ORNL/TM-2025/3733

Baseline Cost Model for Hydropower: Documentation (2025)

Gbadebo Oladosu
Yu Ma
October 2025

Approved for public release.
Distribution is unlimited.

OAK RIDGE National Laboratory

ORNL/TM-2025/3733

Environmental Sciences Division

BASELINE COST MODEL FOR HYDROPOWER: DOCUMENTATION (2025)

Gbadebo Oladosu
Yu Ma

October 2025

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

BCMH	Baseline cost model for hydropower
DOE	US Department of Energy
EIA	Energy Information Administration
FERC	Federal Electricity Regulatory Commission
GRW	Generator rewind
CXP	Capacity expansion
ICC	Initial capital cost
IIR	Industrial Info Resources
NPD	Non-powered dam
NSD	New stream development
O&M	Operations and maintenance
ORNL	Oak Ridge National Laboratory
PSH	Pumped storage hydropower
RS	Reference System
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamations
WPTO	Water Power Technologies Office

ACKNOWLEDGMENTS

The authors acknowledge and express their appreciation to the US Department of Energy (DOE) Water Power Technologies Office (WPTO) for overseeing and funding the Hydropower Cost Modeling (HCM) project under which this study was performed. Special thanks to the following for valuable guidance and support for the study, and reviewing the report: Colin Sasthav and Zion Clarke (WPTO Leads for the Hydropower Cost Modeling Project); Shih-Chieh Kao (ORNL Water Power Program Manager); Rocio Uria-Martinez (ORNL Technical Reviewer). In addition, we acknowledge Colin Sasthav's valuable contribution for his work on data collation and processing in support of this effort while a member of the ORNL Water Power Program.

Finally, we acknowledge and are indebted to Patrick W. O'Connor, Qin Fen (Katherine) Zhang, Scott T. DeNeale, Dol Raj Chalise, Emma Centurion, and Abigail Maloof who developed previous versions of the hydropower baseline cost model in 2015. Although the current effort is a thorough update of the underlying data, model specifications and report, including a new Excel Workbook of the Baseline Cost Model for Hydropower(BCMH), their previous work laid the invaluable groundwork for this iteration of the work.

EXECUTIVE SUMMARY

New hydropower projects can help meet the growing demand for electricity supply, but the available data suggests that the rate of new hydropower development has been declining. The US hydropower industry needs a significant amount of information to evaluate the feasibility of potential projects due to the high variability of remaining resources. Therefore, assessments of the associated techno-economic issues are necessary for a better understanding of future new hydropower development. To facilitate these assessments, the Baseline Cost Model for Hydropower (BCMH) was developed by Oak Ridge National Laboratory (O'Connor, et al., 2015) using data for planned or active projects to support national-scale evaluation of hydropower costs.

This report documents a major update of the BCMH, including new data and specifications. The report presents the background, data sources, summaries of the data sample, and a series of parametric models for estimating the initial capital cost (ICC) and the cost of operation and maintenance (O&M) of US hydropower projects. For the ICC, this report presents sub-models for evaluating the capital cost of four categories of hydropower projects (non-powered dams (NPD), new stream-reach development (NSD), canal/conduits (Canal/Conduit), and pumped storage hydropower (PSH)), and the potential cost of capacity expansion (CXP) and generator rewind (GRW) modifications to existing hydropower projects. While more sophisticated and bottom-up cost estimation techniques are necessary for specific investment decisions, the aggregate parametric models described in this report are useful for a rapid evaluation of potential US hydropower projects.

Based on the compiled dataset, Table ES-1 shows that the cost of constructing a new hydropower plant ranges from $400/kW to 27,000/kW, with the average costs of approximately $5,048/kW for NPD, $4,909/kW for NSD, $2,009/kW for PSH, and $7,449/kW for Canal/Conduit. PSH projects, which are generally much larger plants that benefit from scale economics, have the lowest costs per kW.

Table ES-1 Summary of initial capital costs (2020$/kW) for hydropower projects (1980 to 2021).

	Minimum (2020$/kW)	**Maximum** (2020$/kW)	**Average** (2020$/kW)
Non-Powered Dams	398	91,604	5,048
New Stream Development	945	16,493	4,909
Pumped Storage	288	12,824	2,009
Canal/Conduit	1,167	26,531	7,449
Capacity Expansion	106	14,867	1,740
Generator Rewind	33	432	148

Costs per kW were noticeably lower for NPD projects with high relative to low hydraulic heads. In contrast, cost distributions for low-head and high-head NSD projects are similar to the values for high-head NPD projects. Self-selection bias may be one explanation for the low costs of NSD projects as developers tend to focus on low-cost greenfield projects. Cost data for the capacity expansion and generator rewind projects at existing powerhouses show average costs of about $1,740/kW, and $148/kW, respectively.

The parametric BCMH equations estimated from the data compiled in this study are intended to generate representative cost estimates suitable for initial national or regional-scale evaluation of hydropower cost competitiveness. These equations can be used to estimate the cost of constructing a hydropower plant at the reconnaissance stage based on estimates for a few key parameters, including capacity, hydraulic head, flow, and development stage. The modeled costs represent average capital costs to construct/modify generating facilities, impoundment structures, and supporting water conveyance infrastructure. The actual cost of developing a project may vary owing to unique, site-specific conditions that cannot be accommodated with the available data. In addition, the O&M cost model was developed using FERC Form 1 data. Following a similar statistical approach to the development of the ICC models, the annual O&M model is based on key variables, such as capacity, age, and capacity factor. All models use the log-log specification, and many of the coefficients are significant and have the expected signs. All costs are escalated to 2020 dollars (2020$) for estimating the equations.

The BCMH is now available as an Excel Workbook tool to aid stakeholders' use for the rapid evaluation of costs[1]. Since the BCMH coefficient estimates depend on the available data sample, particular attention is necessary when applying the model to projects that are outside the range of sample data. In addition, the BCMH equations cannot fully account for the multiple determinants of costs, and necessarily predict costs with varying degrees of accuracy. Therefore, mean-response and prediction confidence interval estimates around the estimated costs were evaluated to account for these sources of uncertainty. In-sample estimates show that nearly all observations are within the 95% prediction-interval boundaries whereas only the most accurately estimated observations are within the narrower 95% mean-response confidence interval boundaries.

Throughout this report, substantial discussions of the data are included in order to provide the reader with a transparent evaluation of the strengths, limitations, and appropriate uses for each of the BCMH sub-models. The data quality framework discussed in this and previous BCMH documents will be used for the continual updating of the data and re-evaluation of the sub-models.

[1] https://hydrosource.ornl.gov/data/datasets/updated-baseline-cost-model-hydropower-2025/

1. INTRODUCTION

1.1 BACKGROUND

Hydropower currently contributes about 80 GW of conventional and 23 GW of pumped storage capacity to the United States (US) power grid. Previous studies have estimated a considerable amount of remaining US hydropower resources, including non-powered dams (NPD) (Hadjerioua et al., 2012), new stream-reach developments (NSD) (Kao et al., 2014), pumped storage hydropower (PSH) and canal/conduit (Kao et al., 2022). The combined theoretical capacity potential of these various hydropower resources is comparable to the existing US hydropower capacity. There is a continuing interest in developing this hydropower potential, particularly to help meet the increasing demand for electricity. However, available data (Sasthav and Oladosu, 2022) show that the rate of new hydropower development has slowed considerably over time despite the interest of industry stakeholders. This is partly due to the competition from other energy resources and from the highly dispersed nature of remaining hydropower resources, which lead to high information requirements for evaluating the feasibility of potential projects.

Cost information provides the most succinct summary of the feasibility of a potential hydropower project required by stakeholders, including developers, investors, policymakers, consumer groups, etc., considering investment options. The best estimates of hydropower costs can be obtained through detailed engineering design and cost assessments of individual projects. However, this approach has high data and resource (time, funds, cross-disciplinary expertise) requirements that render it inapplicable for rapid cost estimation with limited data. Although innovative approaches can overcome some of these impediments (see Oladosu and Ma, 2024 for such an application to potential NPD projects), the development of such approaches still requires significant amounts of resources and are not generally applicable to all hydropower project types. Therefore, statistical and parametric methods using simpler cost specifications remain of significant utility to hydropower stakeholders and are, at the least, complementary to more detailed approaches, particularly when evaluating many potential projects.

1.2 PURPOSE AND PLAN

The Baseline Cost Model for Hydropower (BCMH) was developed at ORNL to fill the cost information gap for hydropower project evaluation using historical project data (O'Connor et al., 2015). The BCMH includes 1) equations for estimating the aggregate initial capital cost (ICC) of developing six categories of hydropower projects in the US and 2) an equation for estimating the average cost of hydropower plant operation and maintenance (O&M).

The current iteration of the BCMH builds on the previous version, which was last published in 2015, to support stakeholders' need for preliminary insights into the aggregate costs of different types of hydropower projects. This information is useful for hydropower research, initial project evaluations of national hydropower costs, and strategic planning by policymakers, such as the DOE Water Power Technologies Office (WPTO) and the Federal Electricity Regulatory Commission (FERC), hydropower developers or utilities evaluating potential projects, and other stakeholders that require cost data on potential hydropower projects.

The BCMH includes four sub-models for evaluating the capital costs of new hydropower where no powerhouse currently exists, including:

1. **Non-powered Dams (NPD)** – Encompassing the construction of a new powerhouse at existing dams or other facilities. This sub-model may also be useful for estimating the costs of adding a powerhouse to an existing powered dam.

2. **New Stream-reach Development (NSD) projects** – Greenfield projects with no existing facilities.

3. **Canal or Conduit projects** (Canal) –Power development at existing canals or conduits.

4. **Pumped Storage Hydropower (PSH) projects** – Connects an upper and lower reservoir via a pump-turbine arrangement to provide energy generation as well as pumping power for maintaining storage availability.

The BCMH also includes two sub-models for evaluating the potential costs of modifying existing powerhouses under two categories:

1. **Capacity Expansion projects (CXP)** – Existing plant renovation or expansion that clearly involves a change in installed capacity. This type of project may include acquisition and installation of a new turbine-generator unit but excludes construction of a new powerhouse.

2. **Generator Rewind projects (GRW)** – Generator refurbishment to improve efficiency, extend unit service life or repair a damaged unit.

In addition, there is a BCMH sub-model for evaluating the O&M costs of hydropower projects.

This report documents significant updates to the 2015 BCMH version including updates to the historical database for the model to 2021, revised specifications that improve the estimation efficiency for the various sub-models by reducing the need to split the data and estimate separate models along dimensions, such as capacity groups and project status, and the transformation of the BCMH into an Excel Workbook tool for improved accessibility to stakeholders.

The rest of the report is organized as follows. Section 2 discusses data sources and presents summaries of the data for the seven BCMH sub-models. Section 3 presents the revised specifications for each sub-model. Section 4 presents the BCMH Workbook tool and instructions for its use and discusses uncertainty evaluation of the cost estimates. Section 5 ends with conclusions and potential future efforts. Additional information is available in Appendix A, which presents alternative models based on different restrictions on the time span of the data used to estimate the ICC where applicable.

2. DATA SOURCES AND OVERVIEW

2.1 DATA SOURCES

Similar to the 2015 version, the dataset for the BCMH updates discussed in this report was obtained from two main sources. The first source is the Industrial Info Resources (IIR) PECWeb database (IIR, 2021) which provides proprietary information on industrial investment activities. ORNL subscribes to the hydropower section of the IIR database. The second source of data is the publicly available Federal Energy Regulatory Commission (FERC) Form 1 database (FERC, 2020), which provides data collected from utilities that are subject to certain submission criteria. Other sources of data for the 2015 BCMH version include FERC license application documents and a series of reports retrospectively detailing the activities of the Department of Energy's (DOE) small hydropower development efforts in the late 1970s and early 1980s (DOE and EPRI, 1985a, 1985b, 1986, 1987). A description of these additional data sources can be found in the 2015 BCMH documentation (O'Connor et al., 2015).

The IIR data, complemented by data from other sources included in the 2015 BCMH, were used to update the BCMH capital cost dataset. Since the resulting data are aggregate project investment values, these are assumed to represent the overnight capital costs of project construction, including the cost of licensing and studies but not financing costs. Capital cost data from the Form 1 database were excluded due to a couple of issues. First, the Form 1 capital cost data were recorded from year to year in cumulative nominal values, making it difficult to associate a specific year with the costs. Second, most of the plants in the Form 1 database were constructed many decades ago relative to the 1994 starting point of the database. For example, only 8 of the 198 "Large Hydro" plants extracted from the Form 1 database were constructed after 1980. Thus, the Form 1 capital cost data are less relevant to potential new hydropower projects due to both the age of the plants and difficulties with timing the capital expenditures. In contrast, the data from the IIR and other sources are provided for specific hydropower projects at the planning, engineering or construction stages.

The FERC Form 1 database is the only available public source with consistent estimates of hydropower O&M costs and was used for the O&M sub-model in the updated BCMH. Since the Form 1 O&M data are annual values, they do not suffer from the nominal cumulative and plant age issues associated with the capital cost data. Oladosu and Sasthav (2022) provided a detailed review of the Form 1 dataset, exploring plant characteristics, plant operation measures, capital costs and O&M costs for conventional and PSH plants.

2.2 DATA PROCESSING

Several steps were necessary to generate the final dataset used for updating the BCMH from the original sources. Oladosu and Sasthav (2022) described the steps for processing the Form 1 database used for the O&M sub-model. The highlights below are similar to those used for the Form 1 database but apply strictly to processing the IIR and other data sources used for the BCMH capital cost sub-models:

1. **Mapping categories of projects from the original sources to the categories in the BCMH**. In many cases, project types in the original sources are not consistent within the dataset or cannot be directly matched to the BCMH project categories. Issues include use of different names for the same category of projects, use of shorthand, instead of full category names, and typographical errors, but the most serious issue is incorrect classification of project types. Ultimately, the description column of the IIR data was used to manually identify a set of 26 text strings that more accurately reflect the project types and were mapped to the BCMH project categories. The project categories in the non-IIR capital cost data from the 2015 BCMH dataset were also re-examined and corrected as needed.

2. **Filling in missing data**. A few variables needed for the BCMH model were not present in the key data sources. Projects in the 2021 IIR dataset do not include estimates of hydraulic head which is an important variable for modeling the cost of new hydropower plants. This was addressed in the following ways. Projects common to both the 2021 and 2015 IIR datasets were identified and the associated hydraulic head values from the latter were added to the corresponding 2021 data points. In addition, we evaluated other potential sources of data, including hydropower datasets on the ORNL HydroSource website, FERC license documents, and online resources. Together, these additional sources provided hydraulic head estimates for a large number of the projects, but a significant number of projects remained without this data. Values in the IIR capacity column were also validated by examining other references to project capacity in the dataset, such as the project long name and description columns. This approach helped fill missing capacity values and resolve errors in stated values. In particular, many of the capacity values for capacity expansion and generator rewind projects were corrected because these frequently represented the entire plant, rather than the added or rewound, capacity.

