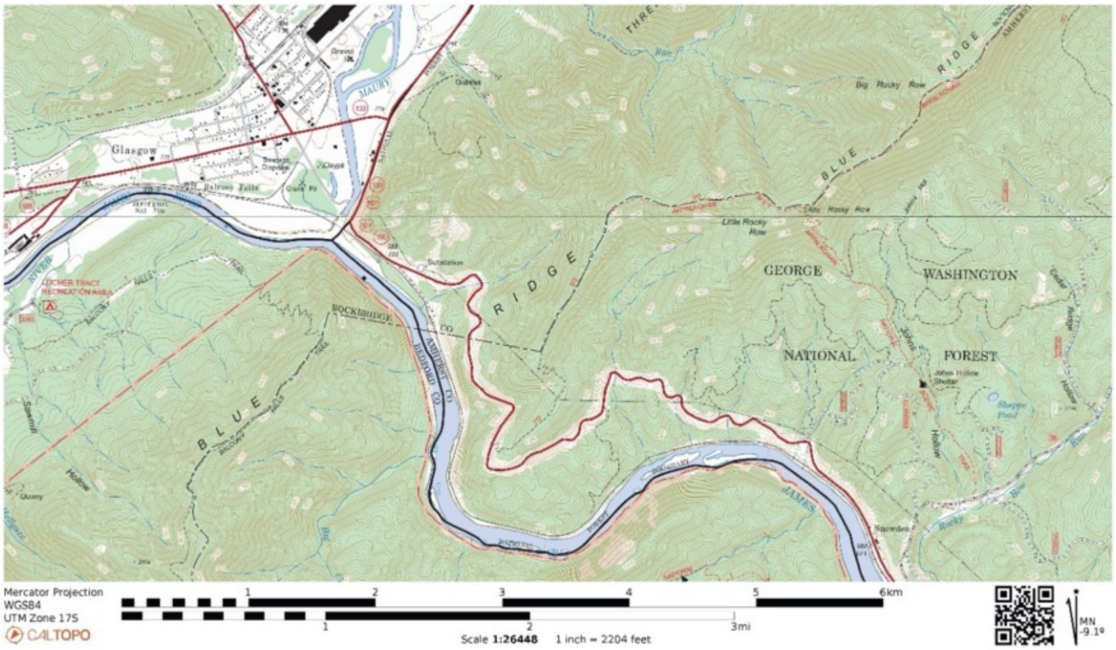

Figure 50: Balcony Falls site on the James River near Glasgow, Virginia.

Figure 51: View of Balcony Falls (far left) viewed from US Hwy 501 looking south from the north (left) bank, the river flowing from right to left.

Environmental Evaluation

Fish Passage

Potential Impact

There are eleven dams downstream of the Balcony Falls site (Table 22). The seven mainstem dams between Balcony Falls and Lynchburg have no provisions for fish passage. The eighth dam downstream, Boshers Dam near the western edge of Richmond, has a vertical slot fishway. The Williams Island dam (7 ft height) is notched to allow fish passage. The last two dams (the first two encountered by upstream-migrating fishes) have been breached, which allows upstream passage.

Table 22: Mainstem dams on the James River are ordered from upstream to downstream.

Dam	Height (ft)	Coordinates	Fish Passage	Diadromous Species Documented Downstream1	
				Current2	Historic
Cushaw	26.0	37.59, -79.38	No	--	AW, BH, AS
Snowden		37.58, -79.38	No	--	AW, BH, AS
Big Island	18.0	37.54, -79.36	No	--	AW, BH, AS
Colemans Falls	20.0	37.5, -79.3	No	--	AW, BH, AS
Holcomb Rock	24.4	37.51, -79.27	No	--	AW, BH, AS
Reusens	40.0	37.46, -79.19	No	--	AW, BH, AS
Scotts Mill	21.0	37.42, -79.14	No	AS AE	AW, BH,
Bosher	14.0	37.56, -77.58	Vertical Slot	AS, AE, BH, SB	AW, AT, SS
Williams Island Z-Dam	7.0	37.56, -77.53	Notch	AW, AS, AE, BH, SB	AT, SS
Hollywood Power Plant	25.0	37.53, -77.46	Breach	AW, AS, AE, BH, SB	AT, SS
Brown's Island	8.0	37.53, -77.44	Breach	AW, AS, AE, BH, HS, SB, AT, SS	

- Source: Martin, E. H. 2019. Chesapeake Fish Passage Prioritization: An Assessment of Dams in the Chesapeake Bay Watershed. The Nature Conservancy. https://maps.freshwaternetwork.org/chesapeake/ Species codes: AE: American eel, AS: American shad, AT: Atlantic sturgeon, AW: alewife, BH: blueback herring, SB: striped bass, SS: shortnose sturgeon.
- Species are presumed to be present at all sites downstream of a site where they have been documented. Species documented as currently present are also not listed as historically present at a site.

Table 22 highlights the degree to which migration of diadromous fish to Balcony Falls is blocked by several dams between Balcony Falls and Scotts Mill dam in Lynchburg. Two diadromous species (American shad and American eel) have been recently documented below Scotts Mill dam, demonstrating successful upstream passage by these species at the four dams downstream of Scotts Mill with some form of fish passage. These two species would pass upstream of Cushaw if the intervening barriers were mitigated or removed. Note that the American eel is not documented to have existed historically upstream of Scotts Mill; however, this species reached the headwaters of the James River before the emplacement of dams on the river. American shad and American eel could be expected to migrate upriver of Balcony Falls if Scotts Mill and upstream impediments to migration were mitigated or removed. Scotts Mill dam is ranked among the top 5% (191) of approximately 3800 dams within the Chesapeake Bay watershed by the Chesapeake Fish Passage Prioritization Project8, and some of these dams already have a fish passage (e.g., Bosher Dam). Consequently, Scotts Mill dam is a high priority for future fish passage mitigation. The dams upriver of Scotts Mill, however, are ranked much lower (top quintile to top third of 3820 dams).

