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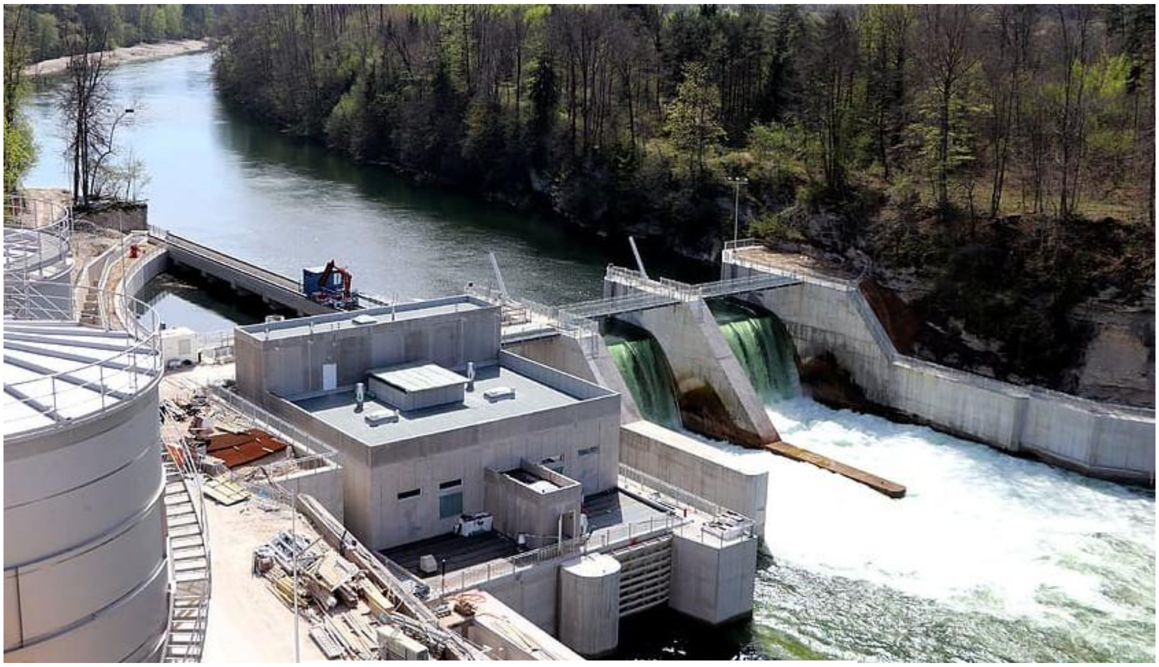
A Reduced-form Cost Model for Prefeasibility Analysis of Hydropower at Non-Powered Dams



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September 2024

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Environmental Sciences Division

A REDUCED-FORM COST MODEL FOR PRE-FEASIBILITY ANALYSIS OF HYDROPOWER AT NON-POWERED DAMS

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September 2024

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CapEx	Capital expenditures per kilowatt
DOE	US Department of Energy
EIA	Energy Information Administration
FERC	Federal Electricity Regulatory Commission
IRENA	Internal Agency for Renewable Energy
LCOE	Levelized cost of energy
NID	National Inventory of Dams
NPD	Non-powered dam
O&M	Operations and maintenance
ORNL	Oak Ridge National Laboratory
PSH	Pumped storage hydropower
RS	Reference System
USACE	US Army Corps of Engineers

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EXECUTIVE SUMMARY

Overview and Scope

This study presents a reduced-form model to support a better understanding of the capacity potential and drivers of costs for hydropower development at U.S. non-powered dams (NPD), which are existing dams that are not currently used for hydropower. With information on nineteen reference sites, a set of reduced-form design and cost equations were estimated to enable rapid assessments of aggregate costs and their components for a large number of NPD sites. The model was then applied to 36,000+ potential U.S. NPD sites using the limited data commonly available. Although the cost estimates span a wide range, there exists a significant amount of U.S. NPD hydropower capacity potential, which are considered cost-competitive in the current market using baseline technologies.

Objectives

The global demand for clean electricity to meet greenhouse gas (GHG) emission targets is increasing. Hydropower is the oldest renewable source of electricity and is well suited to providing energy and ancillary grid services to support carbon reduction targets. There are more than 90,000 NPD sites that could potentially increase U.S. hydropower capacity, which stands at about 103 GW of conventional and pumped storage hydropower (PSH) from less than 2,500 dams in 2023. However, new hydropower development at NPD sites is challenged by many factors that lead to much higher costs relative to the large existing hydropower sites which benefited from economies of scale and generous public support at the time of their initial development. Addressing these challenges toward increasing the contribution of hydropower to future U.S. sustainable electricity supply requires innovative technologies and approaches to reduce the costs of construction and operation, and minimize potential environmental impacts. The objective of this study is to provide insights into the relative capacity potential and costs of U.S. NPD hydropower, and the drivers of these costs under baseline design conditions. These baseline cost assessments are the basis for identifying new technologies and approaches to overcome current challenges to U.S. NPD hydropower development and serve as a starting point for more detailed evaluation of individual sites.

Methods

Existing approaches for evaluating potential hydropower development at U.S. NPD sites are either based on detailed engineering design and cost assessments, which require vast amounts of data, resources, and time, or aggregate models using simplified functions of water flow and head. Although these two approaches are applicable in many instances, the time- and resource-intensive requirements of the detailed approach and the lack of detail under the aggregate approach are disadvantages when evaluating a large number of sites with limited data. The model developed in this study strikes a balance between these two approaches by providing a method to gain insights into the costs of hydropower at NPD sites using the limited available data, and can be applied to a large number of sites.

The model can be described as a reduced-form NPD Hydropower Cost Model (*NPDHCM)*. We specified and estimated a set of design and cost equations for hydropower components using detailed simulation results for nineteen reference U.S. NPD sites. These equations can be combined with available data to evaluate NPD designs and costs for many sites at a time. Thus, the model was applied to a large number of U.S. NPD sites to provide insights into relative aggregate costs and components across the sites.

This study also provides an Excel workbook to make the NPDHCM accessible to stakeholders for evaluating the costs of hydropower at U.S. NPD sites. This tool estimates pre-feasibility design and costs for NPD sites, supporting the needs of developers, policy-makers, and researchers to better understand the drivers of hydropower costs and components.

Key Findings

The key finding of this study is that there are significant cost-competitive capacity potentials at U.S. NPD sites given the baseline design options and the available data. The results also imply that there are significant differences between lake and lock dams in the number of potential sites, capacity distributions, capital expenditures, and LCOE estimates. Specific additional findings of the analysis include the following:

- The estimated **coefficients of the NPDHCM show that the variables included in the equations are useful for explaining variations in NPD hydropower design and cost variables**. Most coefficients are significant, and signs are as expected.

- **Nearly 14,000 sites out of the initial 36,000+ sites included in the model application fall below a capital expenditure bar of $100,000/kW, of which 13,470 are lake dams and only 147 are lock dams.** The high capital expenditure bar was used to account for uncertainties resulting from both the data and the model. Small water flow and head resources at many of these sites lead to large per kW capital cost estimates.

- **Slightly over 900 sites (about 3% of the initial 36,000+sites) have LCOE estimates of less than $0.40/kWh.** The LCOE threshold of $0.40/kWh is about twice the upper bound for existing North American hydropower. These sites have a total estimated capacity of about 3 GW (or ~3 MW per site); 791 are lake dams with a total capacity estimate of 1,462 MW and 123 are lock dams with a total capacity estimate of 1,585 MW. Most of these sites are in the Eastern U.S. but a considerable number are also in the Western U.S.

- Estimates for the 900+ sites were divided into four LCOE categories, with the first two groups being competitive or marginally competitive, and the other two groups potentially requiring significant innovations to be competitive. **Most of the capacity potentials fall in the second and third groups (LCOE estimates between $0.09/kWh and $0.25/kWh).**

- **In the most competitive group (LCOE less than $0.09/kWh), 12 of the sites are lake dams and only 2 are lock dams** but the average potential capacity per site for lock dams is higher (~42 MW) than for lake dams (~15 MW).

- **Nearly 80% of the sites, 47 of 61, in the US hydropower development pipeline data have estimated LCOE values less than $0.40/kWh** with about half under $0.15/kWh. Of the 47 sites, 36 are lock dams.

Data Sources

The data employed for the analysis in this study comes from several sources. Information for the nineteen reference sites used to estimate the NPDHCM equations were from a previous study by the authors (Oladosu et al., 2021). The ORNL 2012 resource assessment (Hadjerioua et al., 2012) which included about 54,000 U.S. NPD sites was used as the starting point for the sites included in the application of the NPDHCM. The *Dayflow* data (Ghimire et al., 2023), which includes daily and monthly stream discharge estimates from 1980 to 2015, provided daily stream flow data for the 36,000+ sites evaluated with the model. The *NID* dataset (USACE, 2024) provided information on other inputs for the model application, such as dam height, lake/lock dam indicators, and dam construction types.

Limitations and Next Steps

The key limitations of this study are related to the lack of complete and detailed information for NPD sites. Thus, a small number of sites were used for the estimation of the NPDHCM equations, which were in turn based on preliminary engineering design and cost assessment, rather than actual data. This required the equations to be highly parsimonious to preserve a reasonable degree of freedom for the estimation. In addition, while the reference sites span a wide range of U.S. NPD site features and water resources potential, the variation captured in these sites cannot fully reflect those of the U.S. NPD population. Given their engineering foundations, the estimated NPDHCM equations are appropriate for a calibration-type approach to hydropower cost modeling, but a larger and more complete dataset would support more precise estimation of model coefficients and evaluation of a larger set of determinant variables. Since the premise of this study was to address stakeholder needs under these data constraints, the limitations are motivations for next steps. The modeling approach is amenable to incremental improvements by including more data for estimating the model equations and using more accurate dam and water resources data when exercising the model. Therefore, future efforts would include 1) collecting additional detailed data on hydropower sites to supplement the reference sites used in the current study; 2) improving model specifications based on additional data; 3) incorporating new functionalities in the Workbook tool to support users.

1. INTRODUCTION

Hydropower is the oldest renewable source of electricity generation in the US, contributing about 103 GW of capacity, including 81 GW of conventional and 22 GW of pumped storage, to the national grid in 2023 (Uria-Martinez et al., 2024). However, the development of new hydropower projects has slowed down over the last few decades, primarily because the most competitive sites have already been developed. In addition, and in common with most energy development projects, new hydropower projects face stricter environmental and financial constraints than in previous decades. Still, new hydropower developments would be key to meeting future US electricity needs as the demand for clean renewable electricity is expected to increase dramatically over the next few decades to meet ambitious greenhouse gas (GHG) emission reductions targets (EIA, 2023). These GHG reduction targets will require a rapid increase in electricity generation from ultra-low-carbon renewable resources, such as wind and solar, which have the disadvantage of variable generation and the inability to provide ancillary services necessary for long-term grid reliability and supply security. Hydropower is well suited to providing ancillary grid services, and pumped storage hydropower (PSH) plants are the only commercial long-term duration energy storage technologies currently available.

Non-powered dams (NPD), which are dams that do not currently produce electricity, represent one of the near-term options for adding new US hydropower capacity. Of the 90,000+ dams in the US, less than 2,500 are used to produce hydropower. Many of the remaining NPD sites are characterized by small capacity potentials because of limited and highly variable water flow and head. A preliminary estimate of the capacity potential from nearly 54,000 of the remaining dams is about 12 GW (Hadjerioua et al., 2012), representing an overall average of less than 250 kW per site relative to an average of 36 MW for existing US hydropower projects. NPD sites are also characterized by a variety of dam features that were initially designed for non-hydropower purposes. These features may require dam modifications and non-optimal project designs relative to an entirely new hydropower development. In addition, stricter environmental requirements to reduce barriers to fish passage and health, as well as other ecosystem impacts, can lead to cost-prohibitive options for NPD hydropower. Therefore, increasing the pace of US NPD hydropower development requires innovations to reduce construction and operating costs, as well as minimize or avoid environmental impacts in accordance with regulatory requirements. A basic step for identifying such innovations is to develop a better understanding of requirements at these prospective sites under baseline conditions - that is, using currently commercially available technologies. Such analyses would provide greater insights into the relative capacity potential at each site, the drivers of hydropower costs and components, and the cost-reduction potential of innovations to accelerate the development of new NPD hydropower projects. On the one hand, aggregate methods using simple relationships between capacity, flow, and head cannot provide such insights for prospective hydropower sites. On the other hand, the detailed engineering design and cost analysis approach necessary to gain such insights is infeasible when evaluating a large number of sites with limited data and other resources.

This study presents an approach that strikes a balance between the detailed, but information- and cost-intensive, approaches usually needed for understanding the drivers of hydropower costs and the ease of use, but little detail, provided by aggregate cost evaluation methods. The approach uses the results of simulations based on initial engineering designs and cost assessments for representative NPD hydropower sites, referred to as reference sites, to derive a set of reduced-form equations. The resulting reduced-form model can be used to evaluate pre-feasibility costs for hundreds or thousands of sites with limited information while providing insights into the determinants of cost components. The rest of the paper is arranged as follows. The next section presents the reduced-form model, followed by an overview of the estimated coefficients of the model's equations. An application of the model to 36,000+ US NPD sites is then provided to illustrate the use of the model. The paper ends with conclusions.

2. A REDUCED-FORM NPD HYDROPOWER COST MODEL

2.1 AN OVERVIEW OF METHODS FOR NPD HYDROPOWER COST MODELING

Existing approaches for evaluating hydropower costs fall into two broad categories as illustrated in Figure 1. Panel (a) of Figure 1 illustrates the detailed engineering designs and cost assessments, which are usually performed to support investment decisions and regulatory processes (FERC, 2023). These detailed assessments require an extensive and costly set of cross-disciplinary expertise and activities, and the outputs of such efforts are often closely guided, proprietary information. Initial pre-feasibility and feasibility analyses are used to evaluate the potential viability and costs of a hydropower project before the investment decision and final regulatory approval stages. The cost estimates from a pre-feasibility assessment would be significantly different (e.g. +/-50 percent) from those from a detailed assessment. Yet, pre-feasibility cost estimates serve an important purpose in the project development process by providing insights into the potential magnitude of project costs, as well as justifying the value of more detailed assessments.