3. **Identifying and dropping duplicate data points**. As previously discussed, we combined data from the 2015 BCMH dataset with available updates as of 2021 to increase the number of data points in the updated BCMH. Given this, several projects are duplicated in the initial combined dataset, particularly between the IIR 2015 and 2021 databases. The duplicates were identified and dropped from the combined dataset. Projects that were reported at different stages of the development process are retained in the dataset because they are crucial for understanding how cost estimates change with a project's status.

4. **Escalating monetary values to 2020-dollar values (2020$)**. The data points in the dataset are reported in different years, so there is no single base year for translating reported cost estimates to a common dollar year. For the purposes of the BCMH we use 2020 as the common dollar year with the report year for each data point used as the base year. The escalation factors were based on the annual composite hydropower construction cost trends from the Bureau of Reclamation (USBR, 2021). The Form 1 data were escalated to 2020$ using a similar approach as discussed in Oladosu and Sasthav (2022).

2.3 CAPITAL EXPENDITURE DATA OVERVIEW

Figure 1 shows the capital expenditure dataset for the four new hydropower project categories (NPD, NSD, Canal, PSH) while Figure 2 shows the data for the capacity expansion (CXP) and generator rewind (GRW) project categories. Data for most categories are concentrated in the 1980 to 1990 and 2010 to 2020 periods. However, NPD projects are also spread across the 1990 to 2020 period and there is a sizable number of PSH projects centered around 1990. The projects in the 1980 to 1990 period are associated with data from non-IIR sources.

The distribution of projects over the 1990 to 2020 period likely reflects a combination of the recent nature of the IIR hydropower database and the increased interest in hydropower development. In any case, the data implies a sustained interest in the development of NPD and PSH hydropower projects over time. Despite the sizable number of projects in the Construction stage, which are either completed or under construction, the majority of NPD and PSH projects in Figure 1 were in the Planning and Engineering stages, particularly during the most recent decade of the data. Most of the Canal projects reported during the 2000 to 2020 period were in the Engineering and the Construction stages. This is in contrast to Canal projects data reported during the 1980 to 1990 period which were either in the Construction or Planning stages. NSD projects in Figure 1 are mostly in the Planning or Engineering stages across all years, and the overall number of projects in the development cycle was low relative to the other project categories. Figure 2 shows that data for GRW and CXP projects are mostly available during the 2000 to 2020 period with a concentration around 2010.

The maximum capital cost estimate in Figure 1 is about $25,000/kW but most projects are below $10,000/kW, and nearly all PSH projects are below $5,000/kW. The cost of CXP projects in Figure 2 are generally under $3,000/kW but a few projects (not shown in Figure 2) were as high as $15,000/kW whereas nearly all costs for GRW projects are below $500/kW. Figure 3 shows a boxplot summary of capital cost data for the four new hydropower project categories in the Construction stage. The NPD and NSD projects are each divided into low- (≤32.8 ft or 10 m) and high-head (>32.8 ft) projects; Canal and PSH are not split by hydraulic head because they are generally high-head hydropower projects. The boxes represent the spread between lower (25th percentile) and upper (75th percentile) quartiles and are known as the interquartile (IQR) range while the whiskers are the furthest data points within 1.5*IQR of the lower and upper quartiles. The lower and upper quartiles are, respectively, $2,864/kW and $6,363/kW for Canal projects, $2,976/kW and $4,894/kW for NSD (low-head), $3,836/kW and $4,537/kW for NSD (high-head), $4,179/kW and $9,370/kW for NPD (low-head), $2,912/kW and $5,821/kW for NPD (high-head), and $828/kW and $1,644/kW for PSH projects. This confirms the general observation that PSH projects have the lowest cost per kW as observed in Figure 1. These estimates suggest significant scale economics for NPD projects with lower and upper quartile values for low-head NPD projects that are about twice those for high-head NPD projects. In contrast, the lower and upper quartiles for low-head and high-head NSD projects are similar to the values for high-head NPD projects. Since NSD are greenfield projects, this may reflect self-selection bias as developers tend to focus only on low cost NSD sites for new development projects. The presence of an existing dam may help motivate NPD development for other reasons in addition to hydropower. The highly variable features of the NSD projects also means that differences in head may be inadequate for grouping the project costs. Additional information about sources and insight into the data are discussed below for each of the six capital project categories.

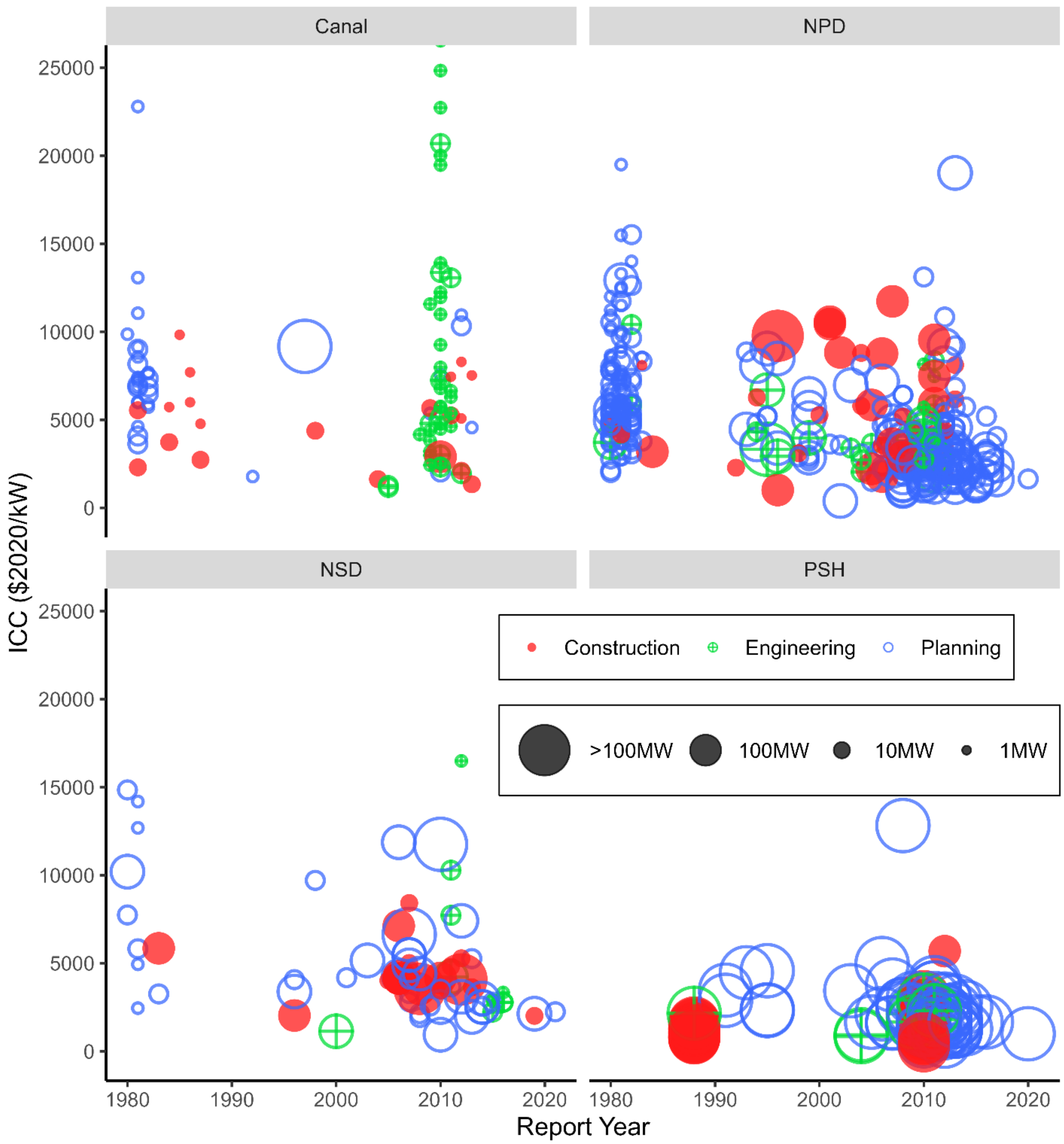

Figure 1. Historical ICC (2020$/kW) by size, development stage and year for new hydropower projects.

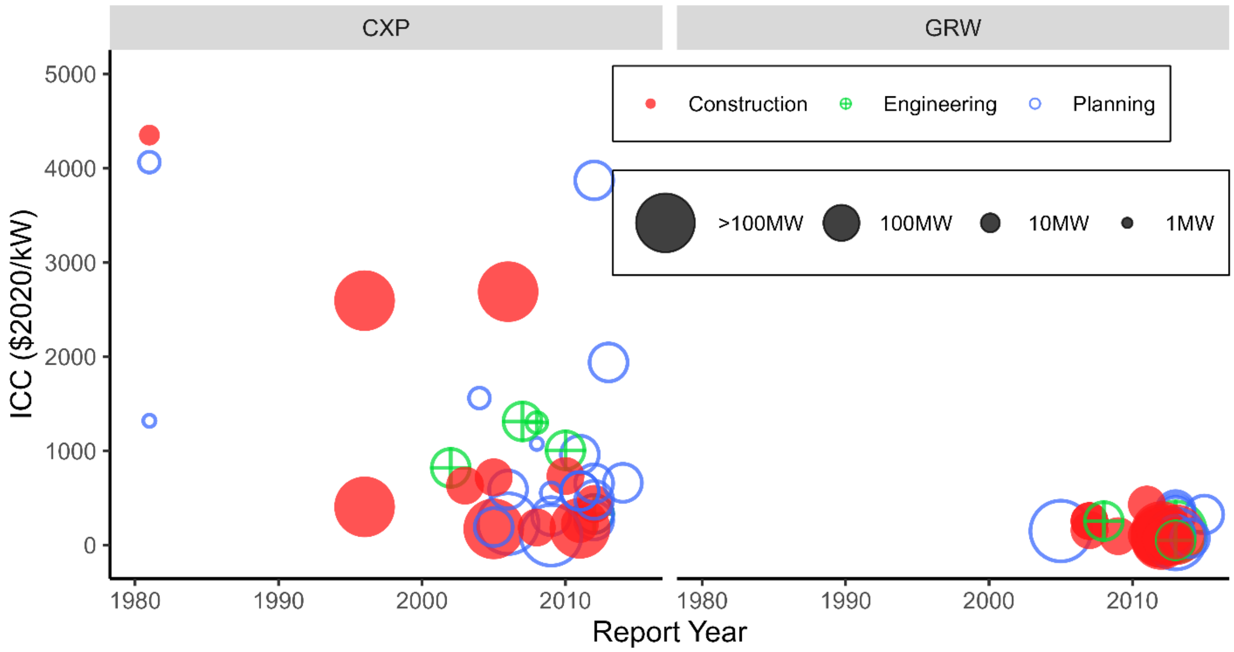

Figure 2. Historical ICC (2020$/kW) by size and year for generator rewind and capacity expansion hydropower projects.

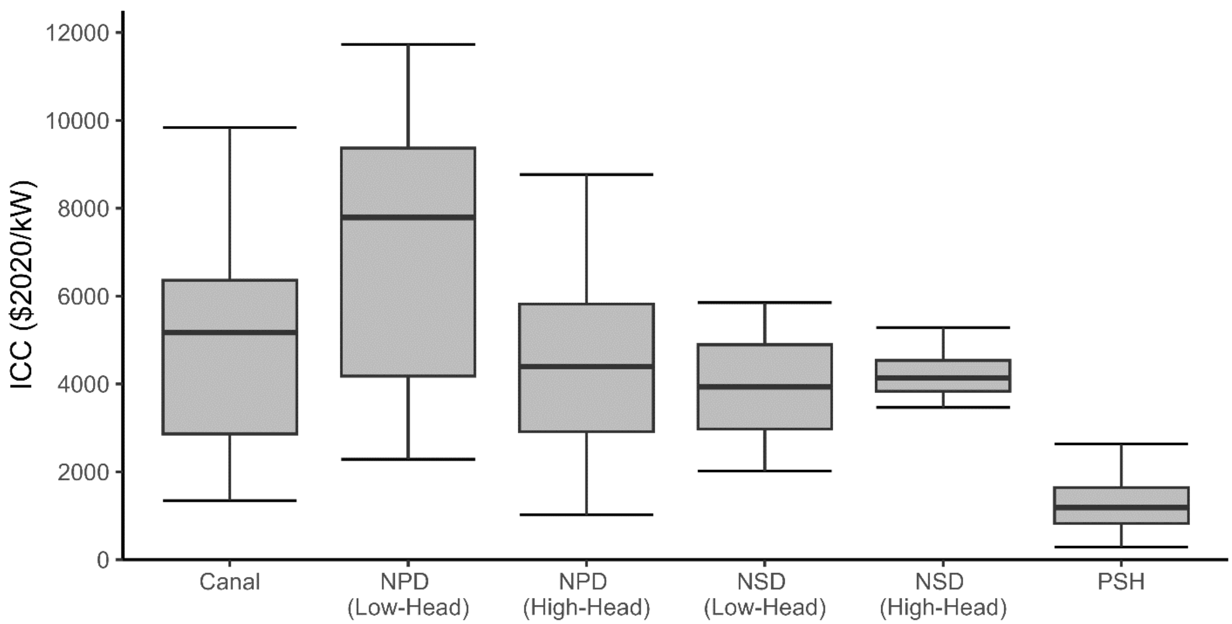

Figure 3. ICC (2020$/kW) distribution for projects in the Construction stage.

2.3.1 NON-POWERED DAMS (NPD)

The updated BCMH dataset included 510 NPD projects. Of these, 84 were excluded due to duplication (73), lack of capacity information (3), and lack of hydraulic head information (8). Thus, the final NPD dataset includes 426 projects. Table 1 shows the NPD data by source, project development stage, project capacity, and hydraulic head. More than half of the data were from IIR and a slightly lower number from EPRI. Most of the projects (83%) are reported in the planning stage (P-stage) and the projects in the construction stage (C-stage) are mostly from the IIR database. The project capacities range from 34 kW to 149 MW with hydraulic head values ranging from about 5 ft to 1,800 ft. Figure 4 shows the distribution of costs per kW and capacities of the NPD projects by stage, confirming the predominance of P-stage projects. It also shows that estimated per kW costs have an inverse relationship with capacity for P-stage projects, but the same pattern is not observed for C-stage projects. However, the cost ranges of projects in the C- and engineering stage (E-stage) are narrower than for the P-stage projects indicating that NPD projects with costs estimates above $15,000/kW generally do not move beyond the latter development stage.

Table 1. NPD projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
EPRI	179	171	4	4	0.07	3.70	22.92	8.00	67.94	1040
IIR	216	181	9	26	0.25	19.52	149	4.87	71.87	1800
FERC	19	5	14	0	0.21	12.50	48	13	111.32	700
Other	12	0	5	7	0.034	24.49	84	10	68.64	262.5

Project Development Stage: P - Planning, E - Engineering, and C - Construction[2]
Other sources: DOE (2014) - 2 projects, ETO (2010) - 2 projects, Consultant - 4 projects, Online Public Records – 1 project, Hydro Finance Summit (2013) – 3 projects.