U.S. Fish and Wildlife Service (USFWS; for eel) and National Oceanic and Atmospheric Administration (NOAA; for anadromous species) have the authority to prescribe fish passage facilities within the Federal Energy Regulatory Commission (FERC) regulatory regime; however, a need for fish passage at Balcony Falls seems unlikely in the near term given the number and diadromous fish passage ranking assigned to the dams upriver of Scotts Mills.

Mitigation Measures

It is unlikely that fish passage would be prescribed at Balcony Falls in the near term. There are cooperative efforts among state and federal resource management agencies and downstream hydropower facility operators to restore diadromous fish runs to their entire historic ranges; however, these efforts are centered downstream of the seven dams arrayed between Cushaw

[8] Martin, E. H. 2019. Chesapeake Fish Passage Prioritization: An Assessment of Dams in the Chesapeake Bay Watershed. The Nature Conservancy. https://maps.freshwaternetwork.org/chesapeake/

Dam and Scotts Mill Dam near Lynchburg. Cushaw Hydroelectric Project (FERC P-906) was relicensed in 2008; USFWS and NOAA declined to prescribe fishways for that project but reserved their authority to do so in the future. If fishways were to be prescribed at Balcony Falls (at some point in the future), fish passage facilities would be retrofitted at the dam.

Sediment Transport

Potential Impact

Sediment delivery to the Chesapeake Bay is a significant concern to regional water quality and natural resource managers. Consequently, sediment transport has been studied throughout the Chesapeake Bay watershed. The James River is the third largest river draining the Chesapeake Bay by mean annual flow and watershed area. High sediment yield (sediment delivery per unit area; estimated $75th$ percentile at Cartersville, Virginia among 43 water gaging sites assessed across the Chesapeake Bay watershed) indicate the James River is a major contributor of sediment load to the Chesapeake Bay. The Balcony Falls project has the potential to trap sediment in the impoundment that would otherwise pass downstream. Most of the sediment load, however, currently arises downstream of Balcony Falls.

The U.S. Geological Survey9 estimated sediment yield to be $95.4\ tons/sq.mi./year$ at Buchanan, Virginia, upstream of Balcony Falls and to be $97.2\ tons/sq.mi./year$ downstream at Cartersville, Virginia. Assuming the estimated yield at Buchanan applies at Balcony Falls, the yield estimated at Cartersville applies to the watershed, and a sediment delivery ratio to Chesapeake Bay of 1 for Balcony falls 39% of the sediment load to Chesapeake Bay arises above Balcony Falls. The delivery ratio for Balcony Falls is less than 1 and the impact of any sediment trapping at Balcony Falls on sediment delivery to the Bay will be proportionally less.

Shoreline erosion along the banks of the impoundment is a potential mechanism for enhanced erosion; however, the run of river operation of the Balcony Falls project will minimize water level fluctuations and sediment trapping by the impoundment will be transitory and offset by reservoir sediment trapping.

Mitigation Measures

Reservoir trapping will offset any transient sediment delivery resulting from the creation of the impoundment. The LPS modular project design includes a Sediment Stack component to be installed at the base of the dam. This module allows for controlled passage of bedload and other sediments via density current venting and flushing during periods of high flow and via

[9] Gellis et al. 2005. Summary of Suspended-Sediment Data for Streams Draining the Chesapeake Bay Watershed, Water Years 1952-2002. Scientific Investigations Report 2004-5056. U.S Geological Survey. Reston, Virginia.

sluicing during periods of impoundment drawdown as needed to manage sediment accumulation in the reservoir.

GHG Emissions

Potential Impact

Greenhouse gas (GHG) emissions from hydropower impoundments vary widely from impoundment to impoundment depending upon numerous regional and site-specific factors. Furthermore, impoundments and their operations may alter the location and chemical composition of GHG emissions, and baseline emissions are not zero; consequently, the net change in radiative forcing at the drainage basin level is the relevant metric. A key factor potentially contributing to a net increase in GHG radiative forcing is the production of methane. The characteristics of this hydroelectric development project all point to minimum net GHG emissions from the project construction and operation and negative net GHG emissions to the extent that the hydropower generation displaces fossil fuel-fired generation and the associated GHG emissions. A full accounting of the net GHG emissions associated with the proposed Balcony Falls hydroelectric project can be made with the net GHG emission estimator tool, G-res version 3.1[10,11] ; however, such an analysis is not warranted for the current analysis given project characteristics.

Mitigation Measures

The dominant means by which reservoir creation contributes to net GHG emissions is by promoting the decomposition of carbon-rich organic matter, especially when reservoir conditions promote the formation of methane as a decomposition product that has a heat-trapping potential 25 times greater than that of carbon dioxide. Under circumstances conducive to methanogenesis and methane emissions from a reservoir, mitigation measures may include the removal of carbon-rich organic matter such as standing and down trees within the inundated area, and management of nutrient loading and water column dissolved oxygen to minimize in-reservoir production and methanogenic decomposition of organic matter. The newly created impoundment associated with this hydropower project, however, is not conducive to the creation of anoxic conditions and the amount of newly inundated organic

[10] Prairie YT, Alm J, Harby A, Mercier-Blais S, Nahas R. 2017. The GHG Reservoir Tool (G-res) User guide, UNESCO/IHA research project on the GHG status of freshwater reservoirs. Updated version 3.0 (27-10-2021). Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association. 41 pages.

[11] Prairie YT, Alm J, Harby A, Mercier-Blais S, Nahas R. 2017. The GHG Reservoir Tool (G-res) Technical documentation. Updated version 3.0 (2021-10-27). UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association. 73 pages.

matter is insignificant compared to the reservoir volume. Furthermore, hydraulic conditions and reservoir geometry are not conducive to reservoir stratification and the formation of anoxic conditions. Limnological conditions within similar reservoirs downstream (i.e., poor thermal stratification and dissolved oxygen concentrations well above the criteria for the protection of aquatic life) support these expectations regarding the absence of methanogenic conditions in the Balcony Falls impoundment.