Pre-feasibility hydropower cost assessments can be performed using a number of approaches. One approach, akin to the detailed assessments used to support investment decisions, uses simulation models that combine engineering or volumetric design/cost equations with preliminary data on infrastructure features and water resources (Masoudinia, 2013; Oladosu et al., 2021). This approach to pre-feasibility cost assessment, though less costly and resource-intensive than for investment decisions, still requires significant information on site characteristics, water resource conditions, and plant design requirements. The most common approach for the pre-feasibility hydropower cost assessments often for academic or initial development appraisals uses aggregate equations to estimate total hydropower costs and its components based on limited data on water flow, head, and capacity as illustrated in panel (b) of Figure 1 (O'Connor et al., 2015; Oladosu and Sasthav, 2023; Tsuanyo et al., 2023).

Identifying innovations to accelerate NPD hydropower development in the US recommends cost analysis approaches based on detailed site-specific and engineering design information. However, the information, engineering, and computation requirements, as well as the implementation costs of these approaches, mean that they cannot be easily applied to hundreds or thousands of sites. In particular, even with the hundreds of variables available in the US National Inventory of Dams (NID, (USACE, 2024)) and other datasets, detailed information for evaluating site-specific project design requirements and costs remains limited. Cost assessments based on aggregate equations or simple averages of capacity, flow, and head, though much easier to use, provide little insights into the drivers of costs and opportunities for technological innovation at these sites. In addition, because aggregate cost methods are based on existing hydropower plant information, the estimates from such models reflect the advantages of larger scales and lower variability of water resources relative to prospective NPD hydropower sites. Therefore, cost estimates from such aggregate models would be typically lower than the costs of developing prospective NPD hydropower sites.

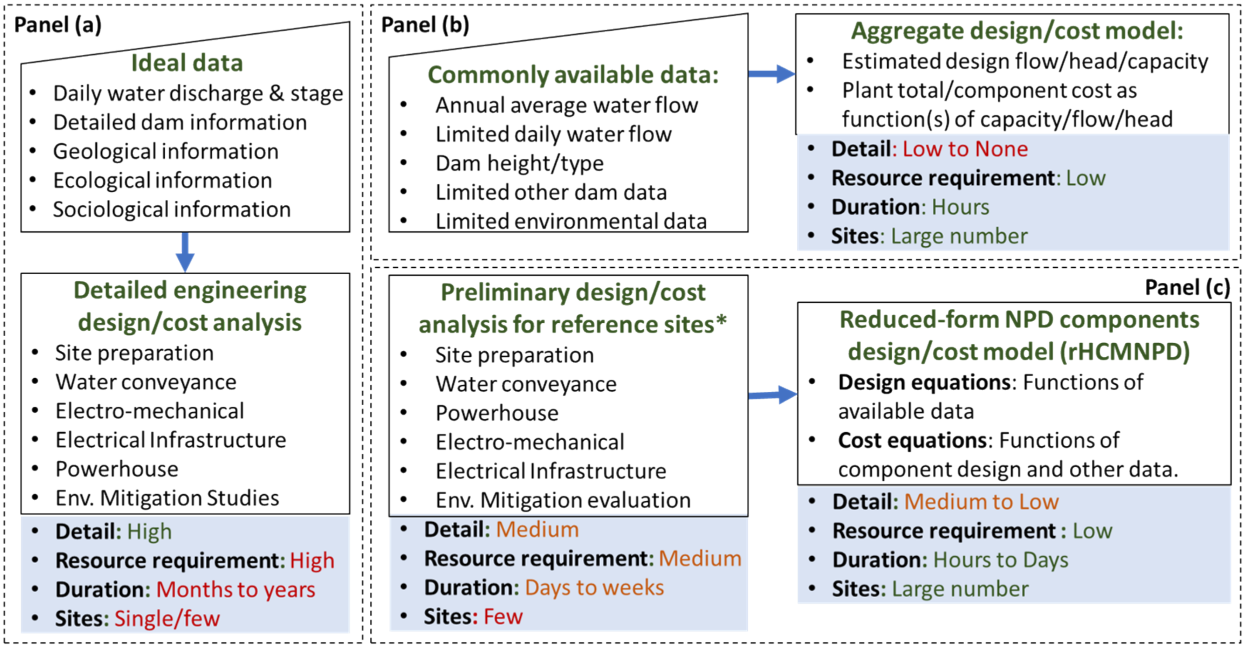

Figure 1 Comparison of detailed, aggregate and study approaches to NPD hydropower cost assessment

This study uses a Reference System (RS) approach to evaluate the baseline cost of developing hydropower from the variety of US NPD sites using commercially available technologies to serve as the basis for evaluating innovation needs and benefits. A RS uses a representative but smaller set of examples, real or theoretical, members to capture the typical attributes of a large population (Corgnati et al., 2013). The RS approach is useful for benchmarking, standardizing, and classifying members of a large population defined by multiple, varying attributes (Corgnati et al., 2013; Hwang et al., 2012; Jamasb and Pollitt, 2008). For hydropower cost analysis, the RS approach circumvents the dimensionality problem by enabling the evaluation of a small set of reference sites whose cost functions can be then extended to the population segment most similar to each site (Corgnati et al., 2013). For application to NPD hydropower, the RS cost evaluation approach can be described as a three-step process:

1. Selection of the reference NPD sites.
2. Detailed evaluation of costs for each reference NPD site.
3. Extension of the reference cost functions to the population of NPD sites.

The first two steps were implemented and reported in a previous study (Oladosu et al., 2021), and the list of reference sites and typical baseline design options for these sites are included in Appendix A. The third step can be implemented in a variety of ways, with the default being a simple extrapolation of the cost estimates for a representative member to its segment of the population of NPD sites. However, such a simple extrapolation would not match the purpose of gaining insights into the multiple site-specific attributes that drive the cost of NPD hydropower in the US. Thus, the extension of the reference site cost analysis is based on a reduced-form model, as discussed in the rest of this section.

2.2 SPECIFICATION OF THE REDUCED-FORM NPD HYDROPOWER COST MODEL

The reduced-form NPD hydropower cost model (*NPDHCM*) discussed in this study is a fusion of the ideal and aggregate hydropower cost analysis methods and is illustrated in panel (c) of Figure 1. In other words, results of the preliminary design and cost analysis of reference sites are translated into a reduced-form model consisting of a set of econometric equations. The model can be easily applied to a large number of sites using commonly available data, yet is capable of providing insights into how cost components change with NPD site features and water resources. This approach recognizes that commonly available NPD site and water resources data are, if imprecise, reflections of their more detailed counterparts. For example, the height of a dam is correlated with its hydraulic height (or head) and/or the water conveyance requirements under common hydropower configurations. On this basis, previous NPD analyses have estimated the design head at NPD sites by adjusting the dam height. This study builds on these approaches by accounting for other important determinants of hydropower design and cost, limited by the available data and the reference site results.

2.2.1 Model Variables and Parameters

Table 1 defines the hydropower design and cost variables calculated for a project in the *NPDHCM*. The design variables are flow, head, number of units, length of water conveyance, plant capacity, and capacity factor. The cost variables include powerhouse, electro-mechanical, electrical infrastructure, site preparation, water conveyance, engineering and management, environmental, capital, and development costs, all in per kW terms. In addition, equations for the capital recovery factor and the levelized cost of energy (LCOE), as well as the annual operation and maintenance cost, based on the 2015 hydropower Baseline Cost Model (BCM)(O'Connor et al., 2015), are included in the model.

Table 1 Definition of endogenous model variables

Endogenous model variables	
Design variables	**Cost variables**
$\mathbf{Q_d}$ = Design flow (cfs)	**PH** = Powerhouse cost ($/kW)
$\mathbf{H_d}$ = Design head (ft)	**EM** = Electro-mechanical cost ($/kW)
$\mathbf{U_d}$ = Number of generating units (cfs)	**EI** = Electrical infrastructure cost ($/kW)
$\mathbf{L_d}$ = Water conveyance length (ft)	**SP** = Site preparation cost ($/kW)
$\mathbf{Cap_d}$ = Design capacity (MW)	**WC** = Water conveyance cost ($/kW/ft)
CapFac = Capacity factor	**ENV** = Environmental mitigation cost ($/kW)
	ENG = Eng.&Const. Mgmt. cost ($/kW)
	CAPEx = Capital expenditure (Initial capital cost) ($/kW)
	DEV = Development cost ($/kW)
	KRFact = Capital recovery factor
	LCOE = Levelized cost of energy ($/kWh)
	annOM = Annual operation and maintenance cost ($/kW)

Table 2 provides the list of exogenous input data for the *NPDHCM*, including water resources (flow and head), dam attributes, turbine requirement, interconnection requirement, financial variables and the reference values of certain variables. The median, as well as the 10^{th}, 30^{th}, 70^{th}, and 90th percentile values, are used to characterize water flow and hydraulic head for an NPD site. Dam attributes are represented by the dam height, non-exclusive dummy variables of dam construction types, and exclusive dummy variables indicating whether the dam is of the lock or lake type. The dam construction dummy variables are non-exclusive because a given dam may include multiple types. The lock or lake dummies capture important differences between these two types of dams and represent the two broad hydropower design categories considered in the reference sites analysis results (Oladosu et al., 2021) used in the current study[1]. In addition to other purposes, lock dams are typically used for navigation and generally have very high flows and lower heads than lake dams. Lake dam is used in this study as a general reference to dams with active water storage reservoirs that are not connected to navigation locks. Interconnection requirements are indicated by the straight-line distance from the NPD site to the nearest substation, mainly reflecting the need for transmission lines. The turbine requirement for a site is specified with exclusive dummy variables indicating whether a Kaplan, Bulb, or Francis turbine is required. These three turbine classes are the most appropriate for the vast majority of US NPD sites, with lock dam sites typically based on Bulb turbines. The two financial input data used in the model are the real discount rate and capital recovery period. Finally, the *NPDHCM* uses the reference site values of certain exogenous and endogenous variables in the calculations. These include the 90^{th} and 10^{th} percentile ratios of water flow and hydraulic head, and the design values of flow, head, capacity, and capacity factor. The reference site name is used to select the corresponding reference values for a given NPD site.

Table 2 Definition of exogenous model inputs

Exogenous input data	
Water resource data	**Turbine data**
$\mathbf{Q}_{med}$ = Median flow (cfs)	$\mathbf{d}_{kpl}$ = 1 (Kaplan); 0 (Otherwise)
$\mathbf{Q}_{10}$, $\mathbf{Q}_{30}$, $\mathbf{Q}_{70}$ & $\mathbf{Q}_{90}$ = 10^{th},30^{th},70^{th} & 90^{th} percentile flow (cfs)	$\mathbf{d}_{blb}$ = 1 (Bulb); 0 (Otherwise)
$\mathbf{Q}_{9010}$ & $\mathbf{Q}_{7030}$ = Ratio of $\mathbf{Q}_{90}$ to $\mathbf{Q}_{10}$ & $\mathbf{Q}_{70}$ to $\mathbf{Q}_{30}$	$\mathbf{d}_{frn}$ = 1 (Francis); 0 (Otherwise)
$\mathbf{H}_{med}$ = Median head (ft)	**Financial data**
$\mathbf{H}_{10}$, $\mathbf{H}_{30}$, H_{70} & $\mathbf{H}_{90}$ = 10^{th},30^{th},70^{th} & 90^{th} percentile head (ft)	**r** = Real discount rate (%)
$\mathbf{H}_{9010}$ & $\mathbf{H}_{7030}$ = Ratio of $\mathbf{H}_{90}$ to $\mathbf{H}_{10}$ & $\mathbf{H}_{70}$ to $\mathbf{H}_{30}$	**T** = Capital recovery period (years)
Dam attributes data	**Reference site data**
NIDH = National Inventory of Dams (NID) height	**RefName** =Reference site name
$\mathbf{d}_{grv}$ = 1 (Gravity dam); 0 (Otherwise)	$\mathbf{Q}_{dref}$ = Reference site $\mathbf{Q}_{d}$
$\mathbf{d}_{emb}$ = 1 (Embankment dam); 0 (Otherwise)	$\mathbf{H}_{dref}$ = Reference site $\mathbf{H}_{d}$
$\mathbf{d}_{cnc}$ = 1 (Concrete dam); 0 (Otherwise)	$\mathbf{Q}_{9010ref}$ = Reference site $\mathbf{Q}_{9010}$
$\mathbf{d}_{lk}$ = 1 (Lake site); 0 (Otherwise)	$\mathbf{H}_{9010ref}$ = Reference site $\mathbf{H}_{9010}$
$\mathbf{d}_{lc}$ = 1 (Lock site); 0 (Otherwise)	$\mathbf{CapFac}_{ref}$ = Reference site capacity factor
Interconnection data	$\mathbf{Cap}_{dref}$ = Reference site design capacity
$\mathbf{SB}_{ds}$ = Site distance from nearest substation (miles)	

Table 3 defines the parameters of the model, which can be categorized into intercepts, scaling factors, and coefficients on model variables. Intercepts and scaling factors have a single index associated with the

[1] https://info.ornl.gov/sites/publications/Files/Pub145012.pdf

corresponding model variable or equation. The coefficients on model variables have two indices. The first index identifies the corresponding model variable or equation, while the second index identifies exogenous input variables, and endogenous variables that are calculated within the model but also used as inputs in another equation. Intercepts are estimated at the same time as the coefficients on model variables as applicable, whereas scaling factors are calculated as the post-estimation ratio of the actual value and its prediction by the model for each reference site. These factors provide a measure of the accuracy of the equations for each reference site. They are also used to scale predictions for a given NPD site to eliminate the effects of differences in the accuracy of each equation relative to its corresponding reference site and can be interpreted as calibration parameters.