2.3.2 NEW STREAM-REACH DEVELOPMENT (NSD)

The updated BCMH dataset included 111 NSD projects. Of these, 20 were excluded due to duplication (6), and lack of hydraulic head information (14). Thus, the final NSD dataset included 91 projects, Table 2 shows the NSD data by source, project development stage, project capacity, and hydraulic head. The majority of the data were from the IIR database. The NSD projects are more evenly distributed across the development stages than the NPD data with about 58% in the planning (P-stage). Unlike NPD

[2] Planning stage refers to the period before project design, which includes site identification, feasibility and other studies, preliminary and detail designs, permitting, etc.; Engineering stage refers to the period of funding approvals, production of construction plans, identification and contract awards for materials, equipment and construction teams, site preparation, etc.; Construction stage refers to the period of physical project installation, completion and maintenance. These stages, while broadly separate in the lifecycle of a hydropower project are not necessarily distinct from each other. For example, depending on regulatory requirements, one project must obtain permits to begin evaluation of a project site with final licensing depending on information only available after detailed studies and design while another project may be licensed based on limited information.

projects, about two-thirds of projects in the construction stage (C-stage) are mostly from non-IIR sources. The project capacities range from 163 kW to 824 MW with hydraulic head values ranging from about 9 ft to 1,900 ft. Figure **5** shows the distribution of costs per kW and capacities of the NSD projects by stage, confirming the predominance of P-stage projects. Although having a smaller number of projects, the cost-capacity relationship and differences across the development stages are similar to those for NPD projects.

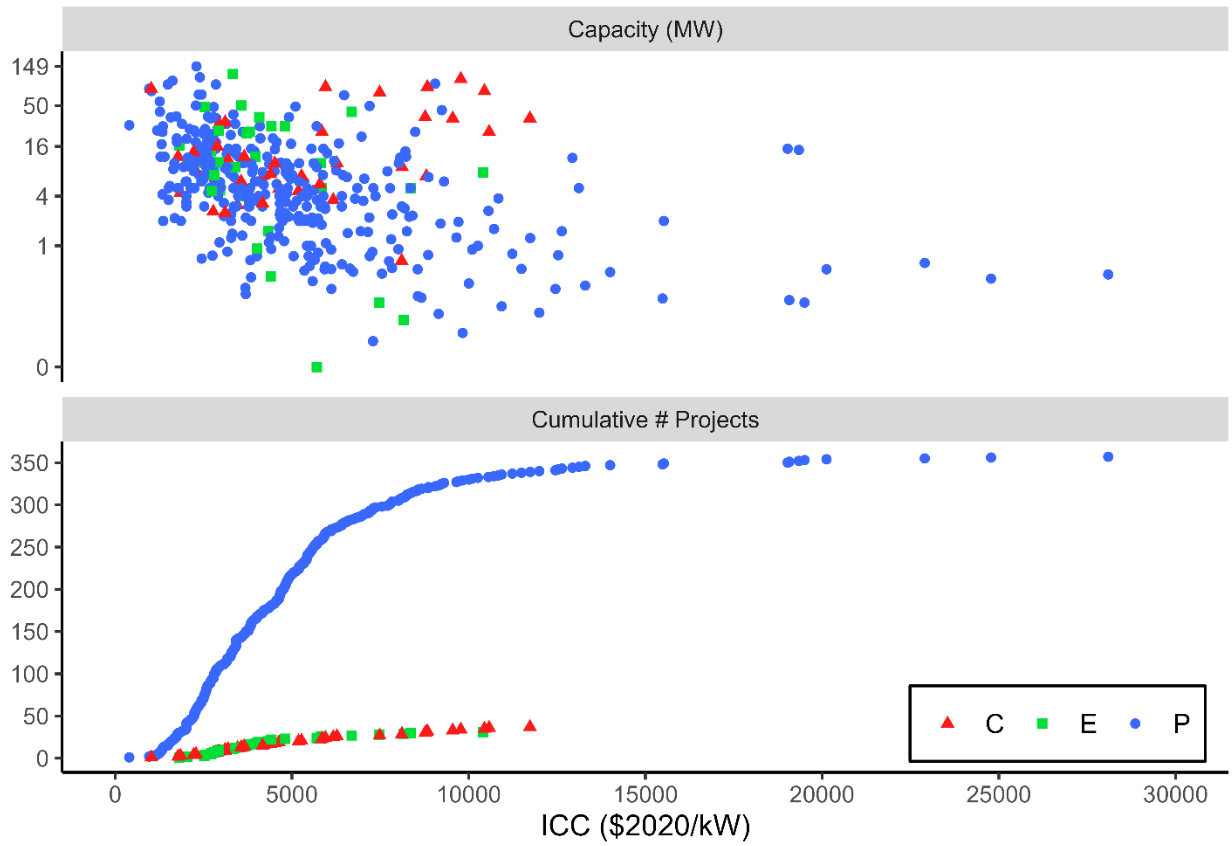

Figure 4. ICC (2020$/kW) distribution and capacity for NPD projects by stage.
(Note: Capacity axis is in log-base 2).

Table 2. NSD projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
EPRI	16	14	1	1	0.163	3.88	24	10	74.54	313
IIR	43	36	0	7	2.50	41.38	600	8.4	782.84	3050
FERC	9	3	6	0	0.40	46.3	121.5	12.25	335.81	965.5
Other	23	0	9	14	0.50	64	824	10	533.65	1896.3

Project Development Stage: P - Planning, E - Engineering, and C – Construction
Other sources: Consultant – 21 projects, TVA (1941) – 1 project, Online Public Records - 1 project.

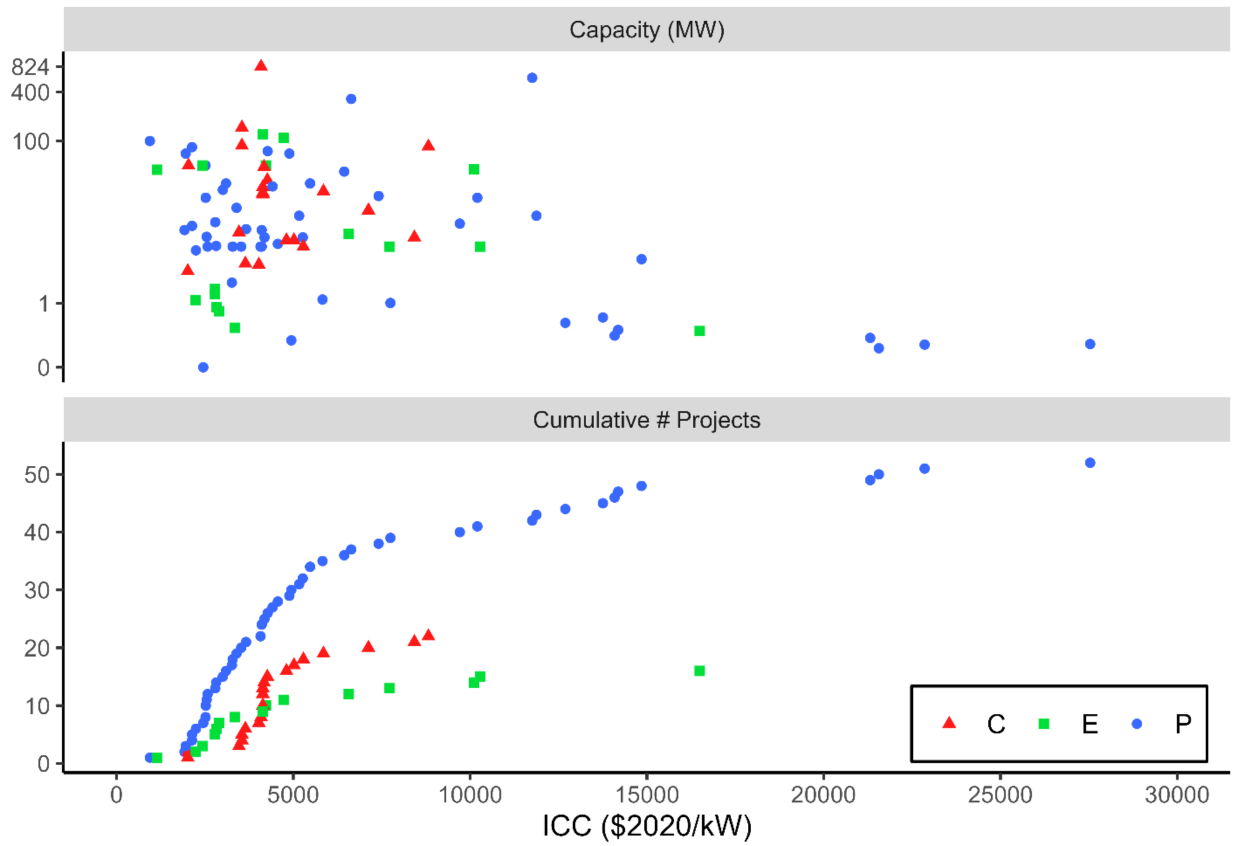

Figure 5. ICC (2020$/kW) distribution and capacity for NSD projects by stage.
(Note: Capacity axis is in log-base 2)

2.3.3 CANAL/CONDUITS (Canal)

The updated BCMH dataset included 118 Canal projects. Of these, 18 were excluded due to duplication (12), and lack of cost information (6). Thus, the final Canal dataset included 100 projects, Table 3 shows the Canal data by source, project development stage, project capacity, and hydraulic head. The majority of data were from the IIR database. The Canal projects were mostly in the P- and E-stages, with only 20% in the C-stage which are from non-IIR sources. The project capacities range from 10 kW to 150 MW with hydraulic head values ranging from about 5 ft to nearly 2,000 ft. Figure 6 shows the distribution of costs per kW and capacities of the Canal projects by stage. Although all project stages show a similar inverse cost-capacity relationship, projects in the C-stage are all below $10,000/kW.

Table 3. Canal/Conduit projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
EPRI	34	29	1	4	0.10	2.24	15	21.20	179.54	904
IIR	5	4	0	1	1.00	34.52	150	146	657.40	1971
FERC	10	4	6	0	0.23	2.26	7.15	33.5	197.45	445
Other	51	1	35	15	0.01	0.98	5	5	238.05	1847

Project Development Stage: P - Planning, E - Engineering, and C – Construction
Other sources: Consultant – 1 project, City of Boulder (2013) – 8 projects, COID (2011) – 5 projects, ETO (2010) – 24 projects, NUID (2009) – 4 projects, Butterfield (2011) – 1 project, Online – 8 projects

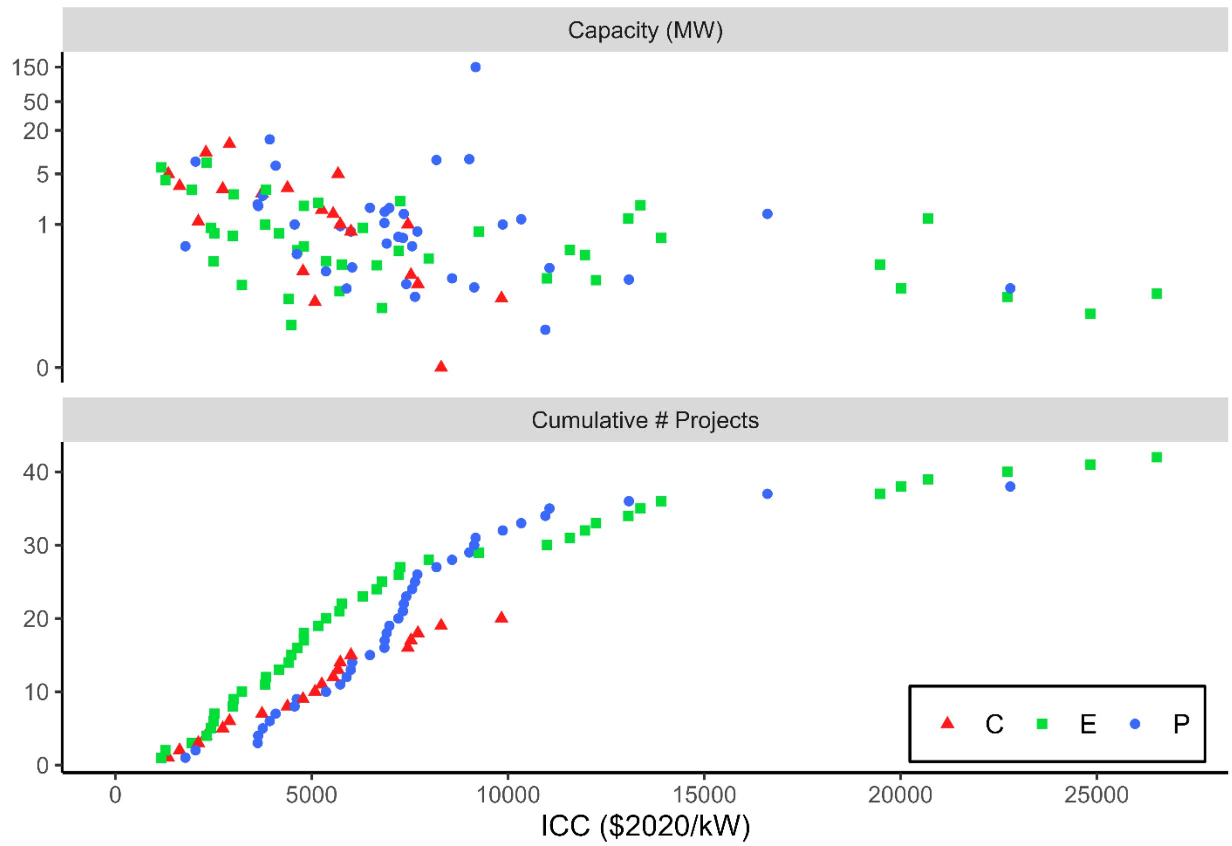

Figure 6. ICC (2020$/kW) distribution and capacity for Canal projects by stage. (Note: Capacity axis is in log-base 2)

2.3.4 PUMPED STORAGE HYDROPOWER (PSH)

The updated BCMH dataset included 190 PSH projects. Of these, 75 were excluded due to duplication (25), and lack of cost information (50). Table 4 shows the PSH data by source, project development stage, project capacity, and hydraulic head. The majority of data were from the IIR database. The PSH projects were nearly all P-stage with only 25 projects in the C-stage. The majority of projects are from the IIR database but nearly all projects in the C-stage are from EPRI. The project capacities range from 40 MW to nearly 3,000 MW with hydraulic head values ranging from about 130 ft to nearly 3,000 ft. Figure 7 shows the distribution of costs per kW and capacities of the PSH projects by stage. Although nearly all projects have cost estimates below $5,000/kW, there is no clear cost-capacity pattern for all development stages. In particular, cost per kW for projects in the C-stage are clustered around $1,000/kW.

Table 4. Pumped Storage projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
EPRI	33	9	0	24	75	890.8	2820	127	1088.7	2684
IIR	72	72	0	0	85	657.5	2000	180	1311.7	2860
FERC	2	0	2	0	1000	1000	1000	1205	1535.5	1866
Other	8	0	7	1	40	698.6	1500	295.3	881.0	1246.7

Project Development Stage: P - Planning, E - Engineering, and C – Construction
Other sources: Consultant – 4 projects, City of San Diego – 1 project, Bureau of Reclamation – 1 project, IEEE journal – 2 projects.