Water Quality

Potential Impact

Impoundment will increase the residence time within the impounded reach. Under some circumstances, impoundment can result in a stratified water column and reduced dissolved oxygen levels in the hypolimnion. Depending on the depth from which water is withdrawn for turbine generation, water temperature, and dissolved oxygen downstream of the impoundment may be adversely affected. The potentially affected waters include the reservoir hypolimnion (if stratification occurs) and the tailwaters downstream of the turbine discharge. As described above concerning GHG production, the characteristics of this project are not consistent with meaningful increases in water temperature or reductions in dissolved oxygen (DO), either in the impoundment or downstream. The project will be operated as a run-of-river facility and water residence time is expected to be short. Given an estimated reservoir volume of $307\ million\ cubic\ feet$ and an average discharge of $1322\ cfs$ during the low flow month of August, the residence time is $65\ hours$ or $2.7\ days$. Thermal stratification and hypolimnetic oxygen depletion are not expected to produce violations of water quality criteria for the protection of aquatic life. For Class III, Nontidal waters, dissolved oxygen criteria are $5\ mg/L$ daily average and $4\ mg/L$ instantaneous; the temperature criterion is $32^{\circ}Celsius$ (90° Fahrenheit). During the period May through October of 2001 and 2002, DO concentrations in the James River $500\ ft$ downstream of the Cushaw Dam, the DO values range from $5.6\ to\ 9.8\ mg/L$ and water temperature did not exceed $30^{\circ}Celsius$.

Mitigation Measures

The limnological characteristics of the reservoir are such that adverse temperature and dissolved oxygen conditions are not to be expected and mitigation measures are not warranted.

Recreational Resources

Potential Impact

Balcony Falls lies within a region where a variety of water-based activities are actively pursued by numerous recreationists. Flatwater boating, whitewater boating, fishing, and swimming are all undertaken in the waters surrounding the project site. The impoundment will be adjacent to existing boat ramps including the Glasgow Boat Launch which is located at the confluence of the Maury River and the James River. The site allows for the hand-carry launching of small boats such as canoes and rafts.

The Balcony Falls impoundment will create new opportunities for flatwater boating This will come at the expense, however, of a whitewater boating opportunity known as the Balcony Falls Whitewater Run between Glasgow and the upstream end of the Cushaw Project reservoir22. The Balcony Fall Whitewater Run is 4.8 miles in length and is identified as Class II-III by American Whitewater. The American Whitewater website contains the following description12:

With a huge watershed providing year-round boatable levels this is THE run for beginner and intermediate paddlers in VA. While people come from all over to paddle this run, during the week you could have the river to yourself. On the weekends it can get crowded, but when the level is good (over 4') or after the weather turns cold most of the recreational canoers and fishermen clear out. Overall, this very fun run is mostly class 2 with an easy class three at Balcony Falls. It is a great run for instructing beginners and has enough play (at levels over 4 feet) to keep intermediate paddlers interested as well.

The Final Environmental Assessment for the Cushaw Project's new hydropower license (2008)22 noted that the James River Basin Canoe Livery, a commercial outfitting firm, serves this run and other firms and organizations including boating and fishing-related businesses, city and county recreation departments, and non-profit organizations bring people from as far away as North Carolina to run the Balcony Falls Whitewater Reach. Several paddling clubs run this reach several times a year.

Mitigation Measures

LPS's Recreational Boating Module can be included in the dam stack to provide a pathway for the downstream passage of canoes, kayaks, and small rafts which partially mitigates the loss of the Balcony Falls rapidly. The Glasgow Boat Ramp could be upgraded to accommodate the launch of heavier boats suitable for the newly created impoundment.

Environmental Benefits and Enhancements

The principal environmental benefits of the Balcony Falls hydropower project are renewable electricity generation yielding a net reduction of GHG emissions, and the creation of new opportunities for flat-/slack-water recreation in the project impoundment. These opportunities include fishing, boating, and swimming.

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[12] American Whitewater. James River, 2 Balcony Falls Run (Glasgow to Snowden). https://www.americanwhitewater.org/content/River/view/river-detail/1949/main

Summary

The project offers renewable electricity generation potentially displacing combustion-based generation that would produce GHG emissions and other air pollutants. The location of the project above existing barriers to diadromous fish migration means that the Balcony Falls project will not interfere with the population recovery of these species, at least as long as the existing barriers downstream of Balcony Falls remain unmitigated. If conditions develop that warrant it fishways can be retrofitted to the Balcony Falls project. The inclusion of a Sediment Management Module in the dam stack will support sustainable sediment management at the dam. The project is not expected to adversely affect water quality above or below the dam. This conclusion derives from an examination of the project and environmental characteristics and water quality conditions at existing similar projects downstream of Balcony Falls.

The potentially most significant adverse impacts of this project are inundation and loss of the recreationally important Balcony Falls Rapid and blockage of recreational craft by the dam. Downstream boat passage can be mitigated by the inclusion of a Recreational Boating Module in the dam stack to provide a pathway for downstream boat movement; however, the impact of inundation of the Balcony Falls Rapid on whitewater boating cannot be mitigated. The impoundment creates a flat-/slack-water boating opportunity near a heavily used hand-carry launching site. This launch site could be upgraded to support the use of trailered boats suitable for the newly created impoundment.

Spokane River

Project Setting and Existing Resources

The Spokane project site is in eastern Washington State east and upriver of Grand Coulee dam, on the Spokane River downstream of Lake Coeur d'Alene near the City of Spokane (Figure 52). The dam site is approximately 5 miles downstream of Spokane Falls in downtown Spokane, and approximately 12 miles upriver from the Nine Mile Falls Hydroelectric Plant (Figure 53).