Table 3 Definition of model parameters and indices

Model parameters	
$\boldsymbol{\alpha_k}$ = Intercept terms for model equation *k* (see parameter indices below)	
$\boldsymbol{\beta_{k,j}}$ = Coefficient estimate for model variable *j* in model equation *k*.	
$\boldsymbol{\gamma_k}$ = Scaling parameter as the ratio of actual to fitted values of reference site variables for model equation *k*	
Parameter indices	
Note: When two indices from the list below are combined with an underscore ("_"), it refers to the coefficient of the interaction of two inputs/variables e.g. "*lk_q*" refers to the interaction of variables with indices "*lk*" and "*q*".	
q = flow	*qmed* = site median flow
h = head	*hmed* = site median head
u = number of units	*q7030* = site 70th to 30th percentile flow ratio
l = conveyance length	*h9010* = site 90th to 10th percentile head ratio
cap = capacity	*sb* = Substation
ph = powerhouse	*lk* = Lake dam
em = electromechanical	*lc* = Lock dam
ei = electrical infrastructure	*nidh* = NID height
sp = site preparation	*grv* = Gravity dam
wc = water conveyance	*emb* = Embankment dam
dev = development	*cnc* = Concrete dam
ref = auxiliary index to indicate Reference site	*blb* = Bulb turbine
capfac = capacity factor	*frn* = Francis turbine

2.2.2 Design Equations

Given that there are only nineteen sites in the reference cost analysis data used to estimate the *NPDHCM* coefficients in this study, the model equations are specified to be parsimonious while capturing important determinants of NPD design and costs. Most of the equations are specified using exponential functions, but note that the natural logarithm transformation of most of the continuous variables means that they are essentially power functions, which were found to produce the best fits during the model estimation process. The design flow in equation (1) is a function of the median flow and the ratio of its 70^{th} and 30^{th} percentiles, as well as the lock dam indicator. Similarly, the design head in equation (2) is a function of the median hydraulic head and the ratio of its 90^{th} and 10^{th} percentiles and the lock dam indicator. The percentile values in these equations reflect the role of water resource variations in hydropower design flow and head levels. The lock dam indicator reflects differences in the very high flow and low hydraulic heads of lock dams relative to lake dams, which tend to have a wider range of flow and head values. The number of generating units is estimated in equation (3) as the product of the design flow and a negative exponential function of indicators for Bulb or Francis turbines, as well as lake and lock indicators interacted with the natural logarithm of the design flow. The Kaplan turbine is the base case, with its number of units estimated from equation (3) when the Bulb and Francis turbine indicators are set to 0.

The length of the water conveyance in equation (4) is a function of the dam height, design flow, and dam construction type indicators. Detailed information on dam design for US NPD sites is scarce but crucial to determining requirements for water conveyance between the dam and the powerhouse. In the absence of this information, the pre-feasibility equations in this study use the dam height, which is commonly available, as a dimensioning variable for water conveyance requirements. The dam height interacts with the lake and lock indicators in equation (4) to differentiate the coefficients for the two dam groups. Given the variety and site-specific options for moving water from the dam to the powerhouse, equation (4) is unlikely to provide a general representation of its physical counterpart in NPD hydropower design, rather serving as relative measures for comparing multiple sites.

Equation (5) calculates plant capacity for a given NPD site by scaling the value for its reference site by the ratio of its nominal design capacity, defined as the product of design flow and head, to that for its reference site. Equation (6) estimates the capacity factor as a function of the site's design flow, the ratio of its 70th to 30th percentile flow, the ratio of its 90th to 10th percentile head, and the interaction of the latter with the design head. Since the capacity factor of a hydropower plant depends on many other variables apart from flow and head, lower and upper bounds of 10% and 70% are imposed when using equation (6) for the calculations in *NPDHCM*.

Design flow (cfs):

$$Q_d = \gamma_q e^{\left(\beta_{q,lk} d_{lk} + \beta_{q,qmed} lnQ_{med} + \beta_{q,q7030} lnQ_{7030}\right)} \quad (1)$$

Design head (ft):

$$H_d = \gamma_h e^{\left(\alpha_h + \beta_{h,lk} d_{lk} + \beta_{h,hmed} lnH_{med} + \beta_{h,h9010} lnH_{9010}\right)} \quad (2)$$

Number of units (cfs):

$$U_d = \gamma_u Q_d e^{-\left(\alpha_u + \left[\beta_{u,lk\_q} d_{lk} + \beta_{u,lc\_q} d_{lc}\right] lnQ_d + \beta_{u,blb} d_{blb} + \beta_{u,frn} d_{frn}\right)} \quad (3)$$

Conveyance length (ft):

$$L_d = \gamma_l e^{\left(\begin{array}{c}\alpha_l + \beta_{l,qmed} lnQ_{med} + \left[\beta_{l,lk\_nidh} d_{lk} + \beta_{l,lc\_nidh} d_{lc}\right] lnNIDH \\ + \beta_{l,grv} d_{grv} + \beta_{l,emb} d_{emb} + \beta_{l,cnc} d_{cnc} + \beta_{l,emb\_grv} d_{emb} d_{grv}\end{array}\right)} \quad (4)$$

Design capacity (MW):

$$Cap_d = Cap_{dref}\left(\frac{Q_d H_d}{Q_{dref} H_{dref}}\right) \quad (5)$$

Capacity factor:

$$CapFac = \gamma_{capfac} e^{\left(\begin{array}{c}\alpha_{capfac} + \beta_{capfac,q} lnQ_d + \beta_{capfac,q7030} lnQ_{7030} \\ + \beta_{capfac,h9010} lnH_{9010} + \beta_{capfac,h\_h9010} lnH_d lnH_{9010}\end{array}\right)} \quad (6)$$

2.2.3 Cost Equations

Equations (7) to (11) are cost functions with specifications similar to equations (1) to (4), while equations (12) to (15) are identities or proportional functions of other cost components. Equation (7) estimates the per kW site preparation cost as a function of design flow interacted with lock/lake indicators, design head, and Bulb/Francis turbine indicators. These variables determine the potential footprint of a hydropower plant and the differences between lock and lake dams, which affect site preparation requirements. Equation (8) estimates the per kW water conveyance cost as a product of the water conveyance length and a multiplier that is different for lake and lock dams. Note that this equation reflects the baseline designs captured in the data used in this study i.e., lake dam NPD hydropower water conveyances are based on lining dam outlets with steel and penstock, whereas lock dam NPD hydropower conveyances are based on power canals with short penstocks.

Equation (9) estimates the per kW cost of an NPD hydropower powerhouse as a function of the design flow, head, number of units, and Bulb/Francis turbine indicators. Equation (10) specifies the electro-mechanical cost (turbine, generator, and associated control equipment) as a function of the design capacity, design head, number of units, and Bulb/Francis turbine indicators. These specifications reflect the role of turbine types, number of units, and the combination of capacity, flow, and head levels in determining the requirements and size of hydropower equipment and its powerhouse and, consequently, the costs. Bulb turbines are used for NPD hydropower at lock dams, whereas Kaplan or Francis turbines are used for lake dams in the baseline data used in this study. The per kW cost of electrical infrastructure to connect a hydropower plant to the transmission system is specified in equation (11) as the ratio of a linear function of design capacity, straight-line distance to the nearest substation and their interaction to the design capacity. The design capacity reflects the required electrical capacity of interconnection equipment, while the distance to a substation is an indicator of the transmission requirement, with the interaction term aimed at capturing their interdependence in determining costs.

Equation (12) estimates the per kW environmental mitigation cost and equation (13) estimates the engineering and management cost as fixed proportions of the sum of the costs in equations (7) to (11). Equation (14) is an accounting equation to calculate total capital expenditures (initial capital cost) as the sum of the costs in equations (7) to (13). Equation (15) calculates the per kW development costs (costs of regulatory processes, studies, and analyses) as a fixed proportion of the initial capital cost. Equation (1) is the O&M cost equation from the 2015 BCM, while equations (17) and (18) are implementations of common formulas for the capital recovery factor and the LCOE, respectively.

Site Preparation cost ($/kW):

$$SP = \gamma_{sp} e^{\begin{pmatrix} \alpha_{sp} + \left[\beta_{sp,lk_q} d_{lk} + \beta_{sp,lc_q} d_{lc}\right] lnQ_d \\ + \beta_{sp,h} lnH_d + \beta_{sp,u} U_d + \beta_{sp,blb} d_{blb} + \beta_{sp,frn} d_{frn} \end{pmatrix}} \quad (7)$$

Water conveyance cost ($/kW):

$$WC = \gamma_{wc} L_d e^{(\beta_{wc,lk} d_{lk} + \beta_{wc,lc} d_{lc})} \quad (8)$$

Powerhouse cost ($/kW):

$$PH = \gamma_{ph} e^{(\alpha_{ph} + \beta_{ph,q} lnQ_d + \beta_{ph,h} lnH_d + \beta_{ph,u} U_d + \beta_{ph,blb} d_{blb} + \beta_{ph,frn} d_{frn})} \quad (9)$$

Electro-mechanical cost ($/kW):

$$EM = \gamma_{em} e^{(\alpha_{em} + \beta_{em,q} lnCap_d + \beta_{em,h} lnH_d + \beta_{em,u} U_d + \beta_{em,blb} d_{blb} + \beta_{em,frn} d_{frn})} \quad (10)$$

Electrical Infrastructure cost ($/kW):

$$EI = \frac{\gamma_{ei}\left(\alpha_{ei} + \beta_{ei,cap}Cap_d + \beta_{ei,sb}SB_{ds} + \beta_{ei,cap\_sb}Cap_d SB_{ds}\right)}{Cap_d} \quad (11)$$

Environmental mitigation cost ($/kW):

$$ENV = \gamma_{env}(PH + EM + EI + SP + WC) \quad (12)$$

Engineering & management cost ($/kW):

$$ENG = \gamma_{eng}(PH + EM + EI + SP + WC) \quad (13)$$

Capital expenditures (Initial capital cost; $/kW):

$$CAPEx = PH + EM + EI + SP + WC + ENV + ENG \quad (14)$$

Development cost ($/kW):

$$DEV = \gamma_{dev}CAPEx \quad (15)$$

Annual Operation and maintenance cost ($/kW):

$$annOM = 226544 * (Cap_d)^{0.547} / \{Cap_d * 1000\} \quad (16)$$

Capital recovery factor:

$$KRFac = r * (1 + r)^T / \{(1 + r)^T - 1\} \quad (17)$$

Levelized Cost of Energy ($/kWh):

$$LCOE = \{CAPEx * KRFac + annOM\} / \{8760 * CapFac\} \quad (18)$$

3. MODEL ESTIMATION RESULTS

3.1 SUMMARY OF ESTIMATION STATISTICS

Table 5 provides an overview of the model estimation statistics. Given that there were nineteen sample sites in the data, most of the equations have at least 13 degrees of freedom, except for the length of the water conveyance equation, which has 11. The r-squared (R^2) values for the equations are above 90% for seven of the ten equations, with those for the length of water conveyance, capacity factor, and water conveyance cost equations at 89%, 66%, and 65%, respectively. Values for the adjusted R^2, which penalizes unnecessary variables in the model, are lower than the R^2 values by less than 3% in most cases. This implies that the variables included in these equations contribute to explaining variations in the dependent variables. The F-Statistic, which tests the null hypothesis that the parameters of the model are jointly zero, rejects the null hypothesis with p-values close to zero. Although the adjusted R^2 and F-Statistic confirm that the variables are useful for explaining estimated variables in this model, the low number of sites means that the variability in the data would be lower than the population of potential NPD sites. However, this issue is addressed in this study by using reference sites, each representing the medoid (or multi-dimensional median representative) of its cluster; differences in site characteristics are minimized within each cluster whereas differences between clusters are maximized. Still, since each cluster consists of members that vary in their multi-dimensional attributes relative to the medoid, the regression model estimates should be interpreted in a "calibration" rather than the traditional "statistical" sense. The "calibration" interpretation is also appropriate because the equations are reduced-form representations of engineering structures and processes defined by the specific baseline designs and other assumptions in the sample. The coefficient estimates discussed in the next section show that the equations provide useful and practical estimates of the role of these variables in relation to their physical counterparts.

Table 4 Summary of model estimation statistics

	Number of Parameters	R-squared	Adjusted R-squared	F-Statistic (P-value)
Design equations				
Design Flow	3	0.998	0.997	0.000
Design Head	4	0.988	0.986	0.000
Number of Units	5	0.987	0.983	0.000
Length of Water Conveyance	8	0.890	0.820	0.000
Capacity Factor	5	0.661	0.564	0.003
Cost equations				
Site Preparation	6	0.956	0.940	0.000
Water Conveyance	2	0.651	0.630	0.000
Powerhouse	6	0.991	0.988	0.000
Electro-mechanical	6	0.995	0.994	0.000
Electrical Infrastructure	4	0.982	0.978	0.000

3.2 COEFFICIENT ESTIMATES FOR DESIGN EQUATIONS

Table 5 shows the estimated values and standard errors of the α_k and $\beta_{k,j}$ coefficients in the design equations (1) to (4) and (6). The columns of Table 5 show the equations, while the rows are the variables in the model with bolded estimates indicating significance at the ≤5% level. The intercept coefficients are significant at the ≤5% level in three of the five design equations, except the design head equation and design flow equation (which has no intercept). Coefficients for the median water flow and its 70th and 30th percentile ratio in the design flow equation are both significant at the ≤5% level and positive. The median water flow coefficient is negative but not significant at the ≤5% level in the length of water conveyance equation, with a p-value of about 25%. The 70th and 30th percentile flow ratio coefficient is negative and significant at the ≤5% level in the capacity factor equation. Given that traditional hydropower design flow generally uses the 70th percentile (equivalently 30% exceedance) flow level for the design flow, the positive value of the 70th and 30th percentile flow ratio in the design flow equation is expected. However, this ratio has a negative effect on the capacity factor, reflecting the reduced ability to generate at the design level over time as the ratio gets larger. Coefficients of the median water head and its 90th and 10th percentile ratio are significant at the ≤5% level in the design head equation. The former is positive, while the latter is negative, reflecting the fact that high head variability tends to lead to more conservative hydropower design head levels, all else equal. The 90th and 10th percentile head ratio coefficient in the capacity factor equation is not significant at the ≤5% level, but its p-value is about 8%. The lock dam indicator coefficient in the design head equation is also significant and negative, matching the generally lower hydropower head available at lock dams relative to lake dams. The negative and significant coefficient of the lock dam indicator in the design flow equation implies that once differences in median water flow and its 70th to 30th percentile ratio are considered, hydropower at lock dams have lower design flows relative to lake dams.