2.3.5 CAPACITY EXPANSION (CXP)

The installation of a new or replacement of an existing turbine-generator unit in an existing powerhouse that increases plant capacity is referred to here as a “Capacity Expansion” project (CXP). The updated BCMH database included 86 CXP projects, of which 35 were excluded due to duplication (9) and lack of hydraulic head information (26). Thus, the final database has 51 CXP projects, most of which are from the IIR database (30), including 11 of the 12 in the C-stage, and EPRI (16) as shown in Table 5. The project capacities range from 133 kW to nearly 1,461 MW with hydraulic head values ranging from about 7 ft to more than 1,100 ft. Figure 8 shows the cost per kW distribution and capacities of the CXP projects by stage. There is a general inverse cost-capacity relationship, particularly for P-stage projects and all projects in the C-stage are below $5,000/kW.

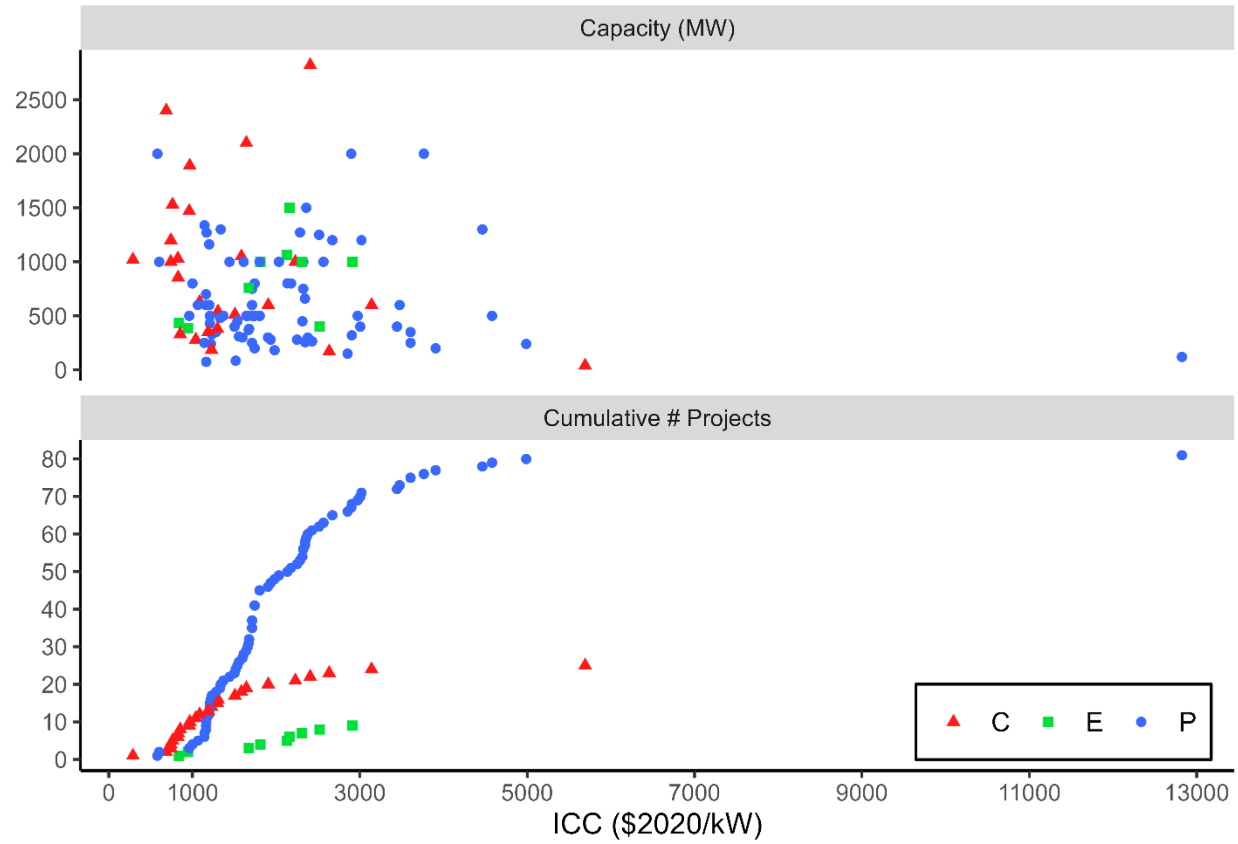

Figure 7. ICC (2020$/kW) distribution and capacity for PSH projects by stage.

Table 5. Capacity Expansion projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
EPRI	16	15	0	1	0.133	1.33	3.64	7.2	29.75	63
IIR	30	16	3	11	5.8	113.5	1461	21	194.85	1136
FERC	4	2	2	0	0.14	56.27	200.03	65.70	459.81	1072
Other	1	1	0	0	8.1	8.10	8.10	320	320	320

Project Development Stage: P - Planning, E - Engineering, and C – Construction
Other sources: Online Public Records – 1 project

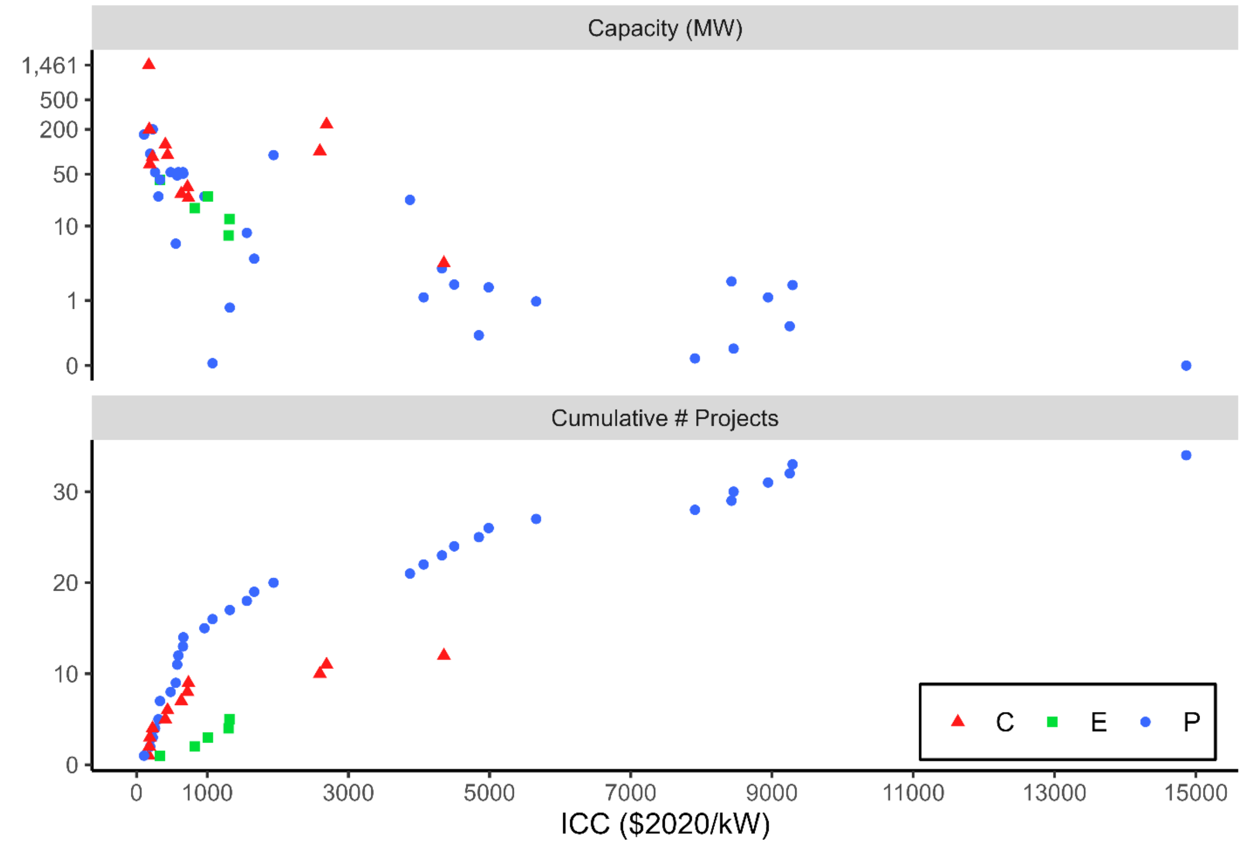

Figure 8. ICC (2020$/kW) distribution and capacity for CXP projects by stage.
(Note: Capacity axis is in log-base 2)

2.3.6 GENERATOR REWIND (GRW)

The updated BCMH database included 78 Generator Rewind (GRW) projects, but more than half (44) were excluded due to duplication (3) and lack of hydraulic head information (41). Thus, the final database has only 34 GRW projects all from the IIR database as shown in Table 6 with most projects (20) in the C-stage. The project capacities range from 12 MW to nearly 660 MW with plant hydraulic heads of 20 ft to more than 1,300 ft.

Table 6. Generator Rewind projects summary statistics.

Data Source	Project Count	Development Stage (count)			Capacity (MW)			Head (ft)		
		P	E	C	Min	Avg	Max	Min	Avg	Max
IIR	34	9	5	20	12	102.3	660	20	310.74	1344

Project Development Stage: P - Planning, E - Engineering, and C – Construction

Figure 9 shows the cost per kW distribution and capacities of the GRW projects by stage. The lack of a discernible cost-capacity relationship is not surprising since these projects can vary greatly from plant to plant. The per kW cost range is generally below $500/kW as previously highlighted.

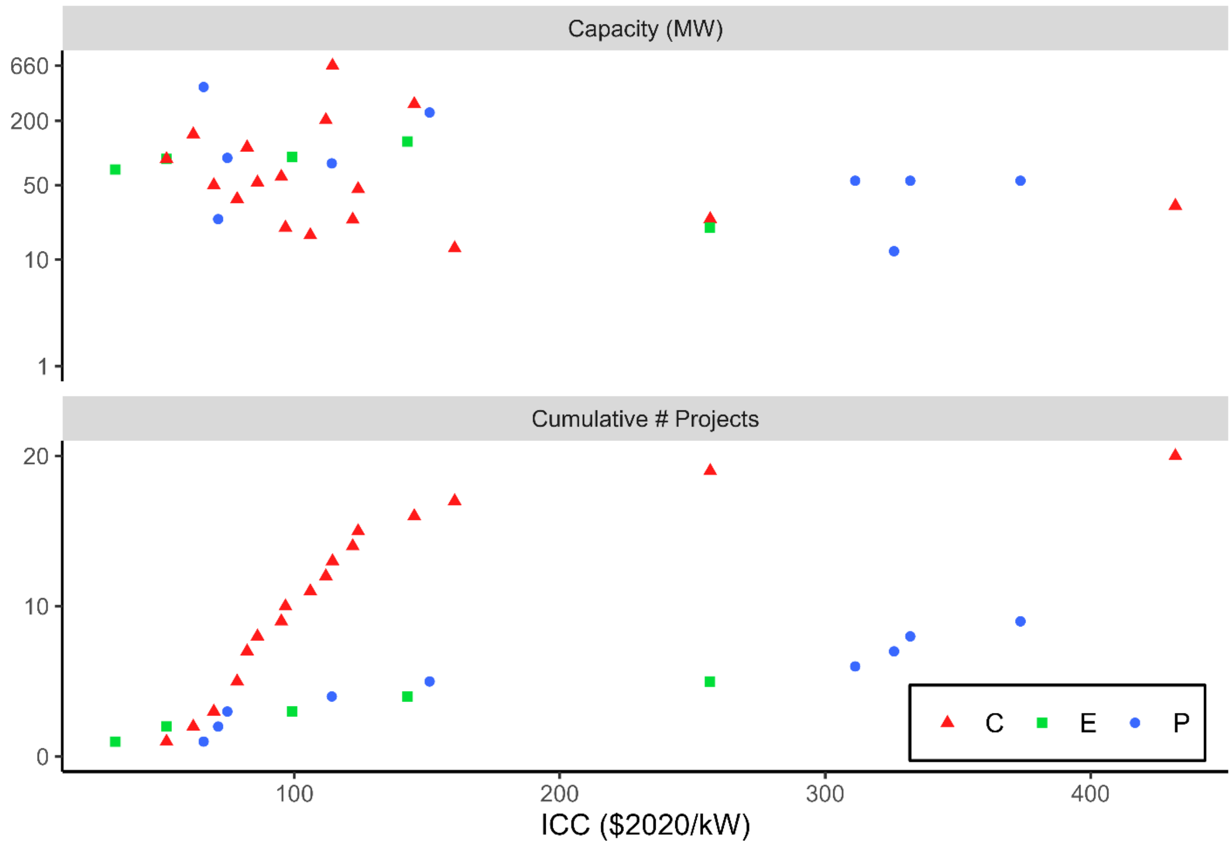

Figure 9. ICC (2020$/kW) distribution and capacity for GRW projects by stage.
(Note: Capacity axis is in log-base 2)

2.4 OPERATION AND MAINTENANCE (O&M) COST DATA OVERVIEW

The annual O&M cost data from the FERC Form 1 database spans the period from 1994 to 2020 and includes 413 unique plants. Figure 10 provides a boxplot summary of the per kW O&M costs for the 140 plants that have full data coverage from 1994 to 2020 and annual averages across all plants are plotted as points. The median cost has a range of $34/kW to $46/kW whereas the mean has a range of $43/kW to $58/kW with lower and upper quartile ranges of $21/kW to $29/kW and $54/kW to $68/kW, respectively. Although outliers are excluded from Figure 10, the lower and upper whiskers across all years cover a wide range of $2/kW to $128/kW reflecting the many characteristics that determine O&M expenditures on a given plant.