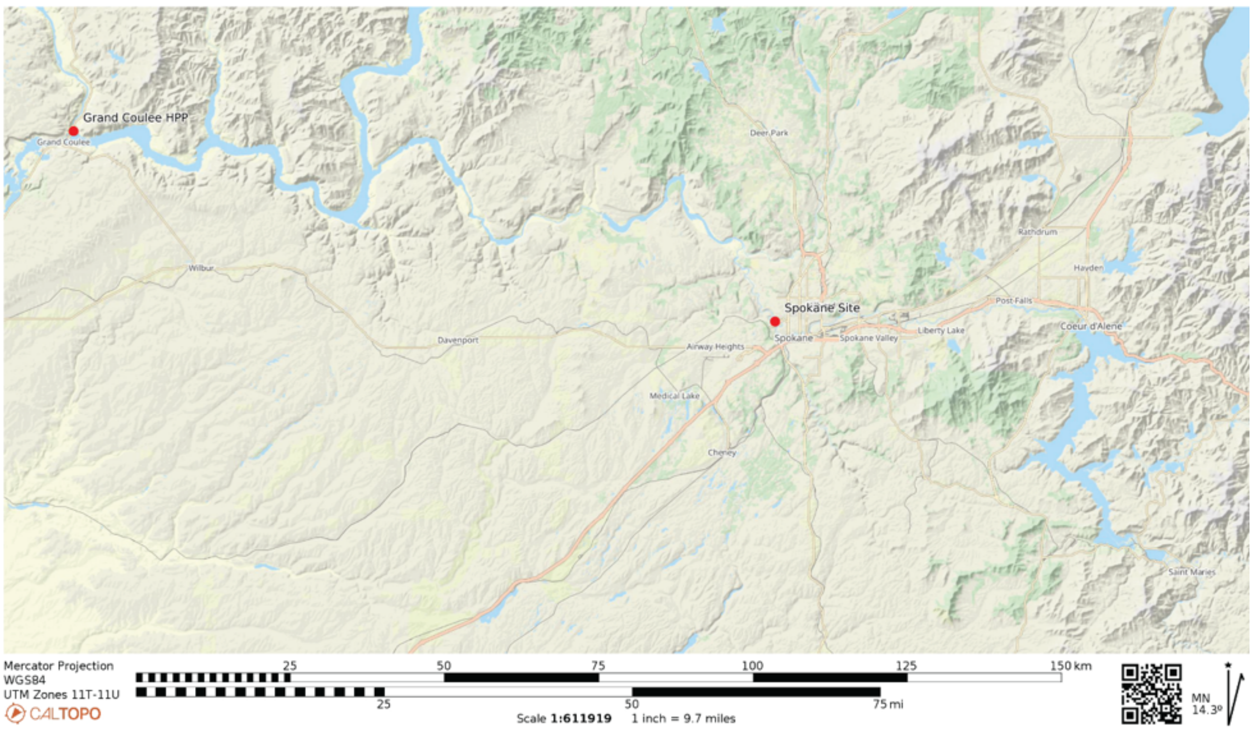

Figure 52: Vicinity map of eastern Washington State, showing Grand Coulee Dam, the Spokane site near the City of Spokane, and Coeur d'Alene in western Idaho.

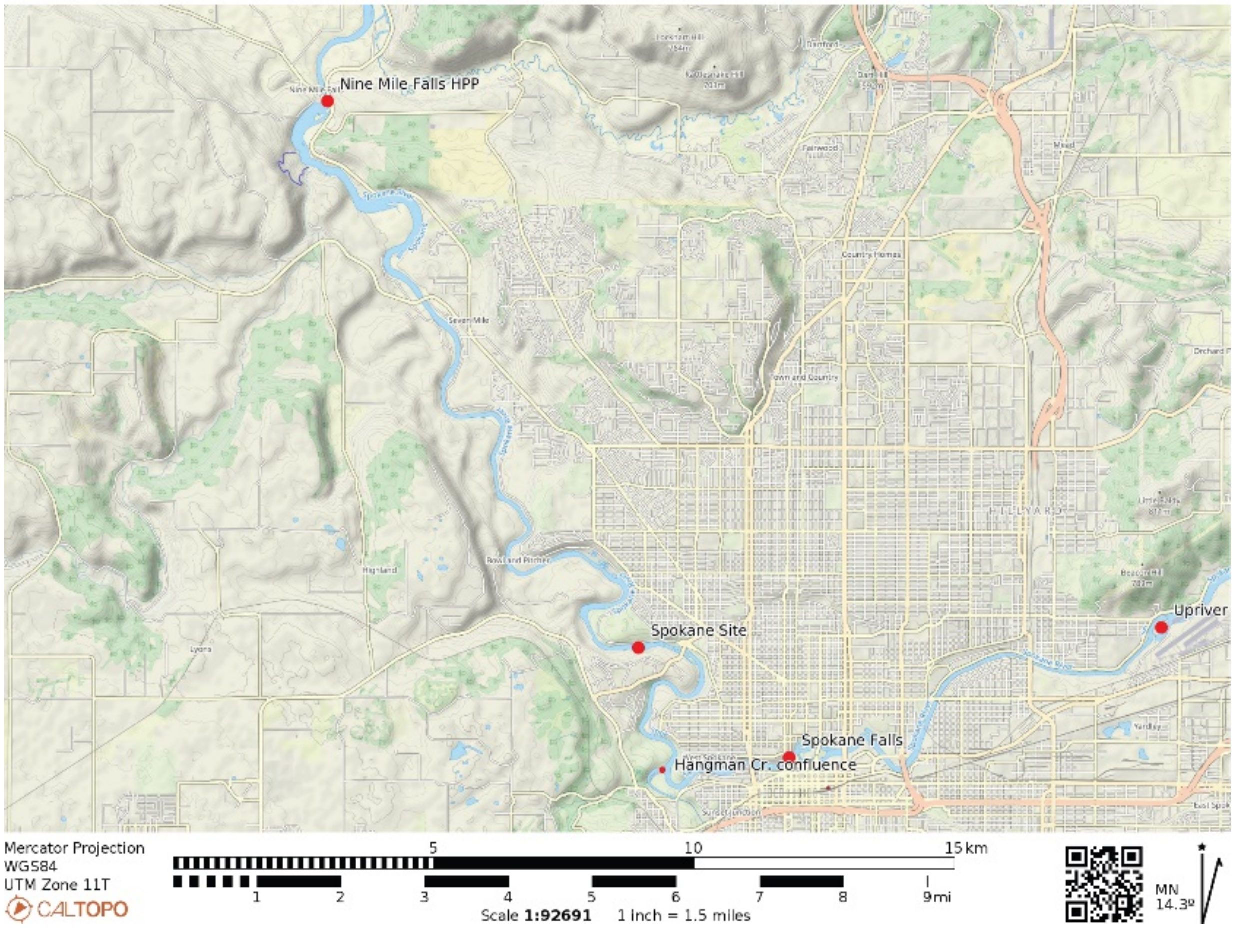

Figure 53: An overview map of Spokane showing the Spokane River Hydropower Project site, Spokane Falls in downtown Spokane, and the location of the Nine Mile Fall hydropower plant.