The design flow coefficient is not significant at the ≤5% level in the capacity factor equation but has a p-value of 12%. The coefficients on interacting the design flow with the lake and lock dam indicators are significant at the ≤5% level and positive in the number of units equations. Coefficients on the interaction of dam height with the lake and lock dam indicators are also significant at the ≤5% level and positive in the length of water conveyance equation. Indicators of dam construction type are used in the length of water conveyance equation to complement the dam height variable. The gravity dam construction indicator coefficient is significant at the ≤5% level and negative, whereas the concrete dam construction indicator coefficient is significant at the ≤5% level and positive. The indicator for embankment dam construction and its interaction with gravity construction are both positive but insignificant with p-values of 54% and 29%, respectively. Recall that a dam can incorporate multiple construction types. As such, the dam construction type indicators are not mutually exclusive in this model, and the permissible combinations would depend on design options for a given site. The Bulb and Francis turbine indicators appear in the number of units equation but are not significant at the ≤5% level. However, their p-values are only about 13%, and both are negative, with the magnitude of the Bulb turbine coefficient nearly five times larger than for the Francis turbine. The relative magnitude of these coefficients matches the generally much larger "gulp size" (unit flow) of bulb turbines relative to the Kaplan and Francis turbines in the data used for this study. Bulb turbines are used for very large-flow/low-head sites, typical of lock dams in the US, reducing the number of units that would be needed for hydropower production relative to other types of turbines.

Table 5 Coefficient estimates and standard errors for the NPDHCM design equations

	Equations				
	(1) Design Flow	(2) Design Head	(3) Number of Units	(4) Length of Conveyance	(6) Capacity Factor
Intercept	—	0.01 (0.16)	**2.74 (0.59)**	**2.23 (0.92)**	**-0.95 (0.20)**
Log Flow-Median	**1.07 (0.04)**	—	—	-0.10 (0.09)	—
Log Flow-7030 Ratio	**0.44 (0.13)**	—	—	—	**-0.16 (0.07)**
Log Head-Median	—	**0.99 (0.04)**	—	—	—
Log Head-9010 Ratio	—	**-0.12 (0.03)**	—	—	-0.55 (0.29)
Lock	**-1.34 (0.30)**	**-0.17 (0.08)**	—	—	—
Lake	—	—	—	—	—
Log Design Flow	—	—	—	—	0.03 (0.02)
Log Design Head	—	—	—	—	—
Log Design Hd. X Log 9010 Hd. Ratio	—	—	—	—	0.20 (0.10)
Lake X Log Design Flow	—	—	**0.48 (0.10)**	—	—
Lock X Log Design Flow	—	—	**0.79 (0.09)**	—	—
Lake X Log Dam Height	—	—	—	**1.04 (0.17)**	—
Lock X Log Dam Height	—	—	—	**1.36 (0.24)**	—
Dam: Gravity	—	—	—	**-0.58 (0.20)**	—
Dam: Embankment	—	—	—	0.18 (0.28)	—
Dam: Concrete	—	—	—	**0.98 (0.27)**	—
Dam: Embankment/Gravity	—	—	—	0.35 (0.32)	—
Bulb Turbine	—	—	-1.66 (1.03)	—	—
Francis Turbine	—	—	-0.36 (0.22)	—	—
Number of Units	—	—	—	—	—
Log Design Capacity	—	—	—	—	—
Design Capacity	—	—	—	—	—
Substation Distance	—	—	—	—	—
Capacity X Subst. Distance	—	—	—	—	—

3.3 COEFFICIENT ESTIMATES FOR COST EQUATIONS

Table 6 shows the estimated values and standard errors of the α_k and $\beta_{k,j}$ coefficients in the cost equations (7) to (11). The intercept estimates are significant in the site preparation, powerhouse, and electromechanical but not the electrical infrastructure cost equations; there is no intercept in the water conveyance cost equation. The coefficients of the lock and lake dam indicators are positive in the water conveyance cost equation, but only the lake dam coefficient is significant. The value of the lake dam indicator coefficient is also one order of magnitude larger relative to the lock dam coefficient, implying that lake dams have larger water conveyance costs than lock dams on a per kW-ft basis. Given the specification of the water conveyance cost equation (8), the exponents of these coefficients are essentially the per kW-ft costs, equal to \$1.2/kW-ft and \$5.4/kW-ft for lock and lake dams, respectively. The design flow has a positive coefficient, and the design head has a negative coefficient in the powerhouse cost equation, both significant at the ≤5% level. The signs of these two coefficients match the general understanding that high-head sites increase the power density of hydropower equipment and, hence, lower costs on a per kW basis, whereas larger flows require larger equipment that tends to lower the power density. The design head coefficients are also negative and significant at the ≤5% level in both the electro-mechanical and site preparation cost equations. Interactions of the lake and lock dam indicators with design flow are both negative and significant at the ≤5% level in the site preparation cost equation. Note that the size of the intercept in the site preparation cost equation suggests it has a large constant component, which is adjusted downward by the other coefficients, except in the case of the Francis turbine. The Bulb and Francis turbine indicators are included in the site preparation, powerhouse, and electro-mechanical cost equations. The Francis turbine indicator is positive and significant at the ≤5% level in all three equations. The Bulb turbine indicator is negative in all three equations but is not significant at the ≤5% level, with p-values of about 9%, 12%, and 42% respectively. The sign and magnitude of the coefficients mean that the Bulb turbine reduces these three cost components on a per kW basis, reflecting its scale benefits relative to the Kaplan turbine and vice versa for the Francis turbine, all else equal. Interestingly, the number of units coefficient is negative and significant at the ≤5% level in the powerhouse cost equation, but positive and insignificant at the ≤5% level in the electromechanical cost equation (p-value of 55%). The design capacity coefficient is significant at the ≤5% level in the electrical infrastructure equation, but both terms involving the linear distance to a substation are insignificant. Given that, along with plant capacity, connection distance is an important determinant of transmission costs, the insignificance of the latter is likely due to inadequate variation in the substation distance data for this study since the sites were generally within 10 miles of a substation.

3.4 SCALING FACTORS AND REFERENCE VALUES

In addition to the estimated coefficients in Tables 5 and 6, two sets of values are needed to fully exercise the *NPDHCM*. The first set is the scaling factors, $\boldsymbol{\gamma}_{\mathbf{k}}$, which are calculated by dividing the actual reference values of the variables specified by equations (1) to (4), (5), and (7) to (11) by the predicted values. As previously highlighted, these scaling factors are used as multipliers to calibrate the associated equations to the original data. The scaling factors are shown in Table B-1. In addition to their scaling role, the values in Table B-1 provide insights into how well the equations predict values for the nineteen reference sites in the model estimation data. Most of the scaling factors are close to 1, with the median across reference sites for individual equations between 0.9 and 1.05, except for the unit water conveyance cost equation whose median is about 1.2. Interestingly, both the lowest and largest scaling factor estimates of 0.05 and 9.8 occur for the unit water conveyance cost equation, implying that the corresponding two sites are far from typical among the nineteen reference sites. One site (Jennings Randolph Dam) had a cost estimate much lower while the other site (Westville Dam) had a much higher cost estimate than typical of the other reference sites. The standard deviations of the scaling factors across sites for the individual equations are generally below 0.2, except for the design flow and electrical infrastructure cost equations with values of about 0.5, and the unit conveyance cost equation with a value of 2. Thus, the unit water conveyance cost equation is the least accurately estimated equation in the model. The second set of values is the "Reference data" listed in Table A-1. The values for these variables are shown in Table B-2, corresponding to the actual reference site data for those variables.

Table 6 Coefficients estimates and standard errors for the NPDHCM cost equations

	Equations				
	Site Preparation	**Water Conveyance**	**Powerhouse**	**Electro-mechanical**	**Electrical Infrastructure**
Intercept	**13.22 (0.60)**	—	**10.18 (0.28)**	**9.66 (0.16)**	134.82 (97.34)
Log Flow-Median	—	—	—	—	—
Log Flow-7030 Ratio	—	—	—	—	—
Log Head-Median	—	—	—	—	—
Log Head-9010 Ratio	—	—	—	—	—
Lock	—	0.17 (0.44)	—	—	—
Lake	—	**1.68 (0.30)**	—	—	—
Log Design Flow	—	—	**0.17 (0.05)**	—	—
Log Design Head	**-1.01 (0.08)**	—	**-1.14 (0.04)**	**-0.63 (0.03)**	—
Lake X Log Design Flow	**-0.61 (0.09)**	—	—	—	—
Lock X Log Design Flow	**-0.27 (0.08)**	—	—	—	—
Lake X Log Dam Height	—	—	—	—	—
Lock X Log Dam Height	—	—	—	—	—
Dam: Gravity	—	—	—	—	—
Dam: Embankment	—	—	—	—	—
Dam: Concrete	—	—	—	—	—
Dam: Embankment/Gravity	—	—	—	—	—
Bulb Turbine	-1.75 (0.95)	—	-0.28 (0.17)	-0.06 (0.07)	—
Francis Turbine	**1.40 (0.24)**	—	**2.06 (0.15)**	**0.29 (0.07)**	—
Number of Units	—	—	**-0.26 (0.06)**	0.02 (0.03)	—
Log Design Capacity	—	—	—	**-0.11 (0.02)**	—
Design Capacity	—	—	—	—	**63.11 (5.86)**
Substation Distance	—	—	—	—	1.45 (24.76)
Capacity X Subst. Distance	—	—	—	—	-0.59 (0.90)

4. MODEL APPLICATION TO US NPD DATA

The *NPDHCM* was used to perform a pre-feasibility analysis of the cost of potential hydropower development at US NPD sites. Available data were obtained from the following sources. The NPD sites included in the analysis were from the ORNL 2012 resource assessment (Hadjerioua et al., 2012) with about 54,000 NPD sites. Stream flow data were obtained from the *Dayflow* dataset (Ghimire et al., 2023) which provides estimates of daily and monthly stream discharge from 1980 to 2015. Although these data are estimates at the mouth of each stream reach, rather than at the outlets of dams, they provide the most comprehensive flow data available for a large number of sites at this level of detail. Daily data for about 36,000 stream reaches that can be matched with the NPD dams were downloaded from the *Dayflow* dataset and used to calculate the flow duration curves used in the *NPDHCM*. The paucity of data on hydraulic head is a well-known issue when evaluating hydropower potential at US dam sites. Given this, the ORNL 2012 resource assessment estimated hydraulic head using the dam height data in the NID and other assumptions. These estimates were adopted for the pre-feasibility analysis in this study. Other inputs to the *NPDHCM*, including dam height, lake/lock indicators, and dam construction types were based on the NID dataset. Distances of NPD locations to the nearest US electric substation were calculated using the QGIS software (Moyroud and Portet, 2018).

4.1 OVERVIEW OF PRE-FEASIBILITY COST ANALYSIS RESULTS

Figure 2 provides 100-bin histograms with bin counts scaled by the modal count, overlaid by the empirical cumulative distribution curves for the capacity, capacity factor, capital expenditures and LCOE estimates. Note that the X-axis in Figure 2 is in base 2 logarithms. Only sites with capital expenditure estimates ≤\$100,000/kW, consisting of 13,470 lake dams and 147 lock dams, are included in Figure 2. Many of the sites had very small water flow and head resources, leading to extremely large per kW capital cost estimates under the baseline technologies considered in the *NPDHCM*. Although the capital expenditure threshold of \$100,000/kW is one order of magnitude larger than the typical estimates of \$5,000/kW to \$10,000/kW for recently developed hydropower sites in the US, this higher limit recognizes the preliminary nature of these estimates, and the uncertainties in the input data and the model equations. In addition, sites with much larger cost estimates have the largest potential savings from innovation.

The capacity estimates in Figure 2 range from 1 kW to 72 MW for the lake dams with a median of only 7 kW, and from 2 kW to 67 MW with a median of 2.65 MW for the lock dams. The 75th percentile capacity estimates are about 23 kW for lake dams and 12 MW for lock dams. Thus, more than three-quarters of the large number of US lake NPD sites in this analysis have potential hydropower capacity estimates of less than 100 kW. The capacity histograms for lake and lock dams in Figure 2 have only limited overlap. The histogram for lake dams is skewed to the right while that for the lock dams is slightly skewed to the left, leading to distinctive cumulative distribution curves for the two types of dams. Still, there are 282 lake dams with estimated capacities of ≥1 MW, which is nearly twice the total number of lock dams in Figure 2. Figure 2 shows that capacity factor estimates for lake dams are generally in the range of 24% to 70% with a median of about 30% while lock dams have a range of 30% to 65% with a median of about 44%. The capacity factors estimates are limited to a range of 10% to 70% in this study, with the lower value considered to be the minimum for a hydropower plant while the upper value is based on limits on the continuous availability of design levels of water flow and head, as well as the overall experience of existing hydropower plants. There is a significant overlap of the lake and lock capacity factor histograms, leading to similar cumulative distribution curves.