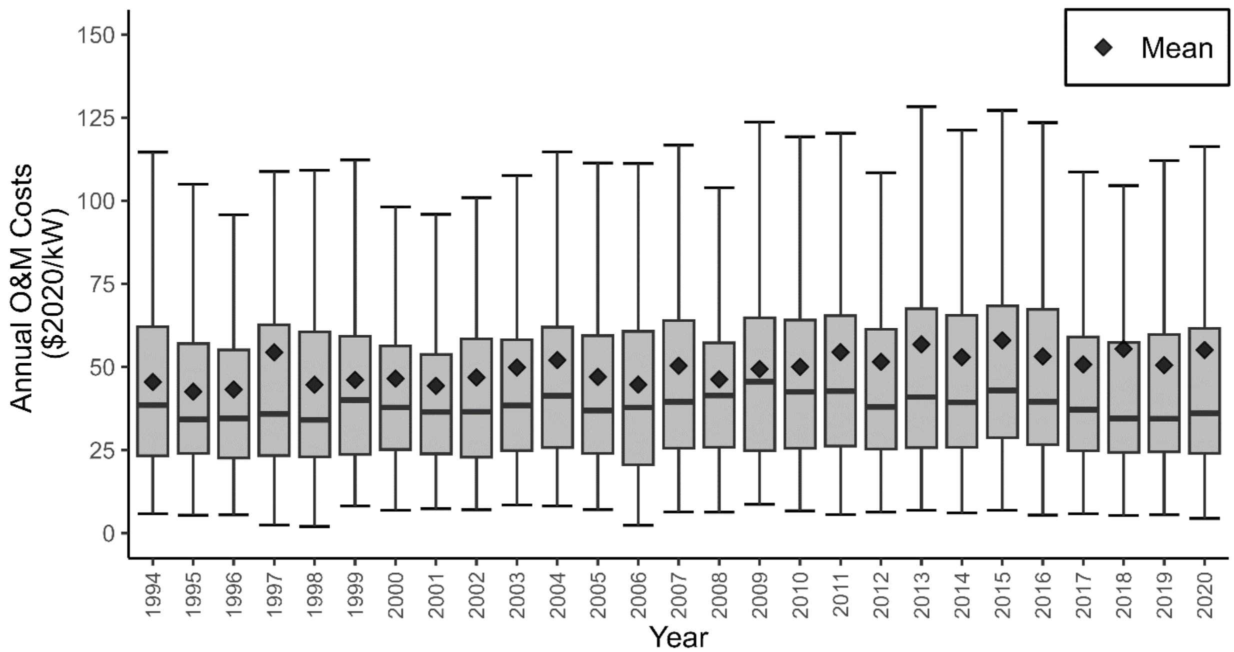

Figure 10. Historical annual average O&M cost trend, 1994-2020

Given that plants report data over multiple years, the FERC Form 1 provides a panel dataset of O&M costs. However, most of the available data on the determinants of O&M costs do not vary significantly over time, preventing a valid panel modeling approach. In addition, the O&M cost data for each plant has a high serial correlation (correlation over time). To reduce serial correlation issues, the analysis in this study uses only the O&M data from 2018 to 2020. Table 7 is a summary of this data which includes 272 unique plants with a capacity range of 500 kW to more than 1,700 MW. The most recent years of the O&M data are most relevant to current hydropower projects and three years are included to partly account for the cyclical nature of plant maintenance activities.

Figure 11 plots the annual average of the 2018 to 2020 O&M cost per kW data for each plant by installation year. Most of the costs are between $5/kW and $300/kW with a few low-capacity plants with costs above $1,000/kW. The per kW cost for higher capacity plants is typically low and shows a slight downward trend over time. Although the newer plants have lower O&M costs per kW, they are also generally larger projects. Note that most of the plants in the database were installed before the year 2000 but there are a few plants concentrated around 2010 with a lower capacity range of 10 MW to 100 MW.

Figure 12 shows the 2018 to 2020 plant O&M cost data points versus capacity and net generation in total, per kW, and per MWh terms. Total O&M costs in the top panels of Figure 12 show a clear positive relationship with both capacity and net generation, which is not surprising since the latter differs from the former only by the capacity factor. However, the higher scatter of the total costs chart on the lower generation end relative to the lower capacity end suggests that capacity factors may be more similar across larger plants than smaller plants. The per kW costs in the bottom panels of Figure 12 show a negative relationship with both capacity and net generation reflecting the importance of scale in determining per kW and per MWh O&M costs.

Table 7. O&M Cost projects summary statistics.

Data Source	Period of Coverage	Project Count	Capacity (MW)		
			Min	Avg	Max
FERC Form 1	2018-2020	272	0.50	85.83	1717.20

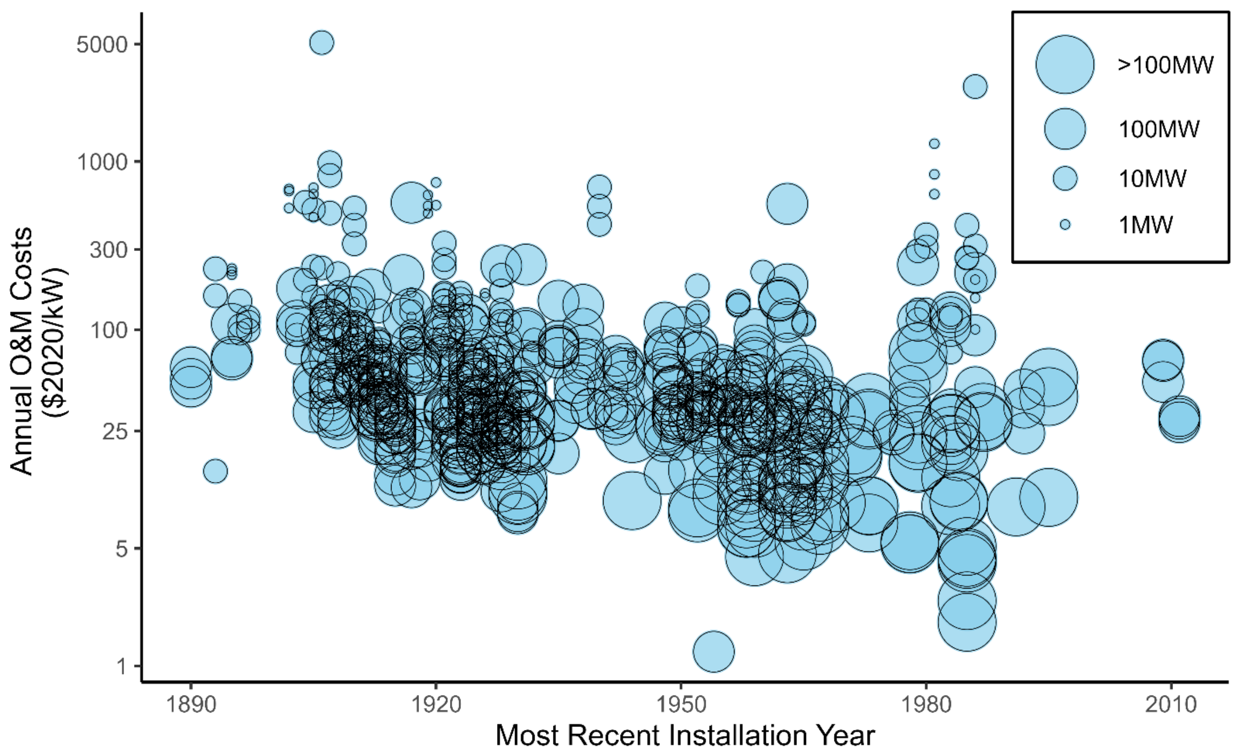

Figure 11. O&M cost trend by installation year and capacity: plant averages over 2018-2020.

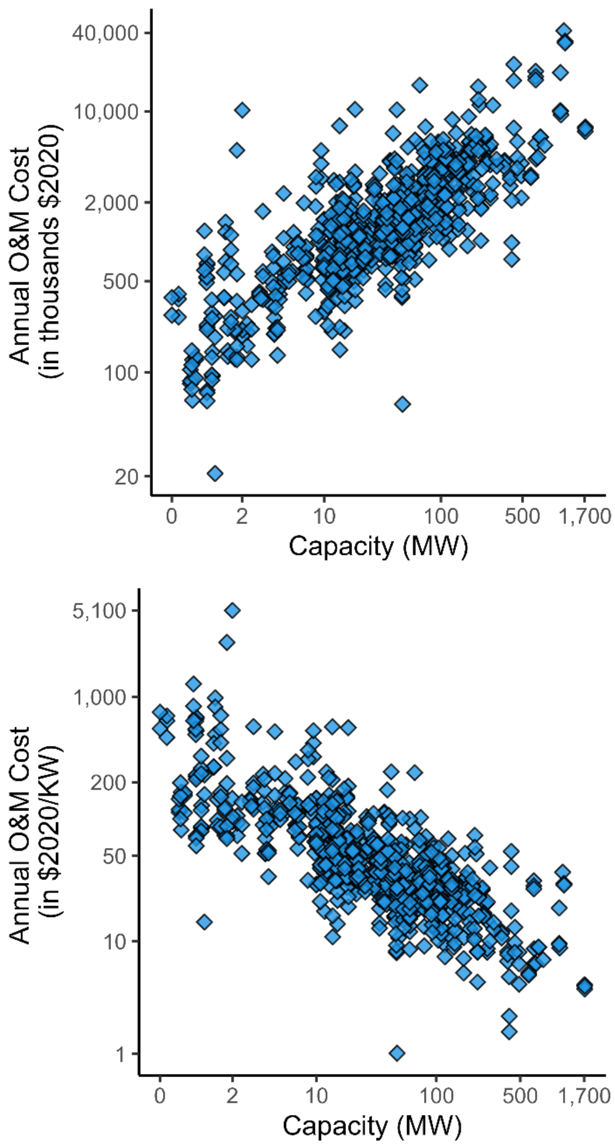

Figure 12. Plant O&M cost data versus capacity and net generation: 2018-2020.

3. MODEL SPECIFICATION AND ESTIMATION

3.1 INITIAL CAPITAL COST (ICC) SPECFICATIONS

The set of variables used in the ICC equations, approaches to bias correction, the ICC equation specifications and coefficient estimates for the six capital cost project categories are discussed in this section.

Table 8 shows the full set of variables used in the ICC specifications, but not all variables are included in each equation. ICC, capacity, added capacity and head values are directly from the updated BCMH dataset as previously discussed in section 2. As a reminder, the ICC data are aggregate investment estimates which are assumed to represent overnight capital costs, including construction, equipment, study and licensing costs but not the financing costs incurred during project development. The ICC data used for the model estimation is the total value in thousand dollars because models based on ICC in dollars per kW performed relatively poorly in tests of fit and prediction. In addition, a few other variables are calculated from the updated BCMH dataset. An estimate of design flows for the four new hydropower project categories are calculated from the data on capacity, hydraulic head and a nominal plant efficiency of 90% using the flow equation shown in Table 8. Three dummy variables (i.e. 0 or 1 values) were created from the stage column of the data to differentiate cost estimates produced during the *Planning*, *Engineering* and *Construction* stages of a project. Dummy variables were also used to differentiate projects by head, capacity and added capacity groups as described in Table 8. Finally, the report year column was used to generate three dummy variables to categorize the recentness of the data which partly reflects the age of plants reported in the *Construction* stage.

The model equations presented below use the log-log model specification, which transforms into a power function for the ICC levels. Also, the presence of dummy variables in the equations mean that the intercept term of the log-log model (or the scaling term in its power function transformation) varies with these characteristics. Four versions of each sub-model that differ only in the number of data points were estimated for each project category, except GRW (Generator Rewind) where the data points prevent further partitioning, as follows:

1. Model 1: All valid data as discussed in section 2.
2. Model 2: All valid data reported in year 2000 and later.
3. Model 3: All valid data with ICC ≤ \$15,000/kW.
4. Model 4: All valid data with ICC ≤ \$10,000/kW.

Root mean squared errors (RMSE) were calculated for the four model variants. The model variant with the smallest RMSE was chosen as the preferred model and its coefficients are presented in this section. Thus, model variants 2-4 are required to perform at least as well as model 1 in terms of the RMSE to be the preferred model.

Table 8. Variables used in the ICC specifications.

Variable	Description
ICC (10^3 dollars)	Project initial capital costs escalated to 2020 dollars.
Capacity (MW)	Project capacity in megawatts.
Added Capacity (MW)	Capacity addition in megawatts.
Head (ft)	The hydraulic head of the project in feet.
Flow (cfs)	Estimates of flows (assuming 0.9 efficiency) $Flow = \frac{3.28084 * 35.3147 * 1000 * \text{ Capacity}}{0.9 * 9.81 * \text{ Head}}$
Development Stages	P: Planning (P) E: Engineering (E) C: Construction (C)
Hydraulic Head Dummies	Hd30: 1 if the plant has head ≤ 30 ft. Hd60: 1 if the plant has head between 30 and 60 ft. Hd100: 1 if the plant has head between 60 and 100 ft. Hd100x: if the plant has head > 100 ft.
Capacity Dummies	Cap1: 1 if the plant has capacity ≤ 1MW. Cap10: 1 if the plant has capacity between 1 and 10 MW. Cap30: 1 if the plant has capacity between 10 and 30 MW. Cap100: 1 if the plant has capacity between 30 and 100 MW. Cap100x: 1 if the plant has capacity > 100 MW.
Added Capacity Dummies	AddCap1: 1 if the capacity addition ≤ 1 MW. AddCap10: 1 if the capacity addition is between 1 and 10 MW. AddCap30: 1 if the capacity addition is between 10 and 30MW. AddCap30x: 1 if the capacity addition > 30 MW.
Year Dummies (add year dummies in 20-year increments)	y20: 1 if the report year of the plant is after 2003. y40: 1 if the report year of the plant is between 1983 and 2002. y40x: 1 if the report year of the plant is 1982 or earlier.

Log-log linear regressions can introduce bias into the back-transformed level variables but can be corrected using different methods (Demetrescu et al., 2020). Bias correction is performed in this report using a linear regression of the original cost level, *ICC*, on the back-transformed fitted cost level from the log-log model estimate, $\widehat{ICC}$, as in equation (1).

$$ICC = \delta \widehat{ICC} + \varepsilon \qquad (1)$$

The estimated bias correction factor or multiplier, $\hat{\delta}$, is used to scale the back-transformed cost level predictions of the log-log model to obtain the final estimates.

3.1.1 NON-POWERED DAMS (NPD), NEW STREAM-REACH DEVELOPMENT (NSD) and CANAL/CONDUITS

The ICC specifications for NPD (Non-Powered Dam), NSD (New Stream-reach Development), and Canal (Canal/Conduit) projects are the same as shown in equation (2) and are presented together, but each model is estimated separately. The key variables are flow and hydraulic head, complemented by dummy variables for project stage, hydraulic head groups, capacity groups and report year groups. Note that the *P-stage*, *Hd100x*, *Cap100*/*Cap100x* and *yr20* dummy variables are dropped from equation (2) so that the baseline model (i.e. when all other dummy variables are set to zero) represents a plant with this combination of characteristics[3]. Since hydraulic power is a function of head and flow, the use of flow and head in equation (2) is a departure from the 2015 BCMH specification which used capacity and head reducing potential collinearity between power and head in the models.

$$ICC_i(in\ 2020\$) = e^{\left\{\begin{matrix}\beta_0+\beta_1 \ln(Flow_i)+\beta_2 \ln(Head_i)+\beta_3 C_i+\beta_4 E_i+\beta_5 Hd30_i+\beta_6 Hd60_i+ \\ \beta_7 Hd100_i+\beta_8 Cap1_i+\beta_9 Cap10_i+\beta_{10} Cap30_i+\beta_{11} y40_i+\beta_{12} y40x_i\end{matrix}\right\}} \quad (2)$$

The preferred model variants are Model 1 for NSD and Model 3 for NPD and Canal projects. Coefficient estimates for these models are presented in Table 9 with significance at the 1%, 5% and 10% levels indicated, and the standard errors in brackets. The preferred models are based on 415 NPD, 91 NSD, and 92 Canal data points and have R^2 values of 0.88 for NPD, 0.89 for NSD, and 0.88 for Canal projects. Bias correction factors are about 1.27 for NPD, 1.54 for NSD and about 1 for Canal projects, with the latter indicating very little bias from the log-log transformation. The flow and head coefficients are as expected positive and significant for all three project categories and close to 1, with only those for NSD slightly above 1.