The dam site is within Downriver Park on the west side of Spokane (Figure 54). Hangman (Latah) Creek enters the Spokane River approximately two miles downstream of Spokane Falls and three miles upriver from the Spokane River HPP dam site. The dam will create an impoundment with a surface area of approximately 120 acres. The head of the impoundment will extend to approximately half a mile from the mouth of Hangman Creek.

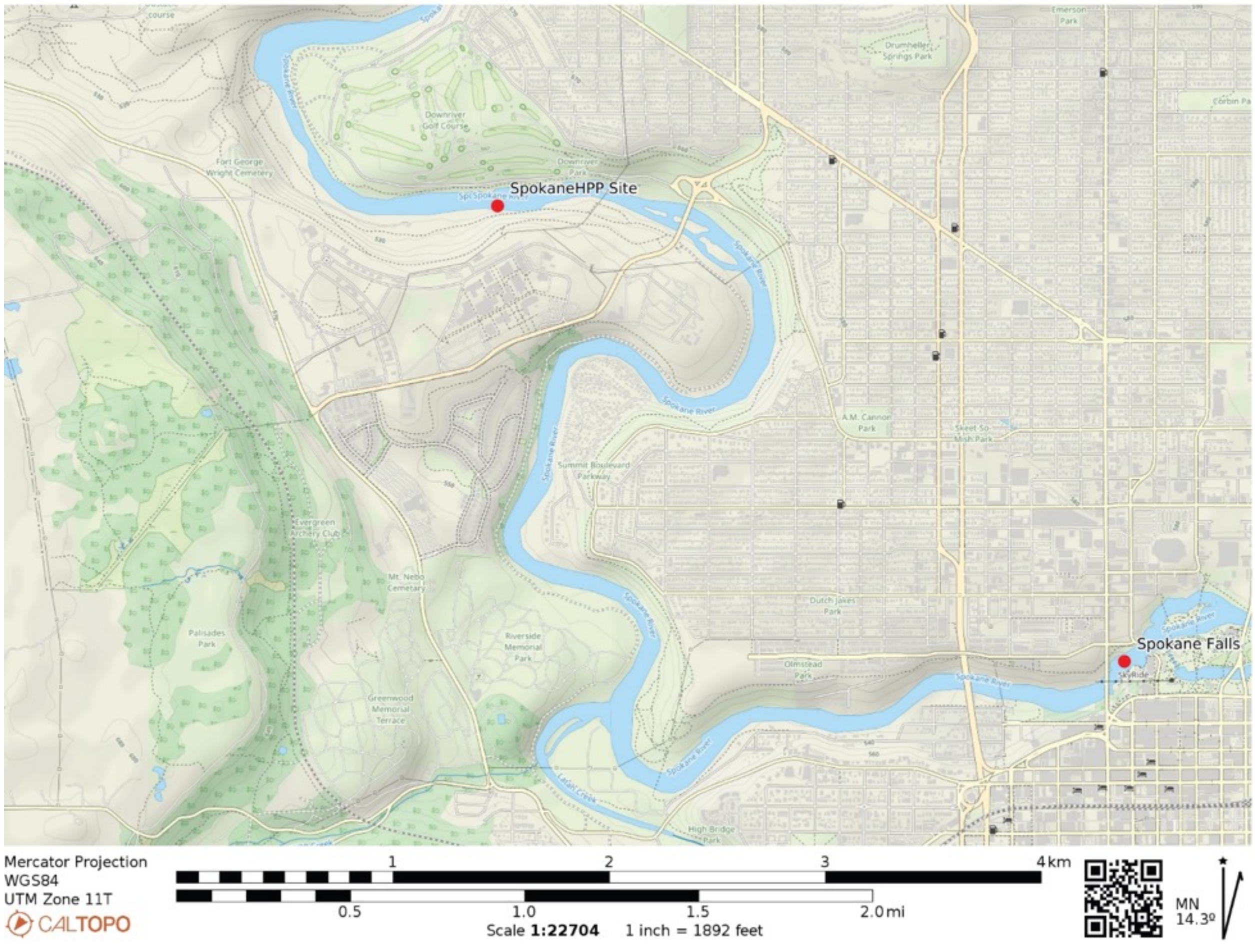

Figure 54: Detailed map of Spokane River hydropower project site on west side of Spokane.

The estimated volume of the future impoundment is approximately $150\ million\ ft3$. Table 23 shows selected streamflow statistics from USGS Station Number 12426000 (Station Name: Spokane River Below Nine Mile Dam at Spokane, WA) and the corresponding hydraulic residence times gave the estimated future pool volume.

Table 23: Flow statistics (USGS Station Number 12426000) and computed hydraulic residence time give an estimated future pool volume of $150\ million\ ft3$.

Statistic	Flow (cfs)	Hydraulic Residence Time
Average Daily	10,000	4.2 hours
50% Duration	4,500	9.3 hours
95% Duration	1,200	1.4 days
Minimum Daily	340	5.2 days

Anadromous salmon and steelhead are no longer present in the Spokane River because Chief Joseph and Grand Coulee dams block upstream migration[13]. While intensive interest in providing passage for anadromous salmon and steelhead at these high-head dams continues[14], the technical challenges are yet to be solved.

Sediment erosion, transport, and fate are significant issues in the Spokane River. Lake Coeur d'Alene, the source of the Spokane River is just approximately 42 miles upriver of the project site and receives very heavy sediment loads; however, the size and depth of the lake and the configuration of the sediment-laden inflows concerning the outflow cause the lake to function as a very effective sediment trap. The sediment yield (sediment delivered per unit drainage area) between Lake Coeur d'Alene and the project site is extremely high, resulting in large sediment loads to the project site.