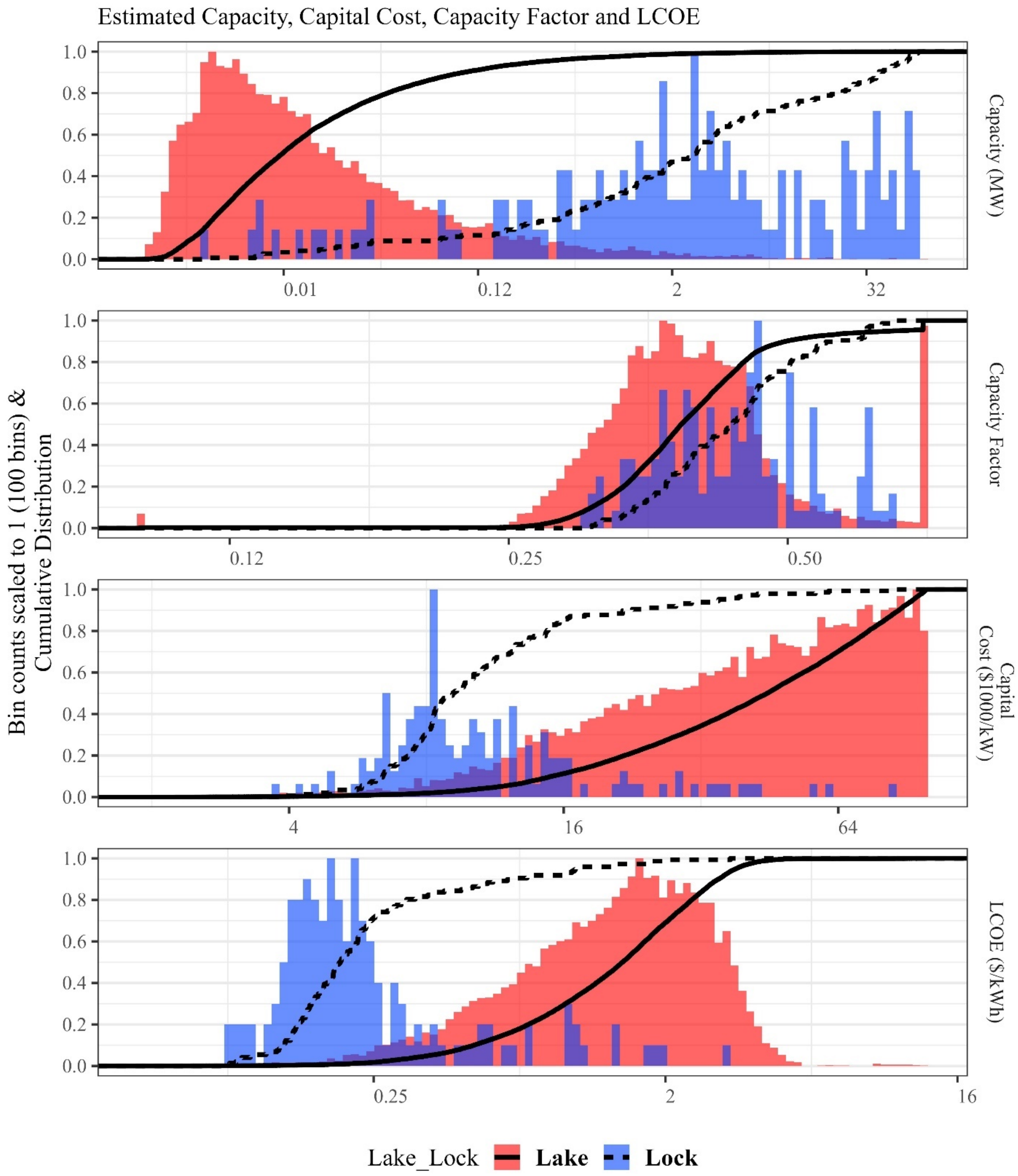

Figure 2 Distribution of capacity, capacity factor, capital expenditure (<=$100K/kW) and LCOE (N=13618; Lake=13,471; Lock=147; x-axis in log base 2)

The capital expenditure histograms for lake and lock dams, like those for capacity, have limited overlap and reflect the effects of decreasing scales on the cost of hydropower using the baseline technologies considered in the *NPDHCM*. The estimated range of capital expenditures for lake dams is \$1,900/kW to \$100,000/kW (the upper range being the limit in Figure 2 as previously highlighted) with a median of \$45,000/kW. The range for lock dams is \$4,000/kW to \$85,000/kW with a median of \$9,000/kW. However, the histogram for lock dams is skewed to the right while that for the lake dams is skewed to the left. Thus, there are more capital cost estimates smaller than the median for lock dams and vice versa for lake dams. The LCOE estimates in Figure 2 reflect the combined pattern of capacity factor and capital expenditure estimates according to equation (18) and includes O&M costs estimates based on equation (16). The range of LCOE estimates for lake dams is \$0.05/kWh to \$13/kWh with a median of \$1.5/kWh. For lock dams, the range of LCOE estimates is \$0.09/kWh to \$3/kWh with a median of \$0.20/kWh. The 75th percentile of LCOE estimates for lake dam is \$2/kWh while it is \$0.30/kWh for lock dams. As highlighted previously, the disproportionately large share of lake dams with small water resources affects the distribution in Figure 2. In the following section, additional details on NPD sites with estimated LCOE ≤\$0.40/kWh, which is slightly above the median LCOE for lock dams, are presented. In addition, this LCOE threshold is about twice the upper bound of estimates for existing hydropower in North America (IRENA, 2021). Figure 3 shows that most of the sites with LCOE ≤\$0.40/kWh are located in the Eastern U.S. but there is a considerable number of sites also in the Western U.S. The lock sites are nearly all in the former region where most of the navigation locks are located.

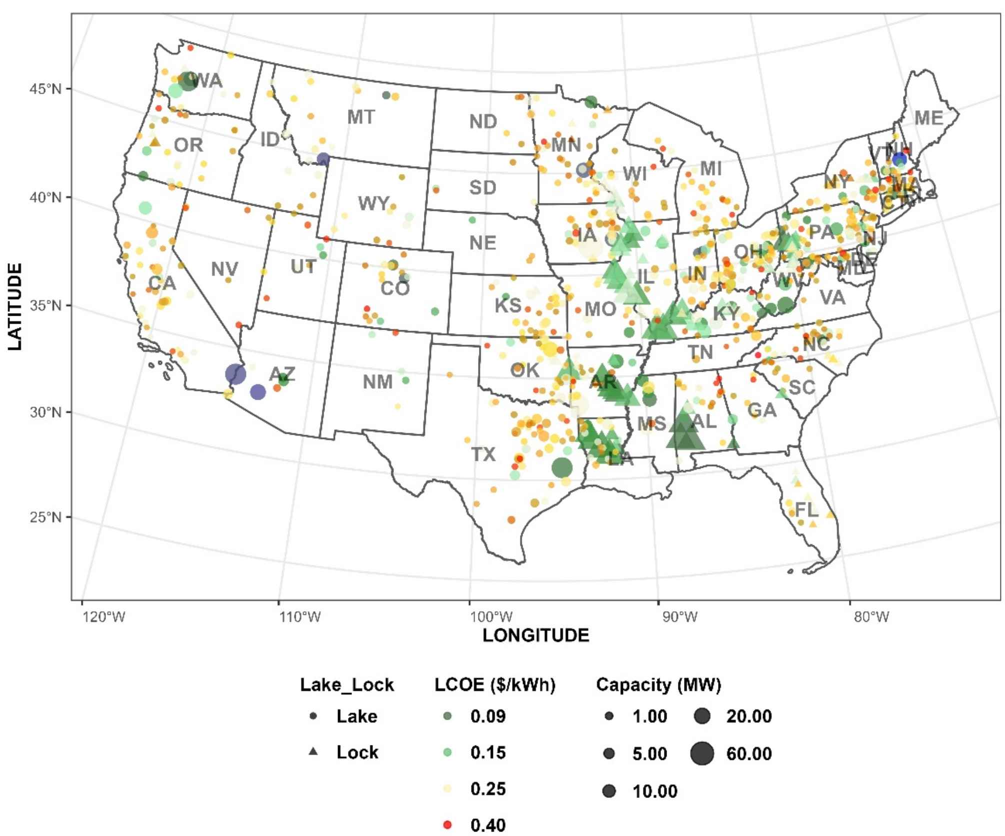

Figure 3 Geographical spread of US NPD sites with LCOE ≤\$0.40/kWh

4.2 SUPPLY CURVES FOR NPD SITES WITH ESTIMATED LCOE ≤$0.40/kWh

Figure 4 presents the estimated supply curves for lake and lock dams with LCOE ≤$0.40/kWh consisting of 791 lake dams and 123 lock dams, and total capacity estimates of 1,462 MW and 1,585 MW, respectively. The curves are divided into four LCOE groups: 1) ≤$0.09/ kWh; 2) $0.09/ kWh to $0.15/ kWh; 3) $0.15/ kWh to $0.25/ kWh; 4) $0.25/ kWh to $0.40/ kWh. The number of sites and total capacity within each LCOE group are shown separately for the two dam types in Figure 4. Sites in the first LCOE group are considered competitive at current electricity market prices, while those in the second group are either marginally competitive or can be competitive with existing innovations or incentives relative to the baseline. Groups three and four are expected to be competitive with medium- to long-term innovations that may require significant breakthroughs relative to baseline technologies. For comparison, there are currently about 70 NPD sites in the ORNL US hydropower development pipeline dataset (Johnson and Uría-Martínez, 2023), 61 of which were mapped to an NID identification label. Of the 61 sites 47 are included in Figure 4, and 36 are lock dams. The range of LCOE estimates for the 47 sites is $0.09/kWh to $0.34/kWh, with about half of the sites under $0.15/kWh.

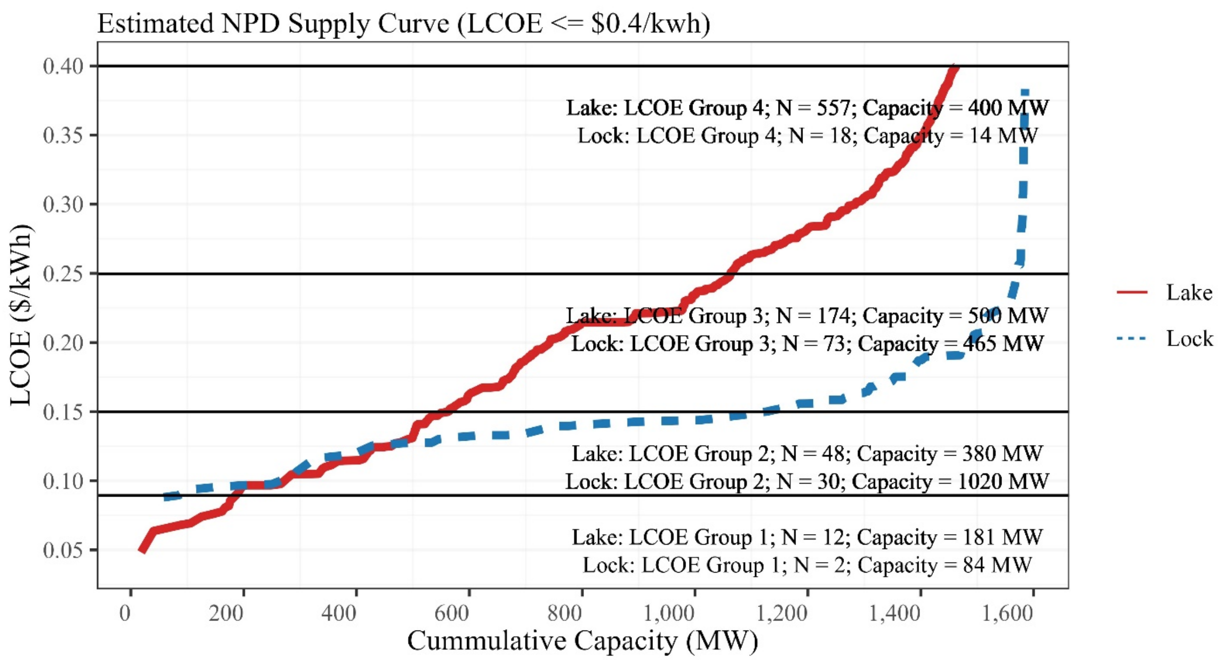

Figure 4 Estimated supply curves for the lake- and lock-type US NPD sites with LCOE ≤$0.40/kWh.

The supply curve for lake dams is much steeper than for lock dams at LCOE values below $0.25/kWh. The cumulative capacity for lake dams increases almost linearly with the LCOE, whereas more than half of the cumulative capacity for lock dams is within the second LCOE group. Still, lake dams include twelve sites in the first LCOE group with a total capacity of 181 MW relative to two sites for lock dams with a total capacity of 84 MW. Thus, on average, the potential capacity per site in the first LCOE group is sizable at about 15 MW for lake dams and 42 MW for lock dams. There are 48 lake dams and 30 lock dams in the second LCOE group with total capacities of 380 MW and 1,020 MW, respectively. The average capacity per site in this group is about 8 MW for lake dams and 30 MW for lock dams. There are 174 lake dams and 74 lock dams in the third LCOE group with about 500 MW of total capacity for each dam type. As such, the average capacity per site drops significantly relative to the first two LCOE groups to about 3 MW for lake dams and 6 MW for lock dams. The number of lake dams in the fourth LCOE group is 557 which is more than twice the combined number in the other three LCOE groups but with less than half the capacity at only 400 MW. There are only 18 lock dams in the fourth LCOE group, with a total capacity of 14 MW. Therefore, the average capacity per site in the fourth LCOE group is less than 1 MW for both lake and lock dams.

4.3 ESTIMATED CAPITAL EXPENDITURE AND CAPACITY FACTOR FOR NPD SITES WITH LCOE ≤$0.40/kWh

Figure 5 plots the capital cost estimates versus the capacity for all sites with LCOE ≤$0.40/kWh (both axes are in log base 2). The chart provides insights into the spread of site capacity and capital cost estimates across the LCOE bands for each dam type. Although there is a general negative correlation between capacity and capital costs as indicated by the linear fit, the range of estimates around this line is wide. As expected from the previous discussion, most of the lake and lock dams in the first LCOE capacity group have capacities larger than 10 MW with capital costs below $10,000/kW but only about a third of these sites, mainly lake dams, are below $5,000/kW. In fact, the overall majority of sites below $5,000/kW are lake dams, cutting across all LCOE groups and capacity estimates. The majority of lake and lock dams in LCOE bands 2 to 4 are between $10,000/kW and $15,000/kW, with the higher LCOE groups falling slightly more in the higher end of this cost range. A few of the sites, mainly in the fourth LCOE group of lake dams are above $15,000/kW.

The plot of capacity factor estimates versus capacity in Figure 6 (both axes in log base 2 scale) shows a slightly positive correlation between the two variables. Sites with ≤10 MW have capacity factor estimates between 30% and 50% but there is no clear distinction across the LCOE groups. Nearly all sites with >10 MW capacity have capacity factors estimates above 35% with most above 45%. Lock dams account for most of the capacity factor estimates above 55% when the capacity is >10 MW. There are also a few of the smallest lake sites with capacity factors close to the upper limit of 70%, but these are likely artifacts of the tiny capacity levels.