Positive coefficients on the *C-stage* dummy variable mean that cost estimates for both NPD and NSD projects at this stage tend to be higher than in the *P-* and *E-*stages but only the NPD coefficient is significant. The *C-* and *E-stage* coefficients for Canal and the *E-stage* coefficient for NSD are negative and insignificant. The coefficients on hydraulic head dummies are all negative for NPD but positive for NSD and Canal projects. However, only the positive values on *Hd30* for NSD and *Hd100* for Canal projects are significant. The coefficients on the capacity dummies for NPD projects are all negative with only the *Cap30* being significant. The capacity dummies coefficients for Canal projects are also negative and significant, whereas those for NSD projects are positive. Most of the coefficients for the report year dummies are positive but significant only for NPD and NSD projects, which means that cost (in 2020-dollar values) for older projects tend to be higher than for more recent projects, all else equal. Appendix A presents the full set of coefficients for all four model variants for each of the project categories.

[3] Thus, the baseline model is Planning stage, head >100 ft, capacity > 30 MW, and report year after 2003. The two capacity dummies (Cap100 & Cap100x) were dropped because they are not well represented in the data and lead to singularity of the data matrix if not dropped from the estimation.

Table 9. ICC model estimates (NPD, NSD, and Canal Projects).

Variable	NPD (Model 3)	NSD (Model 1)	Canal (Model 3)
Intercept	0.7014	-4.612 ***	2.1176 *
	(0.6471)	(1.7139)	(1.0722)
ln(Flow)	0.8767 ***	1.1822 ***	0.8252 ***
	(0.0418)	(0.11)	(0.0646)
ln(Head)	0.7442 ***	1.2736 ***	0.8294 ***
	(0.073)	(0.1468)	(0.1022)
C-Stage	0.414 ***	0.0739	-0.112
	(0.0838)	(0.1589)	(0.2009)
E- Stage	0.1755 **	-0.2363	-0.1708
	(0.0873)	(0.1875)	(0.2073)
Hd30	-0.1251	0.7376 **	0.2385
(Head ≤ 30 ft)	(0.1622)	(0.3562)	(0.2995)
Hd60	-0.1759	0.3317	0.0615
(30 ft < Head ≤ 60 ft)	(0.1191)	(0.3265)	(0.2458)
Hd100	-0.1276	0.1567	0.3703 *
(60 ft < Head ≤ 100 ft)	(0.1002)	(0.3036)	(0.2085)
Cap1	-0.2228	1.363 **	-1.4913 **
(capacity ≤ 1 MW)	(0.2168)	(0.6212)	(0.671)
Cap10	-0.1919	0.7654 *	-1.6039 **
(1 MW < capacity ≤ 10 MW)	(0.1319)	(0.3862)	(0.6156)
Cap30	-0.2151 **	0.5908 **	-1.4403 **
(10 MW < capacity ≤ 30 MW)	(0.0986)	(0.2627)	(0.6838)
y40	0.3351 ***	-0.0339	0.0314
	(0.0786)	(0.2241)	(0.219)
y40x	0.5182 ***	0.9509 ***	0.1839
	(0.0593)	(0.1933)	(0.1923)
bias correction	1.2655	1.5381	1.0008
R^2	0.8804	0.9053	0.8936
Adjusted R^2	0.8768	0.8908	0.8775
N	415	91	92

Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.

3.1.2 PUMPED STORAGE HYDROPOWER (PSH)

The PSH (pumped storage hydropower) model specification is shown in equation (3). In addition to the flow and head variables only the project stage and one report year dummy variables could be accommodated in the equation. Attempts to include dummy variables for head and capacity groups, and the other report year dummies resulted in severe collinearity issues in the estimation. This is likely because the updated BCMH dataset for PSH projects consist mostly of all high-head and high-capacity projects with report years concentrated around 2010. The baseline model (i.e. when the dummy variables in equation (3) are all set to zero) can be described as in the *P*-stage with the data reported after 1982 but not between 1983 and 2002.

$$ICC_i(in\ 2020\$) = e^{\{\beta_0+\beta_1 \ln(Flow_i)+\beta_2 \ln(Head_i)+\beta_3 C_i+\beta_4 E_i+\beta_5 y40_i\}} \qquad (3)$$

The preferred PSH model variant is Model 4, which excludes projects with costs per kW greater than $10,000/kW but accounts for 114 of the 115 valid data points in the updated BCMH dataset. Table 10 shows coefficients for the preferred PSH model which has an R^2 value of 0.68 and a bias correction factor of 1.21. The flow and head coefficients are both positive, highly significant and close to 1. The *C*-stage coefficient is negative and significant, whereas the *E*-stage coefficient is positive but insignificant. Thus, unlike the results for NPD, the *C*-stage cost estimates for PSH projects tend to be lower than those in the *P*- and *E*-stages. The positive *E*-stage coefficient implies that these tend to be higher than in the *P*-stage, but the difference is not statistically significant. Similar to the NPD results, the positive coefficient on the *y40* report year dummy variable means that older projects tend to be more expensive (in 2020-dollar values) than newer projects, which is a result consistent with technical change over time. However, these results may also be influenced here by the escalation factors used to convert older cost estimates to 2020$.

3.1.3 CAPACITY EXPANSION

The CXP (capacity expansion) model specification is shown in equation (4). Given that these are not new projects, the key variables found most useful for estimating costs are the capacity added to the existing plant and the hydraulic head. In addition, dummy variables for project stage, hydraulic head groups, capacity groups and report year were included in the model. The baseline model (i.e. when the dummy variables in equation (4) are all set to zero) can be described as in the *P*-stage with added capacity >30 MW, hydraulic head >60 ft, and data reported after 2003.

$$ICC_i(in\ 2020\$) = e^{\left\{\begin{matrix}\beta_0+\beta_1 \ln(Added\ Capacity_i)+\beta_2 \ln(Head_i)+\beta_3 C_i+\beta_4 E_i+\beta_5 Hd30_i+\beta_6 Hd60_i \\ +\beta_7 AddCap1_i+\beta_8 AddCap10_i+\beta_9 AddCap30_i+\beta_{10} y40_i+\beta_{11} y40x_i\end{matrix}\right\}} \qquad (4)$$

The preferred CXP model variant is Model 1, which includes all 48 valid data points. Table 11 shows coefficients for the preferred CXP model which has an adjusted R^2 value of about 0.80 and a bias correction factor of 1.47. The added capacity coefficient is positive, and the hydraulic head coefficient is negative but are both significant with magnitudes slightly below 0.5. The *C*-stage coefficient is positive and significant, whereas the *E*-stage coefficient is negative but insignificant. Although none of the other dummy variables are significant, the results are interesting, and removing these variables was found to reduce the fit of the model. The coefficients on the *Hd30* and *Hd60* dummy variables are negative and positive with implied *t*-statistics of around 1.3 and 0.6, respectively, so the former would be significant at about the 25% level. All capacity dummy coefficients are negative with larger magnitudes for the smaller capacity levels. The different sign of the coefficients on the *y40* and *y40x* dummy variables lead to inconclusive results on the role of plant age and may simply reflect the nature of the data.

Table 10. ICC model estimates (PSH Projects).

Variable	PSH (Model 4)
Intercept	-0.3076
	(0.9503)
ln(Flow)	0.8304 ***
	(0.065)
ln(Head)	0.9734 ***
	(0.0762)
C-stage	-0.3955 ***
	(0.1265)
E-stage	0.0427
	(0.1653)
y40	0.2398*
	(0.1378)
bias correction	1.2071
R^2	0.6911
Adjusted R^2	0.6768
N	114

Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 11. ICC model estimates (CXP Projects).

Variable	Unit Addition (Model 1)
Intercept	11.4931 ***
	(1.3017)
ln(Added Capacity)	0.4161 *
	(0.2137)
ln(Head)	-0.3752 *
	(0.1917)
Construction Stage	0.5681 *
	(0.2925)
Engineering Stage	-0.2519
	(0.3636)
Hd30	-0.6541
(Head ≤ 30 ft)	(0.5088)
Hd60	0.2536
(30 ft < Head ≤ 60 ft)	(0.3667)
AddCap1	-1.4701
(Added Capacity ≤ 1 MW)	(0.9553)
AddCap10	-0.6695
(1 MW < Added Capacity ≤ 10 MW)	(0.636)
AddCap30	-0.4292
(10 MW < Added Capacity ≤ 30 MW)	(0.535)
y40	0.0124
	(0.5054)
y40x	-0.4227
	(0.4043)
bias correction	1.4762
R^2	0.8427
Adjusted R^2	0.7946
N	48

Standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1.

3.1.4 GENERATOR REWIND

The GRW (generator rewind) model specification is shown in equation (5). Given that these are not new projects, like capacity addition, the key variables found most useful for estimating costs are the rewound capacity and the hydraulic head. In addition, project stage and capacity group dummy variables were included in the model. The baseline model (i.e. when the dummy variables in equation (5) are all set to zero) can be described as in the *P*-stage with rewind capacity >100 MW).

$$ICC_i(in\ 2020\$) = e^{\{\beta_0+\beta_1 \ln(Capacity_i)+\beta_2 \ln(Head_i)+\beta_3 C_i+\beta_4 E_i+\beta_5 Cap30_i+\beta_6 Cap100_i\}} \quad (5)$$

The small number of data points could not accommodate the inclusion of additional dummy variables or estimation of the different model variants. Table 12 shows the GRW model coefficients with an adjusted R^2 value of 0.67 and a bias correction factor of about 1, which indicates little to no bias in the log-log model. Coefficients on the capacity and head variables are, like the CXP results, positive and negative, respectively, and both significant. The *C*- and *E*-stage coefficients are both negative with a higher magnitude for the latter, but both suggest that cost estimates in these two stages are generally lower than in the *P*-stage. Although both coefficients on the *Cap30* and *Cap100* capacity variables are negative they are insignificant, with implied *t*-statistics above 1.

Table 12. ICC model estimates (GRW Projects).

Variable	**Generator Rewind**
Intercept	8.5828 ***
	(1.5231)
ln(Capacity)	0.5706 **
	(0.2497)
ln(Head)	-0.2114 **
	(0.0933)
Construction Stage	-0.5908 **
	(0.2377)
Engineering Stage	-0.7917 **
	(0.3264)
Cap30	-0.782
(10 MW < Capacity ≤ 30 MW)	(0.668)
Cap100	-0.5602
(30 MW < Capacity ≤ 100 MW)	(0.4089)
bias correction	1.0092
R^2	0.7322
Adjusted R^2	0.6727
N	34

Standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1

.

3.2 OPERATION AND MAINTENANCE (O&M) COST SPECFICATION

The set of variables used in the O&M equation, the equation specification, and coefficient estimates are discussed in this section. The O&M sub-model, like the ICC sub-models, uses a log-log regression specification. Therefore, the discussion in section 3.1 about the power function transformation in levels, the role of dummy variables in the intercept term, and bias correction also apply to the O&M model.

Table 13 shows the variables used in the O&M equation. Annual O&M costs and capacity data are directly from the updated BCMH dataset as previously discussed in section 2.3. The O&M data used for the model estimation is the total value in thousand dollars; tests of model fit, and prediction were relatively worse for the dollars per kW model. In addition, a few other variables are calculated from the updated BCMH dataset. Plant age was calculated as the difference of the report year and first year of commercial operation, and the annual plant factor was calculated as shown in Table 13. Capacity was grouped into the following intervals of ≤1 MW, 10 MW, 30 MW, 100 MW, 500 MW and >500 MW to better capture the role of plant size in O&M costs. In addition, two dummy variables were used to reduce the influence of large per kW O&M cost on the model estimates representing values from $500/kW to $1000/kW and >$1000/kW. Large per kW O&M costs are not necessarily outliers but may reflect the nature of maintenance in hydropower plant operations, which consists of routine or recurring, non-recurring, and major maintenance activities that involve progressively larger costs.

Table 13. Variables used in the O&M Cost specification.

Variable	Description
Annual O&M (10^3 dollars)	Total annual operating expenses escalated to 2020 dollars.
Capacity (MW)	Nameplate capacity rating for the plant.
Age	Number years of first commercial operation relative to the report year.
Capacity Factor (capfactor)	$0 \leq \frac{annual\ net\ generation}{8760 * (total\ capacity)} \leq 1$ Average capacity factor (avgcapfactor) is calculated for each plant over the years present in the data from 1994 to 2020.
Capacity Dummies	Cap1: 1 if the plant has capacity ≤ 1 MW. Cap10: 1 if the plant has capacity between 1 and 10 MW. Cap30: 1 if the plant has capacity between 10 and 30 MW. Cap100: 1 if the plant has capacity between 30 and 100 MW. Cap500: 1 if the plant has capacity between 100 and 500 MW. Cap500x: 1 if the plant has capacity > 500 MW.
Major Expense Dummies	MajExp500x: 1 if annual O&M (per kW) is $500/kW to $1000/kW. MajExp1000x: 1 if annual O&M (per kW) is > $1000/kW.

The O&M sub-model specification is shown in equation (6):

$$O\&M_i(in\ 2020\$) = e^{\begin{Bmatrix} \beta_0+\beta_1\, ln(capacity_i)+\beta_2 Cap1_i+\beta_3 Cap10_i+\beta_4 Cap30_i+\beta_5 Cap100_i \\ +\beta_6 Cap500_i+\beta_7 majExp500x_i+\beta_8 majExp1000x_i \\ +\beta_9 ln((avgcapfactor)_i \times age_i)^2+\beta_{10} ln(capfactor_i) \end{Bmatrix}} \quad (6)$$

As previously discussed in section 2.3, only 272 unique plants in the data reported from 2018 and 2020 were used in the regression. Since not all 272 plants reported data over this three-year period, there are 781 rather than 816 data points in the model estimation. The baseline O&M model (i.e. with all the dummy variables in equation 6 set to zero) represents plants with capacities >500 MW and O&M expenses below $500/kW.

Table 14 shows the estimated model coefficients which has an adjusted R^2 value of 0.71 and a bias correction factor of 1.21. The capacity coefficient is positive, significant and slightly below 1. The capacity dummy variables are also all positive but only those for *Cap10* and *Cap30* are significant while two of the remaining three have implied *t-statistics* above 1. The dummy variable coefficients for capacity groups larger than 10 MW are progressively lower in magnitude, revealing potential scale economics in O&M costs. The lower coefficient on *Cap1* (i.e. ≤1 MW group) relative to *Cap10* suggests there is a threshold in hydropower O&M scale economics. Thus, O&M costs would increase with capacity up to the 10 MW level, all else equal, based on the estimated sub-model in Table 14. The two dummy variables for expenses above $500/kW are both significant and reduce their influence on the other coefficients of the O&M sub-model, which focuses on operations and non-major maintenance activities.