Hangman Creek is a major source of sediment loading to the Spokane River, which is particularly important because the sediment is delivered to the Spokane River just a half mile upstream of the new impoundment, with no intervening impoundments to sort and sequester sediment before it enters the newly impounded reach. Nine Mile Reservoir, the next impoundment downstream, is small compared to the rate of sediment delivery; consequently, the reservoir has long-ago filled with sediment and is in long-term dynamic equilibrium whereby sediment is resuspended and flushed from the reservoir during periods of high flow and replaced with new deposition during periods of relatively low flow. Northwest Hydraulic Consultants15 estimated that 2.2 million cubic yards of sediment have been deposited with Nine Mile Reservoir since impoundment. A diversion tunnel was constructed in 1997 and 1998 to provide a route for coarse sediment to bypass the turbines and mitigate turbine wear. The new Spokane River hydropower project will intercept this sediment load.

Like the high sediment load in the Spokane River, nutrient concentrations are high. This has potential implications for dissolved oxygen concentrations and GHG emissions. The project area comprises a river reach that is extensively used for water-based recreation.

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[13] Brennan, B.M. 1938. Report of the preliminary investigations into the possible methods of preserving the Columbia River salmon and steelhead at the Grand Coulee Dam. Prepared for the United States Bureau of Reclamation by the State of Washington, Department of Fisheries, in cooperation with the Department of Game, and the United States Bureau of Fisheries. Vol. 121 Numb. L. January 1938.

[14] NPCC (Northwest Power and Conservation Council). 2016. Staff Paper: Review of Fish Passage Technologies at High-Head Dams. Document Number 2016-14. December 2016. 174pp.

[15] NHC (Northwest Hydraulic Consultants). 1999.

Environmental Evaluation

Fish Passage

Potential Impact

The Spokane River hydropower project lies within the historic range of anadromous salmon and steelhead; however, the closure of the Grand Coulee hydropower dam 80 years ago blocked anadromous salmon and steelhead from reaching the Spokane River. Extensive effort has been directed toward R&D to develop technologies to facilitate fish passage at those two high-head dams on the Columbia River; however, success has proven elusive and no practical and effective technology exists at this time to accomplish this feat. Until such technology is developed, anadromous salmon and steelhead will be blocked from the Columbia River and Spokane River above these migration barriers and fishways are not needed for these species, and management agencies with fishway prescription authority defer that authority until circumstances warrant an exercise of the authority. FERC license terms and conditions uniformly include a reopener clause that allows the agency to exercise its fishway prescription authority post-licensing if changed conditions warrant it. Accordingly, license terms for the project almost certainly would not include a fishway prescription; however, a fishway could be prescribed later under a license amendment if circumstances change (i.e., the fish passage becomes a reality at Chief Joseph and Grand Coulee dams).

Mitigation Measures

No mitigation is warranted under current conditions; however, fishway retrofit could be required in the future. The modularity of the project design facilitates fishway retrofit if it becomes necessary.

Sediment Transport

Potential Impact

Based on the observations and experiences at other hydropower projects on the Spokane River, especially at the Nine Mile Falls project, sediment and sediment management will be a significant issue. Sediment delivery from Hangman Creek is particularly significant given the magnitude of the loading and the proximity of the confluence to the head of the newly created impoundment. Sediment accumulation in the newly impounded reach could be rapid. Furthermore, sediment deposition and bed aggradation could begin at the head of the impoundment and progress upstream in a self-reinforcing process culminating in the elevation of the river and creek beds and inundation of areas upstream of the head of the reservoir and mouth of Hangman creek causing localized flooding of low-lying areas.

Mitigation Measures

Sediment management will be critically important to the long-term operation of the hydropower project. Detailed modeling of sediment transport will be valuable for predicting patterns of sediment deposition and mobilization and for devising management and mitigation measures. The full suite of sediment management methods should be considered, including routing, sluicing, flushing, bypass, and drawdown.11 Inclusion of Sediment Passage modules near the bottom of the dam stack will provide flexibility for managing sediment at the project. Appropriately designed hydraulic structures at the Hangman Creek – Spokane River confluence may be useful for discouraging delta formation and riverbed aggradation and routing sediment toward the dam where it can be passed downstream.

GHG Emissions

Potential Impact

The interaction of numerous factors determines the net magnitude and chemical composition of GHG emissions from reservoirs. Methane emissions are of particular concern because methane has a heat-trapping potential of 25 times that of carbon dioxide. Methane emissions are promoted by organic matter-rich, anoxic conditions in which anaerobic decomposition of organic matter produces methane that can escape the water column in gaseous form (ebullition) before it is oxidized.16 Nutrient loading to a lake or reservoir can indirectly promote methane formation by stimulating phytoplankton production that ultimately senesces and sinks into the hypolimnion of a thermally stratified waterbody where it provides the substrate for both aerobic decomposition that consumes available oxygen and produces carbon dioxide and anaerobic decomposition that produces methane. Other factors such as degree and duration of thermal stratification, baseline hypolimnetic oxygen content, the temperature dependence of microbial decomposition rates, and bubble travel time through toxic water can all affect CO2 and methane ebullition. Complicating things further, inorganic suspended sediment can deliver adsorbed nutrients, block sunlight thereby inhibiting light penetration and water column photosynthesis and bury organic matter with inorganic material which can inhibit microbial decomposition. This presents a complex measurement and modeling scenario for quantifying net GHG emissions.

Mitigation Measures

Nutrient delivery to the impoundment is one of the few factors in this scenario tending to promote GHG emissions. Short residence time and limited potential for thermal stratification both tend to diminish the potential for the development of hypolimnetic anoxia and methanogenesis.

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[16] EPRI (Electric Power Research Institute). 2010. The Role of Hydropower Reservoirs in Greenhouse Gas Emissions. Palo Alto, CA. 1017971. May 2010. 108pp.