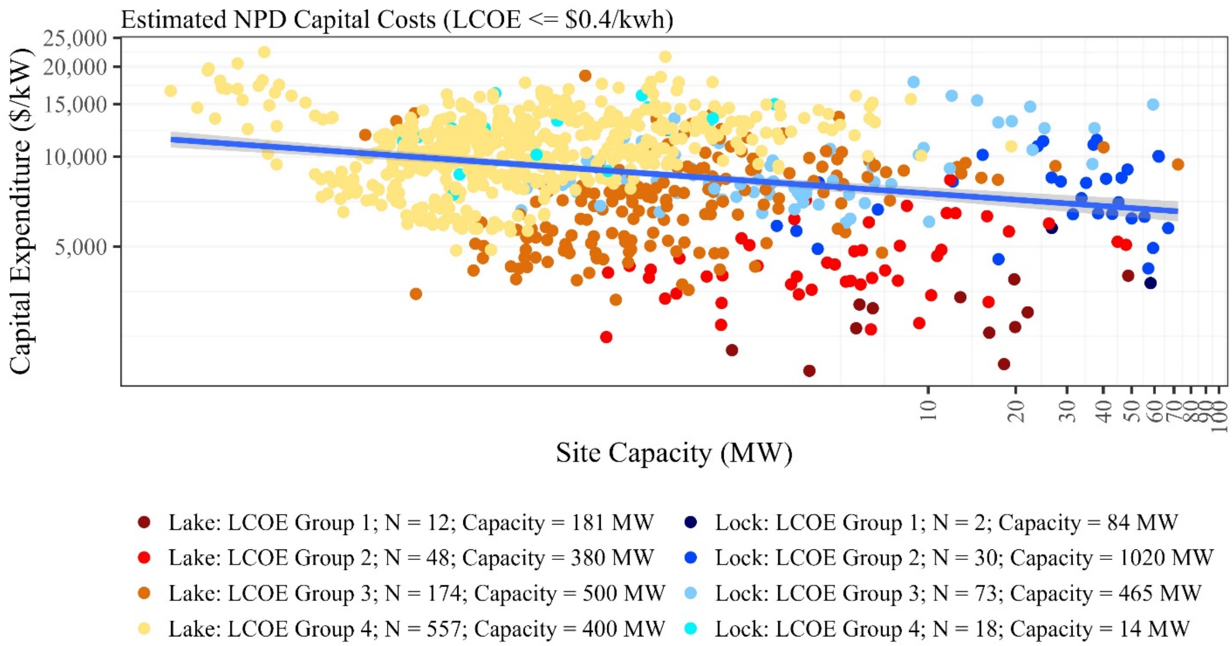

Figure 5 Estimated capital expenditures vs. capacity for US NPD sites with LCOE ≤$0.40/kWh (both axes in log base 2)

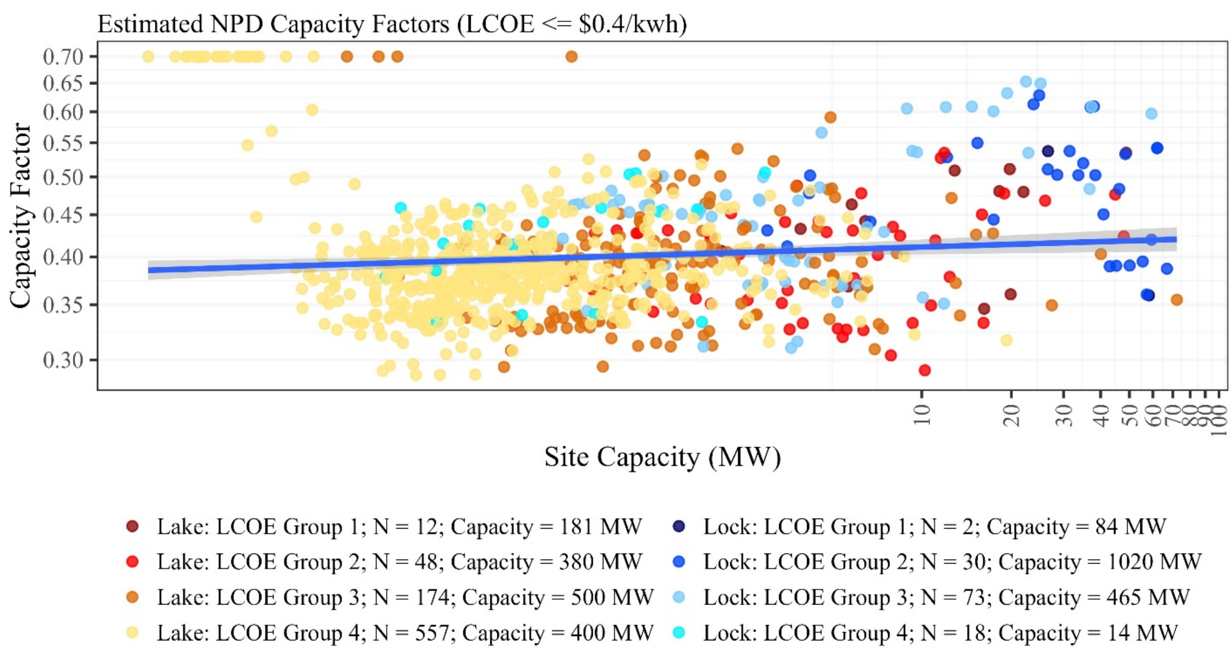

Figure 6 Estimated capital factors vs. capacity for US NPD sites with LCOE ≤$0.40/kWh (both axes in log base 2)

4.4 NPD HYDROPOWER COMPONENTS AND COSTS

Given that the hydropower baseline design options in the *NPDHCM* are those used for the reference sites, an important use of the model is to explore the cost drivers of NPD hydropower as a starting point for more detailed site-specific evaluation. The *NPDHCM* results should reflect the detailed preliminary engineering design and cost simulations underlying the reference site analysis. Therefore, this subsection explores the designs and costs results for hydropower components from the *NPDHCM* application in this report across sites with LCOE ≤$0.40/kWh.

4.4.1 Design Variables: Flow, Head, Turbine, and Conveyance Length

Figure 7 shows the pattern of unit design flow-head-turbine combination results from the *NPDHCM*. Francis turbines are used for sites with design heads of more than 100 ft with low to medium design flow levels, while Bulb turbines are mainly used for sites with low design heads and medium to high unit design flow levels. The Kaplan turbine straddles the space between the Francis and Bulb turbines, with significantly greater overlap with the latter than the former; the Bulb turbine is a member of the Kaplan class adapted for low-head and high-flow sites. Turbine selection charts are often used to depict the limits of unit head-flow combinations for different turbine classes, but there is a variety of these charts that differ both in the classes and the limits used for the turbines (Haas et al., 2014). Approximate Kaplan, Francis, and Bulb turbine limit lines are overlaid on the flow-head-turbine estimates in Figure 7. Although the turbine options in the *NPDHCM* are limited to those used for the reference site data in this study, these patterns are generally in line with the “turbine chart”.

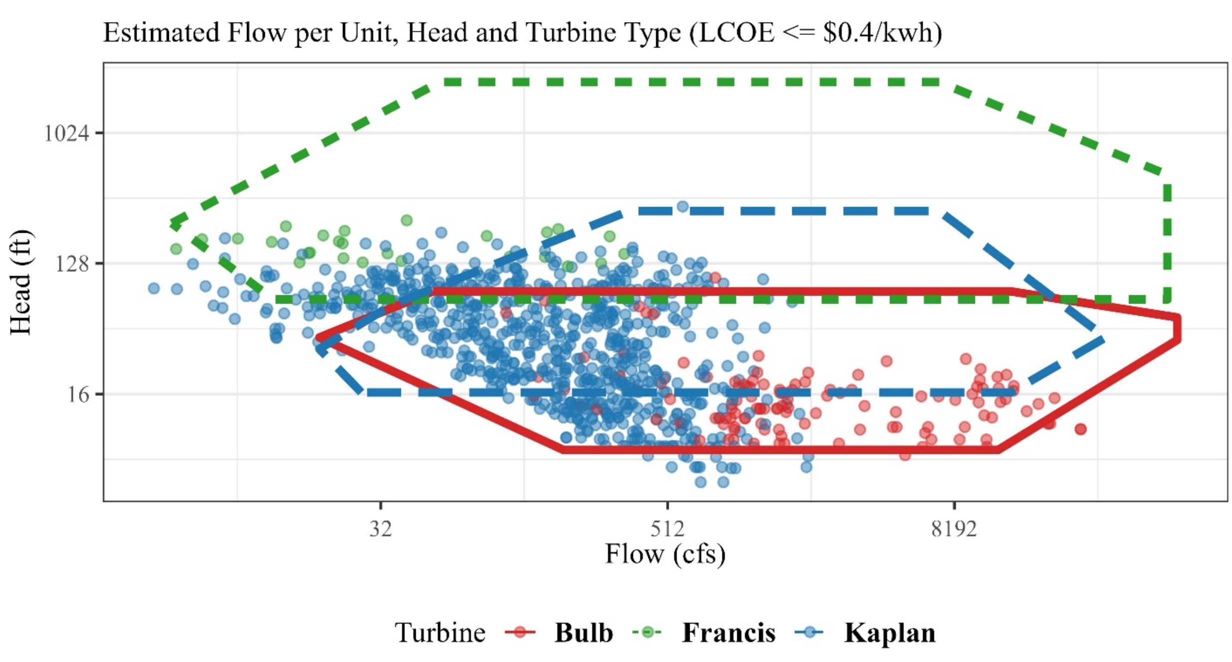

Figure 7 Estimated design flow, head, and turbine type for US NPD sites with LCOE ≤$0.40/kWh (both axes in log base 2)

Since both the design head and water conveyance length are specified as functions of the dam height in the *NPDHCM*, Figure 8 shows the head and water conveyance length versus the dam height. Lake dams have a generally linear log-log relationship with dam height for the two variables. In contrast, the conveyance length for lock dams has a more linear log-log relationship with the dam height than the design head. The design head for lock dams is generally below 32 ft, which reflects the operation and much lower head available at these navigation dams relative to the dam height. Although the patterns in Figure 8 reflect the preliminary engineering choices embedded in the reference sites data, the econometric equations in the *NPDHCM* are likely to produce incorrect estimates in some cases. For example, given that the tailwater elevation is not considered in the *NPDHCM*, the few sites with head values much higher than the dam height may be incorrect. Similarly, the water conveyance length estimates are unlikely to be very accurate since it is directly dependent on dam design and other site characteristics. Still, these estimates provide initial relative values for these variables for which data are generally unavailable for a large number of sites.

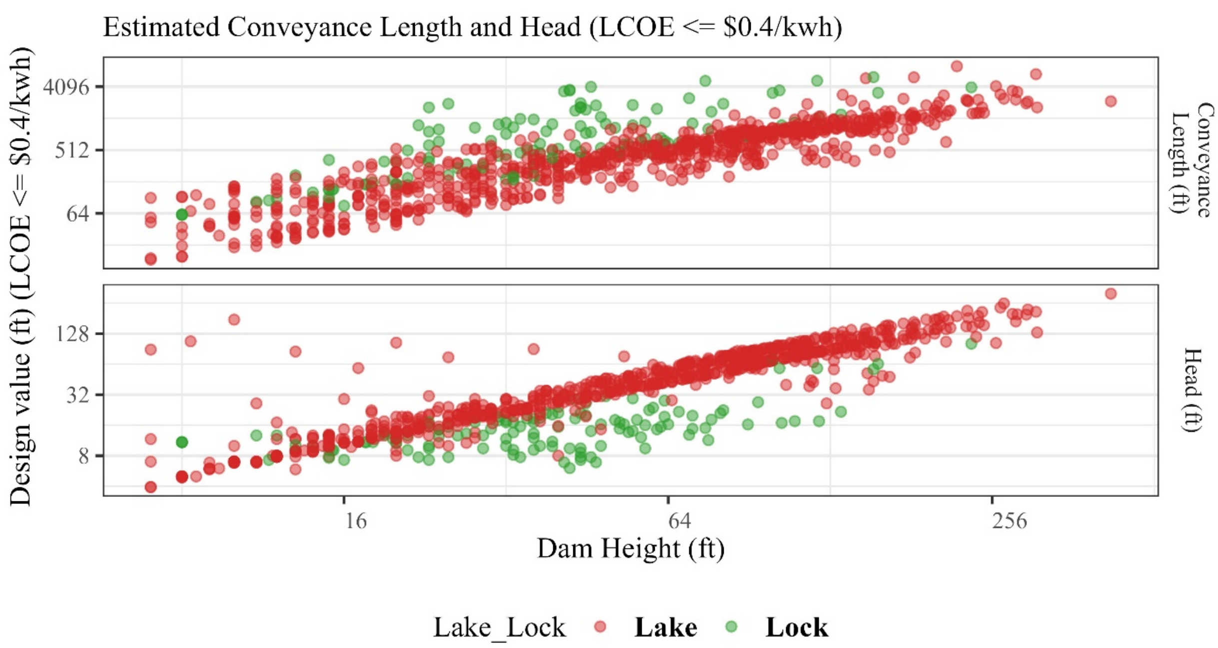

Figure 8 Estimated conveyance length and design head vs. dam height for US NPD sites with LCOE ≤$0.40/kWh (both axes in log base 2)

4.4.2 Shares of Major Components in per kW Capital Costs

Figure 9 presents boxplots of the per kW capital cost shares for major hydropower components. The cost components exclude environmental mitigation, engineering and construction management, and development costs, which are calculated in proportion to aggregates of the other costs. The distributions are shown separately for lake and lock dams, and each of the four per kW capital cost groups. Cost share patterns for site preparation and electrical infrastructure are the most similar between lake and lock dam sites, and across capital cost groups. The median site preparation cost shares are close to 10%, while those for electrical infrastructure are below 5%. The interquartile ranges of cost shares for both components are slightly wider for lake dams than for lock dams. The narrower interquartile range for lock dams reflects the fact that these dams are located closer to existing electrical interconnections than lake dams. Although the median distance from the nearest substation is between 2-3 miles for both lock and lake dams, the standard deviations are less than 3 miles and slightly higher than 4 miles, respectively. In addition, there is a larger number of lake dams than lock dams.