The terms containing the age and capacity variables in equation (6) are aimed at capturing non-linearities in the determinants of plant O&M costs over time, especially the maintenance component. Plants with consistently higher capacity factors over time would experience greater wear and tear that require regular maintenance and may reach end-of-life faster than plants with lower capacity factors. At the same time, maintenance activities, particularly major ones, require funds and downtime that could reduce the capacity factor. The specification used in equation (6) was compared to several others and found to provide the best option within the limits of the available data. The coefficient of the capacity factor term is negative and significant. However, note that because the capacity factor is less or equal to one (1) the logarithmic term is negative, so that increasing capacity factor levels have a positive but decreasing effect on O&M costs. This term would have no effect on O&M costs in a particular year for a plant that was operated 100% of the time, an unlikely case, with the effect increasing as the capacity factor decreases. Thus, this term may capture the empirical effect of maintenance downtime on O&M costs – which is also likely to be correlated with labor and other costs. The term interacting age with the average capacity factor is a measure of the accumulated plant operation over its lifetime. Since age is generally greater than one (1), this term is always positive and its positive and significant coefficient means, as would be expected, that a plant's O&M costs is an increasing function of its operational-age. We further explore the role of these two terms by calculating their in-sample combined effects as a cost-scaling factor using the estimated coefficients, which are plotted in Figure 13. The results indicate that the net effect on O&M costs is positive and generally increases with age. The O&M cost effects are lower for newer plants (i.e., plants with age ≤ 40 years) and the oldest plants have the highest O&M cost effects. The effects span almost the entire range of capacity factor levels, except for the largest effects which are associated with plants older than 40 years with very small capacity factors.

Table 14. O&M Cost model estimates.

Variable	O&M
Intercept	3.9946 ***
	(0.366)
ln(total capacity)	0.711 ***
	(0.048)
Cap1	0.486
(Capacity ≤ 1 MW)	(0.3688)
Cap10	0.7631 ***
(1 MW < Capacity ≤ 10 MW)	(0.2941)
Cap30	0.5169 **
(10 MW < Capacity ≤ 30 MW)	(0.2301)
Cap100	0.283
(30 MW < Capacity ≤ 100 MW)	(0.1869)
Cap500	0.1532
(100 MW < Capacity ≤ 500 MW)	(0.1529)
majExp500x	1.6261 ***
(500 $/kW ≤ annual O&M (per kW) ≤ 1000 $/kW)	(0.1439)
majExp1000x	3.0194 ***
(annual O&M (per kW) > 1000 $/kW)	(0.3345)
ln(avg cap factor × age)^2	0.0174 ***
	(0.0066)
ln(cap factor)	-0.122 ***
	(0.0414)
bias correction	1.2083
R^2	0.7122
Adjusted R^2	0.7085
N	781

Standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1.

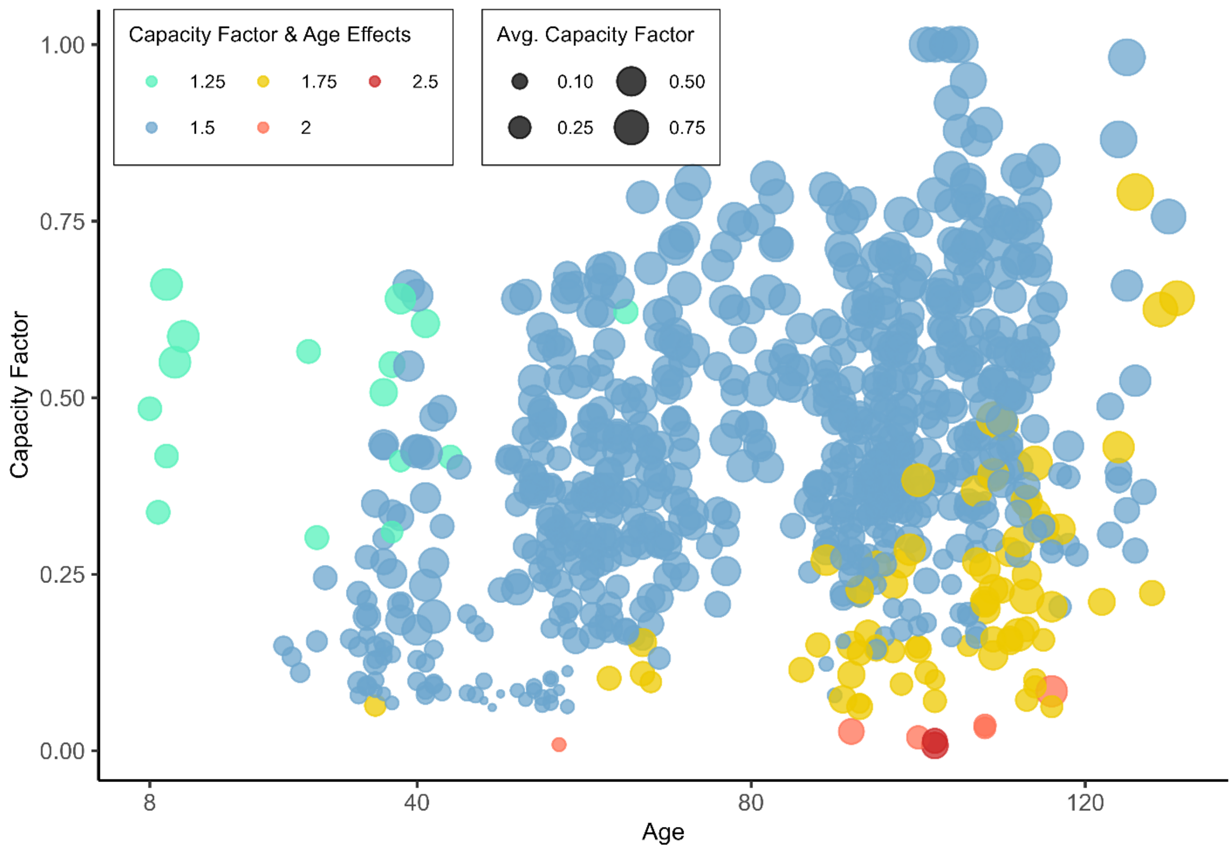

Figure 13. Net multiplicative effects of age and capacity factor in the O&M cost sub-model.

4 MODEL APPLICATION

4.1 THE WORKBOOK INTERFACE FOR THE UPDATED BCMH

The updated BCMH equations have been compiled into an Excel Workbook tool. Hydropower stakeholders can use the Workbook interface to the BCMH to estimate capital costs for US hydropower projects in the six categories (NPD, NSD, Canal, PSH, Capacity Addition, and Generator Rewind), and to estimate O&M costs. The *BCMH* workbook includes five sheets described below.

1. **Read_ME**: This sheet provides a brief overview of the BCMH and instructions on its use.

2. **InputsandResults**: This sheet is used for providing input data and includes the results of cost calculations with BCMH for each project. The model requires a few basic inputs as illustrated in the inputs interface in Figure 14 and described in Table 15. In addition, this sheet provides a dropdown box for selecting the number of projects to be evaluated which is limited to 100. It also provides two dropdown boxes for selecting the prediction confidence interval level (68%, 84%, 90%, 95% and 99%) (see section 4.2 below), The prediction confidence interval is the recommended option for evaluating the range of potential costs when using the BCMH to evaluate potential project costs.

3. **ResultCharts**: This sheet provides summary charts of simulated results. The estimated output columns include results with total and per kW estimates for initial capital costs and annual O&M costs, as well as inputs such as capacity and hydraulic head.

4. **Coeff**: This sheet provides the estimated coefficients of the BCMH equations specifications described in Section 3.

USER INPUTS							
Provide Unique Project Name	Project Type (Click each cell to select)	Set Project Capacity (MW) at Project Completion	Set Added Capacity (MW) - Used ONLY for Capacity Expansion	Set Project Head (ft)	Project Stage (Click the Cell to Select)	Plant Age (Years) Used ONLY for Estimating O&M Costs	Plant Capacity Factor (0 to 1) Used ONLY for Estimating O&M Costs
Project Name	Project Type	Plant Capacity (MW)	Added_Capacity	Head (ft)	Stage	Plant Age (Years)	Capacity Factor (Rate)
Project1	Non-Powered Dam (NPD)	0.25	1.00	1000.00	Construction	0.00	0.50
Project2	New Stream Development (NSD)	0.25	0.00	1000.00	Planning	0.00	0.50
Project3	New Stream Development (NSD)	0.25	1.00	20.00	Engineering	0.00	0.50
Project4	Non-Powered Dam (NPD)	36.50	1.00	57.00	Construction	0.00	0.50
Project5	Canal/Conduit	20.00	1.00	50.00	Planning	0.00	0.50
Project6	Capacity Expansion	500.00	0.10	100.00	Engineering	0.00	0.50
Project7	Generator Rewind	3.60	1.00	20.00	Construction	0.00	0.50
Project8	New Stream Development (NSD)	3.60	1.00	20.00	Construction	0.00	0.50
Project9	Existing Plant (O&M)	10.00	1.00	20.00	Planning	100.00	0.50
Project10	Existing Plant (O&M)	3.60	1.00	20.00	Engineering	90.00	0.50

Figure 14. Illustrative input interface of the BCMH Workbook.

Table 15. Description of input data in the BCMH Workbook (InputsandResults sheet).

Input Names	Description
Project Number	(**Optional**) Number indicator of the dam (the main index for the project)
Project Type	(**Required**) The category of the project (select one category): Non-Powered Dam (NPD) New Stream Development (NSD) Canal/Conduit Pumped Storage Hydropower (PSH) Capacity Expansion (CXP) Generator Rewind (GRW) Existing Plant (O&M)
Capacity (MW)	(**Required**) The capacity of the project in megawatts. Not required for type "Capacity Expansion (CXP)"
Added Capacity (MW)	(**Required for capacity expansion only**) Capacity in megawatts. Not required for types other than "Capacity Expansion (CXP)"
Project Head (ft)	(**Required**) Project hydraulic head Not required for "Existing Plant (O&M)".
Project Stage	(**Required**) The stage of the project (select one): Planning, Engineering, or Construction Not required for Project Type "Existing Plant (O&M)"
Plant Age (Years)	(**Required for O&M only**) Years since plant was originally installed.
Plant capacity factor	(**Required for O&M only**) Values from 0 to 1.

4.2 MODEL UNCERTAINTY EVALUATION

The updated BCMH is an econometric model with estimated coefficients dependent on the available data and its sample characteristics. Thus, applications of the model should be restricted to projects that are not far outside of the range of the data as highlighted in Table 1 to Table 7. Since the range of plant capacities are not equally represented in the data, the most applicable range for each model may be narrower than the minimum and maximum capacity values in these tables. Interpretation of the model results must also bear in mind that the underlying cost data are measured with error in most cases and incomplete. For example, the small number of near zero or negative raw data values in the chart in this section (see below) can result from accounting practices or potential errors. Such negative values are not included in the models presented in this report.

Other uncertainties arise from the inability to fully account for the multiple determinants of costs in the BCMH equations, which in any case also estimate the costs imperfectly with different levels of fit. The uncertainties attributable to a model's imperfect fit relative to the data can be evaluated with mean-response confidence intervals (*mCI*) and prediction confidence intervals (*pCI*). The *mCI* evaluates uncertainties without considering the role of residuals and represents the expected range of estimates based on a sample of data points. The *pCI* accounts for the variance of residuals and represents the range of estimates for specific new/future data points.

Given a vector of values for the independent variables, x_0, the *mCI* and *pCI* for the log-log cost specifications in this study can be calculated using equations (7) and (8), respectively (Faraway, 2005):

$$mCI = e^{\left\{\hat{y}_0 \pm t_k^{(\alpha/2)} \hat{\sigma} \sqrt{x_0^T (X^T X)^{-1} x_0}\right\}} \tag{7}$$

$$pCI = e^{\left\{\hat{y}_0 \pm t_k^{(\alpha/2)} \hat{\sigma} \sqrt{1 + x_0^T (X^T X)^{-1} x_0}\right\}} \tag{8}$$

Where $\hat{y}_0$ is the mean log of cost estimated from the log-log model using x_0 as inputs, $\hat{\sigma}$ is the estimated standard deviation of the residual term from the log-log regression model, X is the original data matrix of the log-log model, and $t_k^{(\alpha/2)}$ is the critical (1-α) confidence level t-value with k degrees of freedom. The *pCI* is wider than the *mCI* and is the appropriate confidence interval when applying the model.

The *mCI* and *pCI* (with α = 0.05 or 95% confidence level intervals) were calculated for the data used to estimate the updated BCMH equations. Figure 15 plots the mean and the *mCI* and *pCI* estimates against the data points for the six capital cost project categories. In general, nearly all observations fall within the *pCI* boundaries whereas the narrower *mCI* boundaries include the mean estimate and only the most accurately estimated set of data points. A similar observation can be made for the O&M in Figure 16.

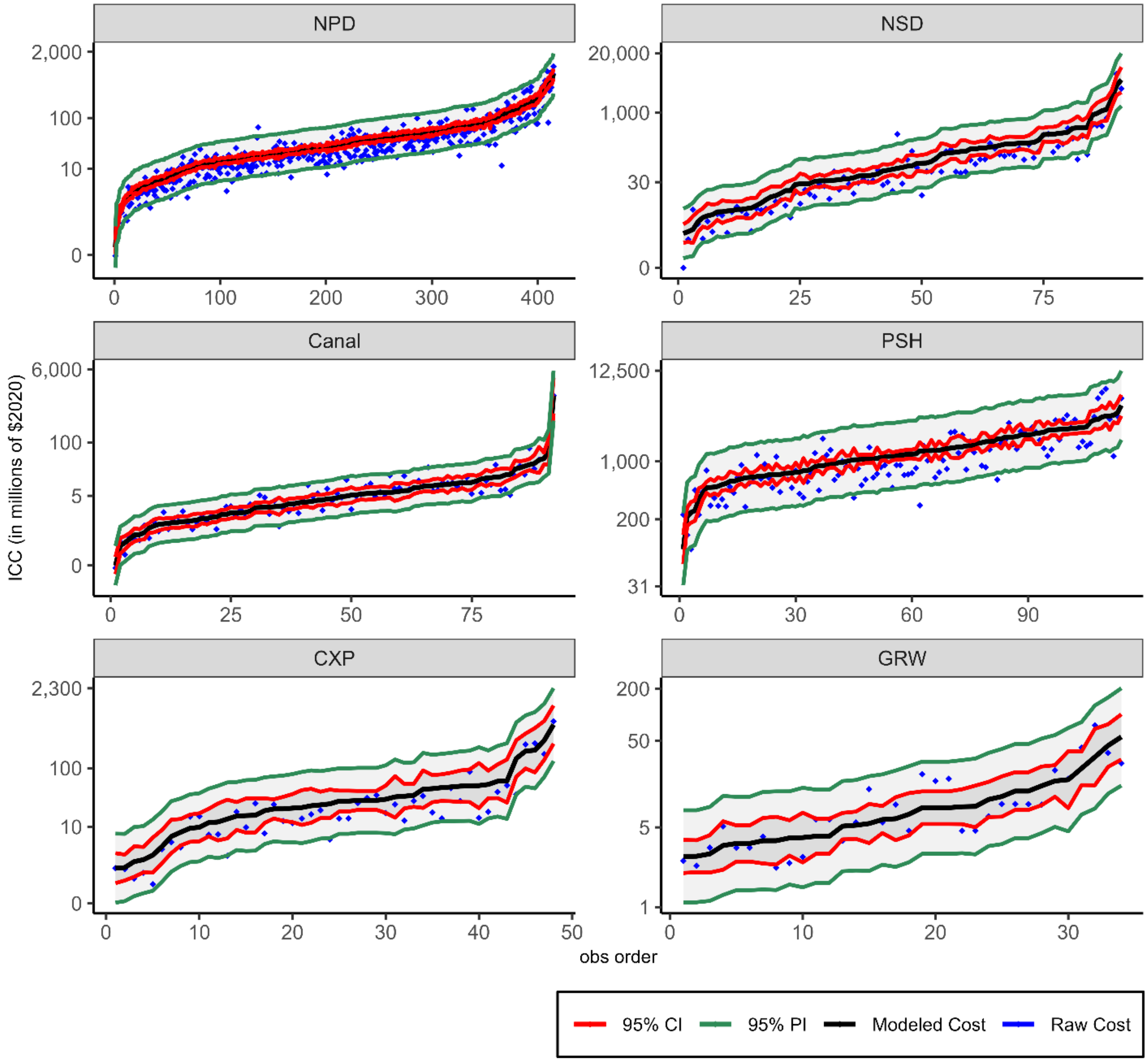

Figure 15. Mean-response and prediction confidence intervals for ICC estimates.