Water Quality

Potential Impact

The two water quality attributes with the greatest potential for exhibiting adverse effects of impoundment are dissolved oxygen (DO) concentration and water temperature. The discussion of factors mitigating the potential for methanogenesis applies to DO depletion as well: short residence time and hydraulic conditions limiting the potential for thermal stratification limit the potential for DO depletion and discharge of water with low DO concentrations from the impoundment. Likewise, hydraulic mixing and short residence time discourage the development of elevated water temperatures.

Mitigation Measures

While induction of water quality exceedances by the impoundment is unlikely, sediment management can reduce the potential for developing in-reservoir conditions conducive to water temperature elevation and oxygen depletion. Specifically, sediment deposition can be managed, primarily through sediment routing to prevent sediment deposition patterns that promote expanses of shallow static water that would promote microbial decomposition of accumulated organic matter.

Recreational Resources

Potential Impact

The dam and impounded reach straddle a section of the river that receives a substantial amount of water-based recreation. Potential impacts are inundation of existing formal and informal water access points and impairment of downstream movement by the dam. A third potential impact is an inundation of whitewater features of value to boaters.

Mitigation Measures

Mitigation of recreation-related impacts may include the construction of new or improved small boat access points and the inclusion of one or more recreational boat passage modules in the dam stack to facilitate the downstream movement of small boats at the dam.

Environmental Benefits and Enhancements

The project produces environmental benefits and enhancements regarding recreational boating and sediment management. The slack water in the impoundment provides an area of a few acres or less suitable for flatwater watercraft use and improved access to this reach. Storage (both short-term and long-term) of incoming sediment allows for improved sediment management downstream of the impoundment.

Summary

The Spokane River hydropower project has positive and negative attributes. It is located within a 110-mile reach that is regulated for hydropower production. Located upstream of a high-head dam that blocks anadromous salmon and steelhead migrations, it will create a new facility for renewable energy production without impacting anadromous fish migration. If fishways are developed at downstream barriers, fish passage facilities can be retrofitted to this project. The project has both positive and negative effects on recreational boating. Sediment loading and sediment management will be a challenge at this site; if managed poorly there is a potential for the creation of undesirable conditions including localized flooding. Managed effectively the project may improve sediment-related conditions downstream of the project. Effective management of sediment will benefit from detailed sediment transport modeling. The project is unlikely to have adverse effects on GHG emissions, DO concentrations, or water temperature.

APPENDIX – II

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Introduction

Littoral Power Systems (LPS)has developed a preliminary concept for downstream fish passage facilities that can be applied to modular hydropower projects. The designs are based on current knowledge and guidelines for providing effective downstream passage for a range of migratory and resident fishes. However, for east coast applications, these facilities would primarily be installed for reducing turbine entrainment of anadromous American Shad and river herring (Blueback Herring and Alewife, collectively; juveniles and adults) and catadromous American Eel (silver-phase adults). Downstream passage facilities developed for these species and life stages should also benefit a wide range of resident freshwater fishes that may undergo downstream movements at various times throughout the year.

To validate the design concepts and provide recommendations for improvement, Littoral requested Alden to conduct an independent review of the downstream fish passage concept for engineering and hydraulic considerations and biological performance. The results of this review are provided in this technical memorandum.

Design Description

The primary goals for LPS's downstream fish passage design include a net environmental benefit, compliance with regulatory requirements, and maintaining simplicity for permitting and operational considerations. The design is focused on the use of an angled guidance structure with standard trash rack bars or louvered slats. The primary guidelines for the design included the following:

- Bar spacing, approach velocities, and downstream bypass design criteria based on established requirements for species with the most restrictive needs for reducing turbine entrainment.

- Approach velocities (perpendicular to structure) of be about $1.5\ ft/s$ or less for silver American Eel and $2\ ft/s$ for all other species and life stages.

- Clear bar or slat spacing of $0.75\ inches$ for silver eels, $1.00\ inch$ if American Shad and/or river herring are only migratory species present (i.e., no eels), and $1.50\ inches$ if diadromous species are not present.

- Downstream bypasses should be located about every $35\ ft$ along the length of an intake structure depending on structure angle to flow and length. For angled structures (i.e., less than perpendicular to flow), a terminal bypass should be located at the downstream end of the rack or louver array with additional bypasses spaced at approximately $35\ ft$ as needed.

In addition to the above guidelines, Littoral will also take into consideration the ratio of sweeping velocity (theoretical velocity vector parallel to guidance structure) to approach velocity, with higher ratios providing better guidance downstream along a bar rack or louver structure.

Engineering And Hydraulic Review

The relationships between the approach, canal (or channel), and sweeping velocity for the guidance structure concept developed by LPS are appropriate. A cursory review of the head loss approach was completed. LPS proposes to calculate head loss at the intake trash racks using a method described in Spangler (1928) based on laboratory experiments. Several different means of estimating the head loss associated with a trash rack are available. These are based on laboratory experiments and field observations and allow estimates to be made based on bar shape, thickness, general configuration, and operating conditions. In our experience, most methods underestimate losses when applied to an operating hydropower intake. Empirical methods based on laboratory results may not take into consideration the site-specific conditions, such as turbulence, approach flow angle, uneven flow distribution, and debris loading. Of the various empirical methods, the Idel'Chik (1996) method includes variables for real-world applications and results in a more conservative head loss estimate. Alden recommends LPS carefully consider the site-specific conditions and account for debris loading as part of the head loss estimate.

Biological Performance Review

The design guidelines (approach velocity, bar spacing, number of bypasses) that Littoral has cited for downstream passage facilities for use with modular hydropower appear to be consistent with what would typically be required for effectively reducing turbine entrainment and providing downstream passage for the target species (silver eels, shad, river herring, and various freshwater fishes) (USFWS 2019). For each site-specific application of the proposed concept, literature-based estimates of passage efficiency could be developed for each species and life stage using the design constraints stipulated. However, these estimates will vary with the guidance structure angle for shad/herring and other non-eel species.