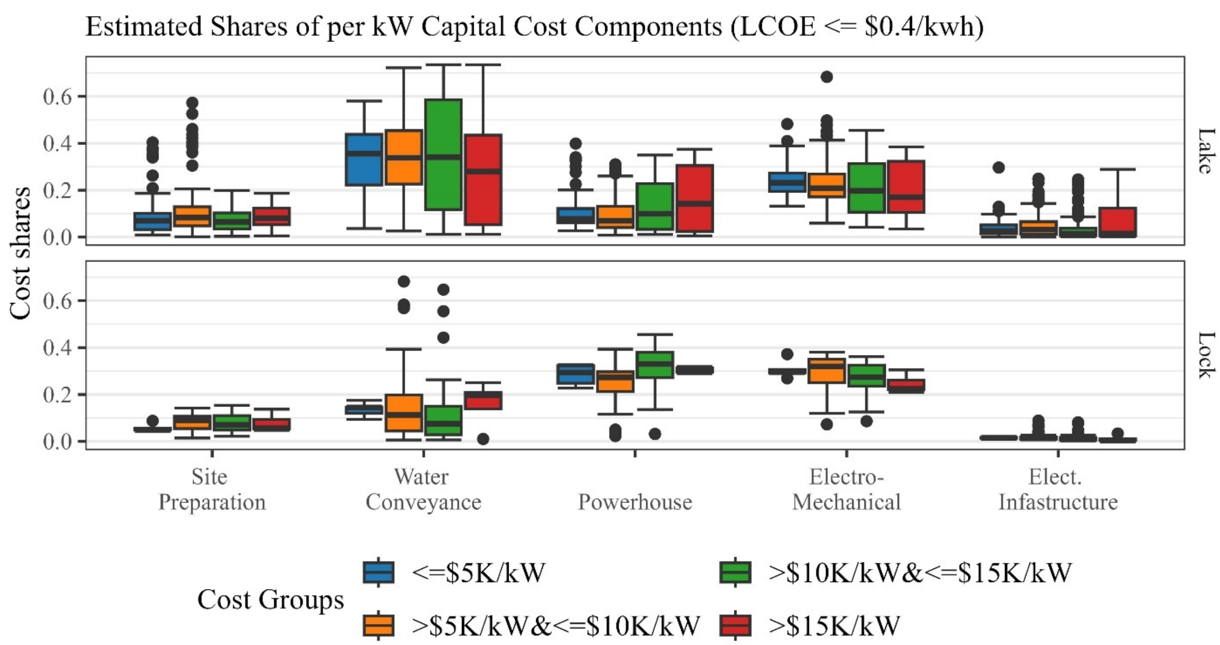

Figure 9 Estimated shares of per kW major capital cost components for US NPD sites with LCOE ≤$0.40/kWh

The median water conveyance cost shares for lake dams are about 30% across the capital cost groups but are generally below 20% for lock dams. Similarly, the interquartile range is much wider for lake dams, with the third quartile of the shares between 40% and 60%, while it is between 15% and 20% for lock dams across the capital cost groups. The wider range of cost shares for lake dams reflects a combination of the variation in estimates of water conveyance length in Figure 8, and the lower fit of the water conveyance cost equation in Table 4. Powerhouse cost shares for lock dams have median values of about 30% with interquartile ranges of 20% to 40%. Powerhouse cost shares of lake dams have a much different pattern for the first two capital cost groups compared with the other two groups. The median shares for the two smaller capital cost groups are below 10%, with their third quartile less than 15%. In contrast, the median costs for the two larger capital cost groups are ≥15%, with the third quartiles of 20% and 40%, respectively. The overall pattern of cost shares for the electro-mechanical component is generally similar to those for the powerhouse component. However, the median electro-mechanical cost shares are similar to those for the powerhouse for lock dams but higher for lake dams. In addition, for both lake and lock dams, the gradient of median shares for the electro-mechanical component across the four capital cost groups is opposite those for the powerhouse component.

4.5 NPDHCM WORKBOOK TOOL

The *NPDHCM* presented in this study has been implemented as a workbook tool to make it accessible to stakeholders for rapid evaluation of the costs of prospective hydropower at US NPD sites. The *NPDHCM* workbook includes the four sheets described below. Appendix C provides more detail on the "ProjectInputs" and "ProjectSummary" sheets, as well as additional instructions on using the workbook.

1. **Read_Me**: This sheet provides a brief overview of the *NPDHCM* and instructions on its use.
2. **ProjectInputs**: This sheet is used for providing the input data needed to run *NPDHCM*. The input columns are grouped into five sub-categories: 1) Dam Identifiers; 2) Infrastructure & Water Conveyance; 3) Financial Factors; 4) Water Resources data; 5) Exogenous Variable options. See Table C- 1 for additional information on each of the input groups.
3. **ProjectSummary**: This sheet provides a table of the NPDHCM simulation results, including a donut pie chart for a site selected from the table of results.
4. **Reference data**: This sheet contains data for the reference sites, which are used internally by the model as described in this study. It also contains an example of the full set of inputs and results of *NPDHCM* simulations for the reference sites.

5. CONCLUSIONS

This study presented the reduced-form NPD hydropower cost model (*NPDHCM*) which uses a Reference System approach to strike a balance between the detailed but cost-intensive approach and the aggregate but lacking detail approach to hydropower cost modeling. The purpose is to provide insights into the potential costs of hydropower at US NPD sites, particularly the underlying cost drivers, under baseline design conditions. Although the model was built on data generated from a fairly detailed preliminary engineering design and cost simulations using daily flow and head data, it can be used with the type of limited data commonly available for thousands of dams in the US.

The study discussed each of the equations for the design and cost variables, and the estimated coefficients. These coefficients demonstrate that while equations are necessarily parsimonious due to limited data, they capture important aspects of the baseline design and costs in the underlying reference sites data. The *NPDHCM* was applied to 36,000+ potential NPD sites in the US. An overview of results for about 14,000 of these sites, with capital cost estimates <= \$100,000/kW was provided. Additional details for about ~900 or about 3% of the initial 36,000+ sites with LCOE estimates of <=\$0.40/kWh were discussed. The 900 sites have an estimated capacity potential of ~3 GW or about 3 MW per site. There were significant differences between lake and lock dams in the number of potential sites, capacity distributions, capital expenditures, and LCOE estimates. The results were grouped into four LCOE categories, with the first two considered competitive or marginally competitive in the current market using baseline technologies, and the other two potentially requiring significant innovations to be competitive. The most competitive category has LCOE values <=\$0.09/kWh and includes about twelve (12) lake dams with about two-thirds of the total capacity versus only two (2) lock dams. In addition, the cumulative capacity potential of lake dams increases almost linearly with the LCOE values. Most of the capacity potential for lock dams fall in the second and third LCOE category with values >\$0.09/kWh to <=\$0.15/kWh and >\$0.15/kWh to >\$0.25/kWh. Overall, these pre-feasibility cost evaluation results indicate there is a significant amount of potential NPD hydropower capacity that can be considered cost-competitive under the baseline designs considered in this study.

The Excel-based Workbook implementation of the model would enable users to incorporate improved data for specific sites as they become available. In this vein, the workbook includes options to set most of the design variables that would usually be calculated endogenously in the model to fixed values. These variables include the design flow, design head, design capacity, length of water conveyance, number of units, and capacity factor. When these variables are fixed to the desired values the cost equations of the model can be used to estimate the associated pre-feasibility costs. Future efforts to improve the model include 1) collecting additional detailed data on hydropower sites to supplement the reference sites used in the current study, 2) improving model specifications based on additional data, 3) incorporating new functionalities in the Workbook tool to support users.

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APPENDIX A: LIST OF REFERENCE SITES AND TYPICAL BASELINE DESIGNS

Table A-1 Reference NPD site information from the NID

Reference sites	Lake/Lock	Length (ft)	Height (ft)	Primary type	Primary purpose
Tioga Dam	Lake	2,710	140	Earth	Flood control
Dillon Dam	Lake	1,400	118	Earth	Flood control
R. D. Bailey Dam	Lake	1,397	310	Rockfill	Flood control
Monroe Lake Dam	Lake	1,350	93	Earth	Flood control
Cowanesque Dam	Lake	3,100	151	Earth	Flood control
Westville Dam	Lake	560	72	Earth	Flood control
Cave Run Lake Dam	Lake	2,700	148	Earth	Flood control
Proctor (Lake O'The Pines) Dam	Lake	13,020	86	Earth	Flood control
William H. Harsha Lake Dam	Lake	1,450	205	Earth	Flood control
Chouteau Lock and Dam	Lock	11,690	53	Earth	Navigation
Jonesville Lock & Dam	Lock	920	94	Gravity	Navigation
Maynard Lock and Dam	Lock	7,780	61	Concrete	Navigation
Jennings Randolph Dam	Lock	2130	296	Earth	Flood control
Lock & Dam 24	Lock	4,584	76	Concrete	Navigation
John Overton Lock and Dam	Lock	914	104	Gravity	Navigation
Mississippi River Dam #14	Lock	2874	39	Concrete	Navigation
Crooked Creek	Lake	1480	143	Earth	Flood control
Tar River	Lake	500	35	Earth	Recreation
East Sidney	Lake	2010	130	Gravity	Flood control

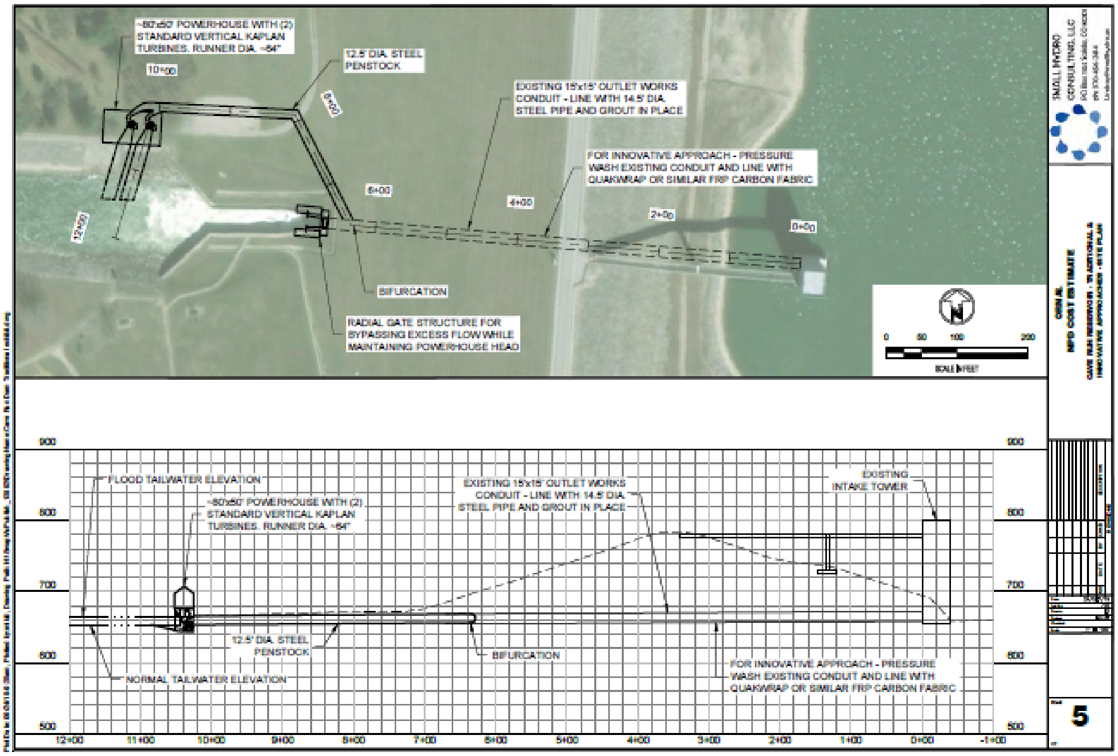


Figure A-1 Typical baseline design for lake dams (Source: Oladosu et al., 2021)

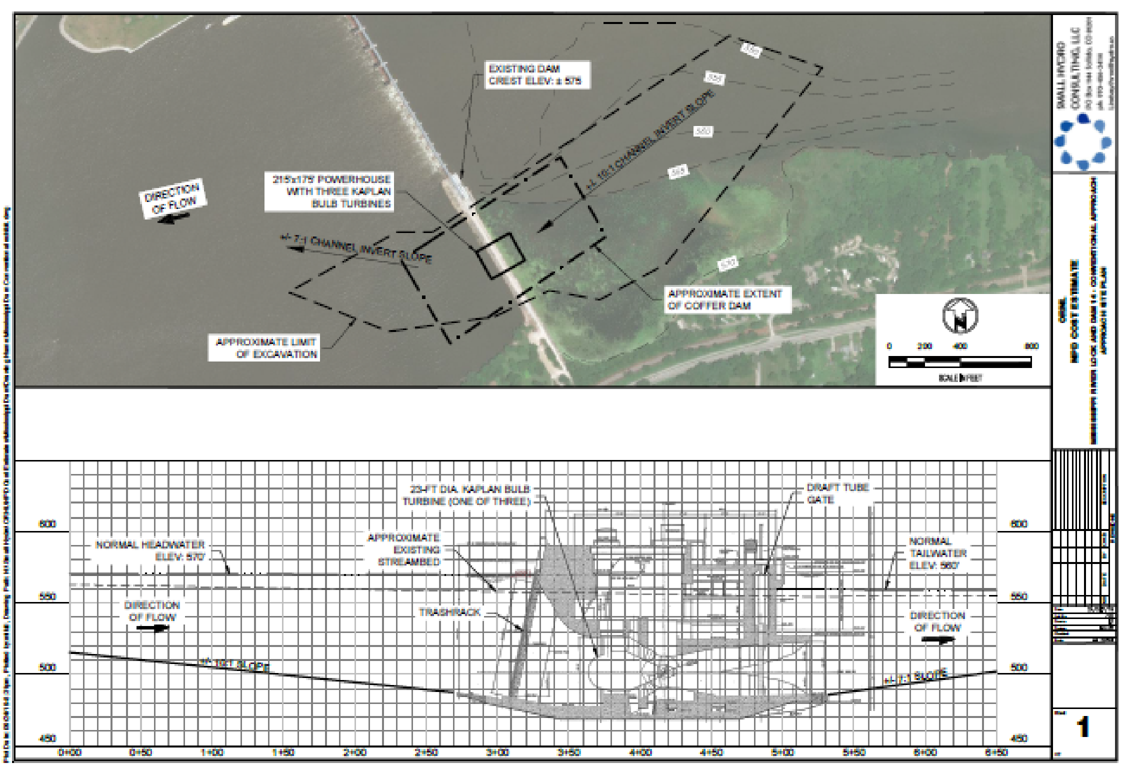


Figure A-2 Typical baseline design for lock dams (Source: Oladosu et al., 2021)

APPENDIX B: SCALING FACTORS AND REFERENCE VALUES

Table B-1 Scaling factors for the reduced-form NPD cost model equations for each reference site

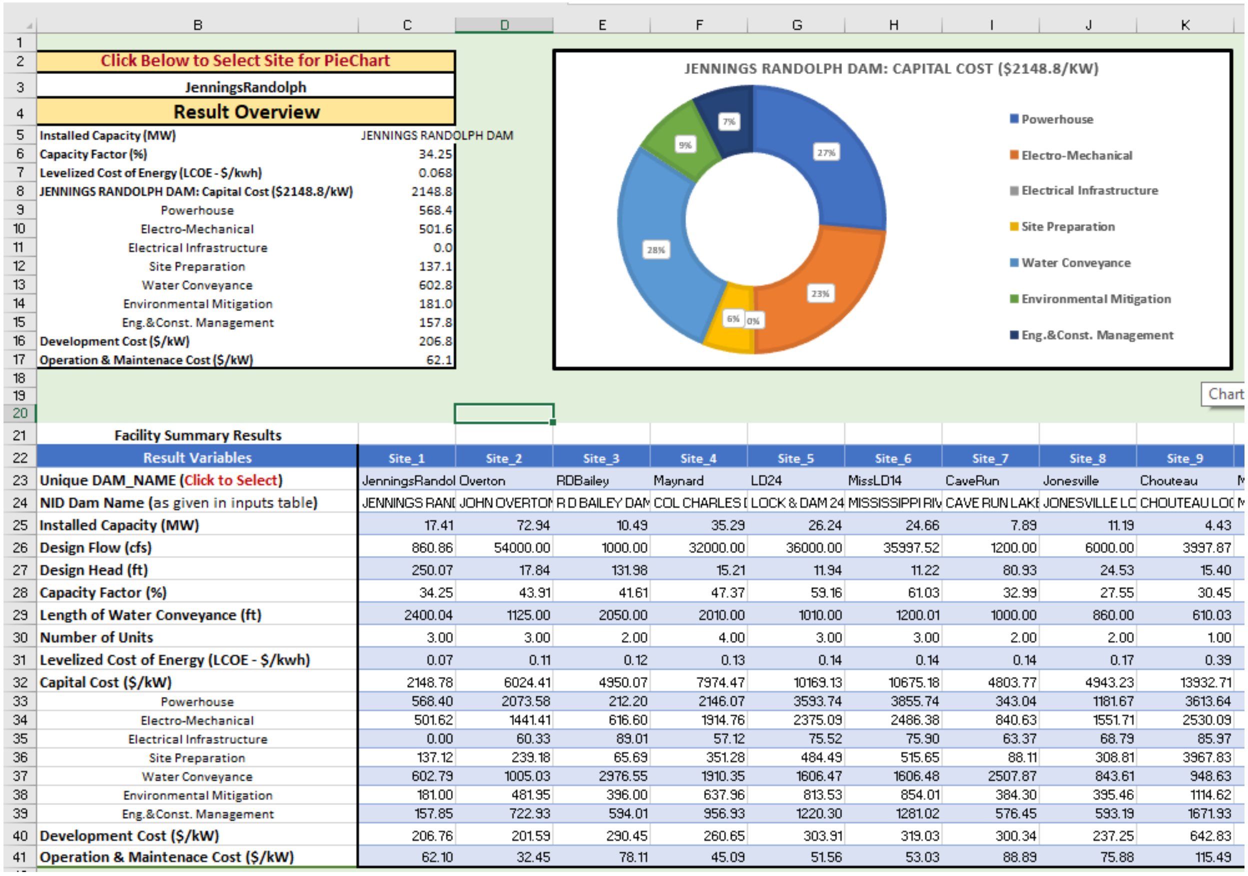
	Design Equations					Cost Equations				
	(1)	(2)	(3)	(4)	(6)	(7)	(8)	(9)	(10)	(11)
Reference Sites	Design Flow	Design Head	Number of Units	Length of Conveyance	Capacity Factor	Site Preparation	Unit-length Conveyance	Powerhouse	Electro-mechanical	Electrical Infrastructure
CAVE RUN	1.19	1.04	0.80	0.94	0.89	1.022	0.467	0.956	1.023	0.797
CHOUTEAU	1.42	0.93	1.01	0.96	0.88	1.092	1.313	0.961	1.038	0.929
COWANESQUE	0.83	1.01	0.77	1.13	1.04	1.074	1.173	1.055	0.971	0.818
CROOKED	1.00	1.02	1.27	1.09	1.18	0.931	0.601	0.918	1.012	1.799
DILLON DAM	0.92	0.98	0.87	1.09	0.89	1.094	1.410	0.857	0.994	0.893
EAST SIDNEY	1.22	1.20	1.07	1.02	0.97	0.939	1.453	1.036	0.963	1.991
HARSHA	0.94	1.00	0.92	1.00	1.04	0.941	1.169	1.156	0.992	0.572
JENNINGS	1.30	1.03	1.00	1.08	0.78	1.000	0.046	1.000	1.000	0.000
JONESVILLE	0.44	1.07	0.93	0.89	1.02	0.877	0.828	0.848	0.986	0.966
L&D 24	0.53	0.90	0.95	0.64	0.99	1.089	1.343	1.085	1.040	1.129
MAYNARD	1.11	1.02	1.30	1.54	1.07	0.975	0.802	1.127	0.991	0.871
MISS. L&D 14	1.04	1.27	0.95	1.06	1.18	1.089	1.130	1.085	1.040	1.130
MONROE	0.75	1.01	1.14	1.10	1.08	1.050	1.302	0.939	1.019	0.900
OVERTON	2.54	0.84	0.87	1.11	0.90	0.900	0.754	0.922	0.910	0.999
PROCTOR	1.38	0.97	1.04	0.81	0.97	0.921	3.549	1.006	0.956	0.286
R.D BAILEY	0.80	0.93	0.88	0.92	1.11	1.115	0.270	1.063	1.053	1.191
TAR RIVER	1.22	0.83	1.54	0.94	0.87	0.616	1.563	1.017	0.958	1.163
TIOGA	0.88	0.98	1.15	0.86	0.97	1.049	1.401	0.928	1.015	0.864
WESTVILLE	1.05	0.99	0.77	1.00	1.18	1.446	9.832	1.104	1.044	0.192

Table B-2 Reference values directly used as inputs into the model

Reference Sites	Q_{dref} (crfs)	H_{dref} (ft)	$Q_{9010ref}$	$H_{9010ref}$	$Q_{7030ref}$	$H_{7030ref}$	Cap_{ref} (MW)	$CapFac_{ref}$	Turbine
CAVE RUN	1200	79	49.38	0.82	4.35	0.89	7.70	0.33	Kaplan
CHOUTEAU	4000	15	83.85	0.47	13.82	0.79	4.31	0.31	Kaplan
COWANESQUE	340	77	43.31	1.01	5.11	1.00	2.12	0.39	Kaplan
CROOKED	492	42	40.18	0.99	3.80	0.96	1.67	0.46	Kaplan
DILLON DAM	1030	32	27.75	0.89	3.63	0.95	2.66	0.36	Kaplan
EAST SIDNEY	180	50	27.97	0.82	5.35	0.90	0.73	0.33	Kaplan
HARSHA	240	112	41.87	1.00	6.57	0.97	2.13	0.37	Kaplan
JENNINGS	861	240	7.56	1.01	2.13	1.02	16.71	0.34	Francis
JONESVILLE	6000	18	17.49	0.01	6.32	0.25	8.21	0.35	Bulb
L&D 24	36000	11	5.13	0.05	2.08	0.49	24.18	0.61	Bulb
MAYNARD	32000	15	41.00	0.67	4.50	0.92	34.81	0.47	Bulb
MISS. 14	36000	11	4.28	0.70	1.99	0.89	24.18	0.61	Bulb
MONROE	610	55	34.99	0.91	10.21	0.97	2.72	0.36	Kaplan
OVERTON	54000	17	11.08	0.50	2.38	0.82	69.53	0.44	Bulb
PROCTOR	190	41	107.92	0.80	4.91	0.98	0.63	0.34	Kaplan
R.D BAILEY	1000	140	24.29	0.84	3.92	0.90	11.13	0.41	Kaplan
TAR RIVER	750	16	18.36	0.77	3.81	0.81	0.87	0.35	Kaplan
TIOGA	600	50	31.04	0.96	4.10	0.98	2.43	0.38	Kaplan
WESTVILLE	340	11	15.08	1.00	2.91	1.01	0.22	0.48	Kaplan

APPENDIX C: THE WORKBOOK INTERFACE FOR THE NPDHCM

This appendix provides additional information on the inputs and results of the NPDHCM Workbook. The results interface is illustrated in Figure C-1.



Click Below to Select Site for PieChart	
JenningsRandolph	
Result Overview	
Installed Capacity (MW)	JENNINGS RANDOLPH DAM
Capacity Factor (%)	34.25
Levelized Cost of Energy (LCOE - $/kwh)	0.068
JENNINGS RANDOLPH DAM: Capital Cost ($2148.8/kW)	2148.8
Powerhouse	568.4
Electro-Mechanical	501.6
Electrical Infrastructure	0.0
Site Preparation	137.1
Water Conveyance	602.8
Environmental Mitigation	181.0
Eng.&Const. Management	157.8
Development Cost ($/kW)	206.8
Operation & Maintenace Cost ($/kW)	62.1

Facility Summary Results

Result Variables	Site_1	Site_2	Site_3	Site_4	Site_5	Site_6	Site_7	Site_8	Site_9
Unique DAM_NAME (Click to Select)	JenningsRandol	Overton	RDBailey	Maynard	LD24	MissLD14	CaveRun	Jonesville	Chouteau
NID Dam Name (as given in inputs table)	JENNINGS RANI	JOHN OVERTON	R D BAILEY DAM	COL CHARLES I	LOCK & DAM 24	MISSISSIPPI RIV	CAVE RUN LAKE	JONESVILLE LC	CHOUTEAU LOC
Installed Capacity (MW)	17.41	72.94	10.49	35.29	26.24	24.66	7.89	11.19	4.43
Design Flow (cfs)	860.86	54000.00	1000.00	32000.00	36000.00	35997.52	1200.00	6000.00	3997.87
Design Head (ft)	250.07	17.84	131.98	15.21	11.94	11.22	80.93	24.53	15.40
Capacity Factor (%)	34.25	43.91	41.61	47.37	59.16	61.03	32.99	27.55	30.45
Length of Water Conveyance (ft)	2400.04	1125.00	2050.00	2010.00	1010.00	1200.01	1000.00	860.00	610.03
Number of Units	3.00	3.00	2.00	4.00	3.00	3.00	2.00	2.00	1.00
Levelized Cost of Energy (LCOE - $/kwh)	0.07	0.11	0.12	0.13	0.14	0.14	0.14	0.17	0.39
Capital Cost ($/kW)	2148.78	6024.41	4950.07	7974.47	10169.13	10675.18	4803.77	4943.23	13932.71
Powerhouse	568.40	2073.58	212.20	2146.07	3593.74	3855.74	343.04	1181.67	3613.64
Electro-Mechanical	501.62	1441.41	616.60	1914.76	2375.09	2486.38	840.63	1551.71	2530.09
Electrical Infrastructure	0.00	60.33	89.01	57.12	75.52	75.90	63.37	68.79	85.97
Site Preparation	137.12	239.18	65.69	351.28	484.49	515.65	88.11	308.81	3967.83
Water Conveyance	602.79	1005.03	2976.55	1910.35	1606.47	1606.48	2507.87	843.61	948.63
Environmental Mitigation	181.00	481.95	396.00	637.96	813.53	854.01	384.30	395.46	1114.62
Eng.&Const. Management	157.85	722.93	594.01	956.93	1220.30	1281.02	576.45	593.19	1671.93
Development Cost ($/kW)	206.76	201.59	290.45	260.65	303.91	319.03	300.34	237.25	642.83
Operation & Maintenace Cost ($/kW)	62.10	32.45	78.11	45.09	51.56	53.03	88.89	75.88	115.49

Figure C-1 Illustrative results interface of the NPDHCM Workbook

Table C- 1 Description of input data in the NPDHCM Workbook (ProjectInputs sheet)

Input Names	Description
Dam Identifiers	
Dam_Name	(**Optional**) Name of the dam (usually from the NID)
Dam_Name1	(**Required**) Used to uniquely identify dams in a list
RefName	(**Required**) Drop-down choice from the list of reference sites
NID ID	(**Optional**) Dam identifier in the NID or custom
Lat	(**Optional**) Latitude of dam location
Long	(**Optional**) Longitude of dam location
Infrastructure & Water Conveyance	
Dam height (ft)	(**Required**) Physical dam height (usually from the NID)
Lake/Lock	(**Required**) Drop-down choice from the list: Lake, Lock
Embankment Dam	(**Required**) 0/1 option to indicate if dam construction includes embankment
Concrete Dam	(**Required**) 0/1 option to indicate if dam construction includes concrete
Gravity Dam	(**Required**) 0/1 option to indicate if dam construction includes gravity
Turbine type	(**Required**) Drop-down choice: Use Reference; Francis; Kaplan; Bulb
Substation distance (mi)	(**Required**) Straight-line distance to the nearest substation
Financial factors	
Real discount rate	(**Required**) Real discount rate for LCOE calculation
Capital recovery period (yrs)	(**Required**) Number of years for full capital recovery for LCOE calculation
Flow Duration Curve	
10^{th} percentile intervals (cfs): flw1, flw2, flw3, flw4, flw5, flw6, flw7, flw8, flw9, flw10	(**Required**) Ten values from the flow duration curve, ideally based on daily discharge data. Approximations or a single number for all ten points can be used if data is unavailable
Median Head Duration Curve	
10^{th} percentile intervals (ft); hd1, hd2, hd3, hd4, hd5, hd6, hd7, hd8, hd9, hd10	(**Required**) Ten head values, each corresponding to the median head for each flow duration curve point, ideally based on daily head data. Approximations or a single number for all ten points can be used if data is unavailable
Exogenous Variable Options: Pair of columns for each variable: 1^{st} Column = No for model calculated values	
Design flow (cfs)	(**Optional**) Exogenous design flow (Yes; Value)
Design head (ft)	(**Optional**) Exogenous design head (Yes; Value)
Design capacity (MW)	(**Optional**) Exogenous design capacity (Yes; Value)
Length of conveyance (ft)	(**Optional**) Exogenous length of water conveyance (Yes; Value)
Number of units (#)	(**Optional**) Exogenous number of units (Yes; Value)
Capacity factor	(**Optional**) Exogenous capacity factor set to (Yes; Value)