Silver eels should have guidance efficiencies greater than 90% with any type of bar rack or louver structure (even an existing intake bar rack perpendicular to approach flow) that has 0.75-inch clear bar spacing, approach velocities of less than 2 ft/s (it is the opinion of Alden fish passage engineers and biologists that an approach velocity of 1.5 ft/s or less for silver eels is overly conservative based on existing research), and one or more bypasses at the downstream end of the rack (surface and mid or bottom depth if more than one is installed). For eels, existing intake structures perpendicular to the flow with 0.75-inch clear bar spacing would require bypasses on either end of the intake and possibly in between for very wide intakes.

For juvenile clupeids (shads and herrings), passage efficiency of an angled rack with $1 - inch$ clear bar spacing and approach velocities of $2\ ft/s$ or less will be primarily dependent on the rack angle (typically angled at 45 degrees or less to flow). A $45 - degree$ rack that has the specified bar spacing and approach velocities and a surface bypass at the downstream end will produce passage efficiencies between 60% and 90%. On the other end of the angle spectrum, a $15 - degree$ rack could produce passage efficiencies of 90% or greater, particularly with a clear bar or slat spacings of $1\ inch$. Passage efficiencies for a partial depth $15 - degree$ louver array installed in the Holyoke Canal with a $2.4 - inch$ slat spacing and $1\ ft/s\ to\ 3\ ft/s$ channel velocities depending on canal flow, were reported to be $67\%\ to\ 86\%$ for juvenile shad and herring and 86 to 97% for Atlantic Salmon smolts (Stira and Robinson 1997). The partial-depth louvers were eventually replaced with a full-depth array to accommodate benthic-oriented species (i.e., silver eels and Shortnose Sturgeon). The full-depth structure produced guidance efficiencies of about 80% for silver eels and $55\%\ to\ 100\%$ for sturgeon at canal flow velocities of about $1\ ft/s\ to\ 3\ ft/s$. The current full-depth Holyoke louver array is about $400\ ft$ long with $2 - inch$ clear slat spacing and has a single surface bypass with a ramp leading up from the canal floor at the downstream end. Multiple bypasses along the length of a guidance structure (i.e., every $35\ ft$) should produce higher guidance efficiencies compared to a single bypass at the downstream end.

Based on the results of a laboratory evaluation (Amaral et al. 2001), a $45 - degree$ bar rack structure with $1 - inch$ clear bar spacing will likely have guidance efficiencies of about $30\%\ to\ 60\%$ for various resident fishes at channel velocities of $1\ ft/s\ to\ 3\ ft/s$. This study also reported guidance efficiencies of $55\%\ to\ 100\%$ for resident species evaluated with bar racks and louvers angled at $15\ degrees$ to the flow with $2 - inch$ clear bar spacing and at the same channel velocities. It should be noted that a turbine intake structure may not need to be angled to the approaching flow if clear bar spacing is $0.75\ inches$ (i.e., resource agency criteria for silver eels) and approach velocities are $2\ ft/s$ or less. With these design features, almost all silver eels will be physically excluded from turbine entrainment, and most other species will be either physically and/or behaviorally excluded. Under these circumstances, the number and location of downstream bypasses will be important to providing fish with a reasonable opportunity for bypass discovery and reducing delays in the downstream passage. With clear bar spacings of $1\ inch$ and greater, the need for an angled structure becomes more important for the directional downstream movement of fish (i.e., guidance) towards a bypass entrance while minimizing entrainment.

Bypass System Design Considerations

In addition to approach velocity, guidance structure angle to flow, clear bar/slat spacing, and bypass locations, concepts for angled fish guidance structures will need to incorporate current guidelines for bypass design. Bypass entrance design guidelines are described in USFWS (2019) and include recommendations for entrance configuration and dimensions, conduit diameter, minimum water depths, maximum flow velocities, conduit bend radii, and discharge height and plunge pool depth. Additionally, the flow requirement for downstream bypass systems is typically 5% of a powerhouse (generation) flow but may be as high as 10%. Surface bypass entrances should use design guidelines developed for uniform acceleration weirs (e.g., Alden/NU weir) to reduce rapid accelerations in flow velocity that may elicit avoidance responses from fish. For the same purposes, submerged bypass entrances (e.g., mid-depth or bottom) should be designed with rounded sides or with a bell-mouth opening if possible.

Key Takeaways

- The downstream passage concept developed by LPS for modular hydropower applications uses design standards that are consistent with current recommendations for fish guidance structures installed at hydropower projects (i.e., bar racks and louvers).
- LPS should carefully consider site conditions and potential debris loading in evaluating head loss.
- The target approach flow velocity of $1.5\ ft/s$ or less for silver eels may be overly conservative based on available research. In general, a target of $2\ ft/s$ or less should be sufficient for silver eels, as well as all species and life stages of anadromous fish species found in east coast rivers.
- The angle of a guidance structure to approaching flow should be between $15\ to\ 45\ degrees$. Guidance efficiency will increase with decreasing angles.
- Target bar spacings are appropriate for the diadromous and resident fish species being considered. However, if a clear bar spacing of $0.75\ inches$ is selected because American Eel is present, an intake structure does not need to be angled because nearly all silver eels will be physically excluded from entrainment and a high percentage of other species will be either physically or behaviorally excluded. In the absence of an angled structure, additional bypasses will need to be located along the length of an intake to allow discovery and downstream passage promptly.
- Downstream bypass systems will also need to be designed following current resource agency guidelines.
- Downstream passage efficiencies of angled guidance structures may vary from about 50 to 100% depending on clear bar spacing, structure angle, bypass locations, approach flow velocities, and species and life stage (i.e., fish size).
- Overall biological performance of downstream passage facilities should be determined for total downstream passage survival at any given project. This will allow LPS to determine if a proposed design will meet fishery management goals for migratory or resident species populations. Total project survival can be estimated for a defined migration season or over a year by determining route-specific passage and survival rates (i.e., spillway, fish bypasses, turbines) over the range of expected river discharges for a specified time. If a substantial proportion of fish passes over a dam or through gates during periods of a spill, and/or turbine survival is high, total project survival could reach levels considered appropriate for target species even if guidance efficiencies are at the low end of the expected range (e.g., 50%).