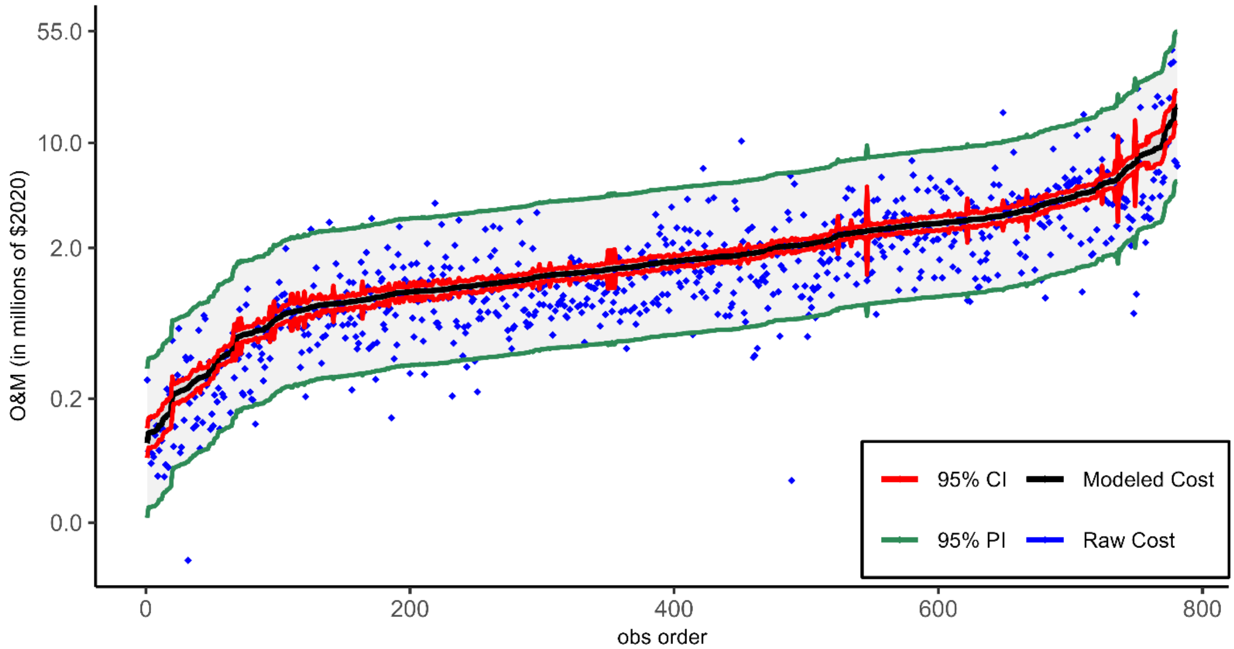

Figure 16. Mean-response and prediction confidence intervals for O&M cost estimates.

5 CONCLUSIONS

This report documents major updates to the BCMH to aid in reconnaissance stage evaluation of US hydropower project economics. The estimated models are useful for hydropower research, initial evaluation of hydropower project costs, and strategic planning for policymakers. The updated dataset used in this report was obtained from two main data sources. Data from IIR provides updated information on capital costs, and the second source (FERC) provides the information on the cost of operation and maintenance. Additional capital cost information from other sources that were included in the previous version of BCMH, such as FERC license application documents and DOE reports, were combined with the updated IIR data. Given the breadth of data collected from diversified sources, significant care and efforts were made to ensure data quality and accuracy.

The models presented in this report provide tools to estimate the aggregate initial capital cost for six categories of US hydropower projects. In addition, the report develops a model to estimate the cost of operation and maintenance. All costs are in 2020-dollar values (2020$). The BCMH equations are compiled into an Excel Workbook tool to aid stakeholders' use for rapid evaluation of ICC and O&M costs. In addition to the recommended models presented in Section 3, alternative models for ICC estimation were also developed based on different partitions of the data and are presented in Appendix A. These alternative models may prove beneficial to some users either as preferred models or for comparison to the recommended models.

The estimated econometric models are dependent on the available data and sample characteristics. Therefore, applications of the estimated sub-models should be limited to projects that are not far outside the range of data as summarized in Section 2. To account for uncertainties arising from the imperfect fit of the models to the data, this report constructs the mean-response and prediction confidence intervals around the cost predictions.

Future efforts will seek to address limitations of the models presented in this report. First, missing information for several variables affected a sizable number of plants in several project categories. As such, plants with missing information on capacity, cost, and head were excluded in the model estimation. Filling in the missing information from other sources of data would improve model estimation results under future model iterations. In addition, the model will be updated as new data on hydropower project development becomes available. Thus, this report is intended to be incrementally updated with continued efforts to capture additional cost data and improve modeling techniques to support the hydropower research community, industry and policymakers.

REFERENCES

Butterfield, S. (2011). Presentation on Swalley Irrigation District's Ponderosa Hydroelectric Project during the Deschutes River Basin Site Visit. Swalley Irrigation District, June 1, 2011.

City of Boulder (2013), City of Boulder Hydroelectric Facility Summary Sheet, available at https://www-static.bouldercolorado.gov/docs/Agenda_5_-_Hydroelectric_Program_Update-1-201307111316.pdf, accessed online March 2014.

COID (Central Oregon Irrigation District) and ODE (Oregon Department of Energy) (2011). Feasibility Study for Six Central Oregon Irrigation District Potential Hydroelectric Power Generation Sites, Oregon.

Demetrescu, M., Golosnoy, V., Titova, A., 2020. Bias corrections for exponentially transformed forecasts: Are they worth the effort? International Journal of Forecasting 36, 761–780. https://doi.org/10.1016/j.ijforecast.2019.09.001

DOE (Department of Energy) and, EPRI (Electric Power Research Institute) (1985a). Small-Hydropower Development: The Process, Pitfalls, and Experience Volume 1: Feasibility Studies Summary and Analysis, EPRI EM-4036.

DOE (Department of Energy) and EPRI (Electric Power Research Institute) (1985b). Small-Hydropower Development: The Process, Pitfalls, and Experience Volume 2: Licensing Activities Summary and Analysis, EPRI EM-4036.

DOE (Department of Energy) and EPRI (Electric Power Research Institute) (1986). Small-Hydropower Development: The Process, Pitfalls, and Experience Volume 4: Guide for Developers, EPRI EM-4036.

DOE (Department of Energy) and, EPRI (Electric Power Research Institute) (1987). Small-Hydropower Development: The Process, Pitfalls, and Experience Volume 3: Summary and Analysis of Technology Development Projects, EPRI EM-4036.

DOE (Department of Energy) (2014). Presentation on Recovery Act: Hydroelectric Facility Modernization Project, accessed on February, 2014.

ETO (Energy Trust of Oregon) (2010). Irrigation Water Providers of Oregon: Hydropower Potential and Energy Savings Evaluation, Oregon.

FERC (Federal Energy Regulatory Commission) (2020). Federal Energy Regulatory Commission Form 1 data, available at http://www.ferc.gov/, accessed online January 2020.

Faraway, J. J. (2005) "Linear models with R." *Chapman & HLL/CRC, Boca Raton, London, New York, Washington DC* (2005).

Hadjerioua, B., Wei, Y., and Kao, S.C. (2012). An Assessment of Energy Potential at Non-powered Dams in the United States, GPO DOE/EE-0711, Wind and Water Power Program, Department of Energy, DC.

IIR (Industrial Info Resources) (2021). PECWeb – A Searchable Database, available at http://www.industrialinfo.com/database , accessed online March 2021.

Kao, S.C., McManamay, R.A., Stewart, K.M., Samu, N.M., Hadjerioua, B., DeNeale, S.T., Yeasmin, D., Pasha, M.F. K., Oubeidillah, A.A., and Smith, B.T. (2014). New Stream-reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States, GPO DOE/EE-1063, Wind and Water Power Program, Department of Energy, Washington, DC.

Kao, S. C., George, L., Hansen, C., DeNeale, S. T., Johnson, K., and Sampson, A. K. (2022). An assessment of hydropower potential at national conduits (No. ORNL/TM-2022/2431). Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States).

NUID (North Unit Irrigation District) (2009). Feasibility Study on Five Potential Hydroelectric Power Generation Locations in the North Unit Irrigation District, Oregon, August 2009.

O'Connor, P. W., Zhang, Q. F., DeNeale, S. T., Chalise, D. R., & Centurion, E. E. (2015). Hydropower baseline cost modeling (No. ORNL/TM-2015/14). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

Oladosu, Gbadebo A., and Colin M. Sasthav. *Hydropower Capital and O&M Costs: An Exploration of the FERC Form 1 Data*. No. ORNL/TM-2021/2297. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2022.

Oladosu, G. A., and Ma, Y. (2024). A Reduced-form Cost Model for Prefeasibility Analysis of Hydropower at Non-Powered Dams (No. ORNL/TM-2024/3299). Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States).

Sasthav, C., and Oladosu, G. (2022). Environmental design of low-head run-of-river hydropower in the United States: A review of facility design models. Renewable and Sustainable Energy Reviews, 160, 112312.

TVA (Tennessee Valley Authority) (1941). The Guntersville Project: A Comprehensive Report on the Planning, Design, Construction, and Initial Operations of the Guntersville Project, Technical Report No. 4, Knoxville, Tennessee.

USBR (United States Bureau of Reclamation) (2021). Hydropower Construction Costs Trends, Bureau of Reclamation, available online at http://www.usbr.gov/pmts/estimate/cost_trend.html, accessed online January 2021.

APPENDIX A. ALTERNATIVE ICC MODELS

APPENDIX A. ALTERNATIVE ICC MODELS

Appendix A discusses the additional models evaluated for ICC. There are four specifications estimated for NPD, NSD, Canal, PSH, and Unit Addition plants. All specifications use the same equations as discussed in Section 3 but each of them applies different data samples. Specification (1) includes full data sample, specification (2) only includes plants with reported year after 2000, specification (3) drops the plants with per kW cost larger than $15k, and specification (4) drops the plants with per kW cost larger than $10k. The bias correction estimation is calculated as discussed in section 3.1.

NON-POWERED DAMS CAPEX (NPD)

Table 16. ICC model estimates (NPD, alternative models).

Variable	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Intercept	1.3744 *	2.2336 *	0.7014	0.3464
	(0.7035)	(1.16)	(0.6471)	(0.6328)
ln(Flow)	0.8402 ***	0.7724 ***	0.8767 ***	0.884 ***
	(0.0453)	(0.078)	(0.0418)	(0.0409)
ln(Head)	0.6792 ***	0.6113 ***	0.7442 ***	0.7971 ***
	(0.0792)	(0.1233)	(0.073)	(0.0711)
Construction Stage	0.3936 ***	0.6304 ***	0.414 ***	0.3508 ***
	(0.0921)	(0.112)	(0.0838)	(0.0823)
Engineering Stage	0.2263 **	0.2386 *	0.1755 **	0.172 **
	(0.0953)	(0.1253)	(0.0873)	(0.0848)
Hd30	-0.2346	-0.2624	-0.1251	-0.0392
(Head ≤ 30 ft)	(0.1765)	(0.2533)	(0.1622)	(0.1574)
Hd60	-0.2667 **	-0.1902	-0.1759	-0.0909
(30 ft < Head ≤ 60 ft)	(0.1295)	(0.1795)	(0.1191)	(0.1154)
Hd100	-0.1694	-0.3094 *	-0.1276	-0.084
(60 ft < Head ≤ 100 ft)	(0.1086)	(0.1572)	(0.1002)	(0.0973)
Cap1	-0.2571	-0.7162	-0.2228	-0.2331
(capacity ≤ 1 MW)	(0.2365)	(0.5364)	(0.2168)	(0.2142)
Cap10	-0.2903 **	-0.3605 *	-0.1919	-0.1465
(1 MW < capacity ≤ 10 MW)	(0.144)	(0.2092)	(0.1319)	(0.1287)
Cap30	-0.231 **	-0.3243 **	-0.2151 **	-0.1838 *
(10 MW < capacity ≤ 30 MW)	(0.1081)	(0.1384)	(0.0986)	(0.0959)
y40	0.3887 ***	0.2344	0.3351 ***	0.322 ***
	(0.0857)	(0.2007)	(0.0786)	(0.076)
y40x	0.5243 ***		0.5182 ***	0.4704 ***
	(0.0645)		(0.0593)	(0.0579)
bias correction	1.2644	1.2874	1.2655	1.2621
R^2	0.856	0.8199	0.8804	0.8874
Adjusted R^2	0.8519	0.8103	0.8768	0.8839
N	426	217	415	393
Model Data Scope				
Plants reported after year 2000		X		
Plants with per kW cost ≤ $15,000			X	
Plants with per kW cost ≤ $10,000				X
Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.				

NEW STREAM-REACH DEVELOPMENT (NSD)

Table 17. ICC model estimates (NSD, alternative models).

Variable	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Intercept	-4.612 ***	-5.3882 ***	-5.2105 ***	-4.1503 ***
	(1.7139)	(1.8776)	(1.4595)	(1.2592)
ln(Flow)	1.1822 ***	1.2506 ***	1.2287 ***	1.1514 ***
	(0.11)	(0.1205)	(0.0933)	(0.0811)
ln(Head)	1.2736 ***	1.3121 ***	1.3077 ***	1.2267 ***
	(0.1468)	(0.1565)	(0.1248)	(0.1074)
Construction Stage	0.0739	0.174	0.1277	0.1929 *
	(0.1589)	(0.1491)	(0.1329)	(0.1092)
Engineering Stage	-0.2363	0.4459	-0.0882	0.0525
	(0.1875)	(0.278)	(0.1701)	(0.1531)
Hd30	0.7376 **	-0.0607	0.3592	0.127
(Head ≤ 30 ft)	(0.3562)	(0.3982)	(0.3071)	(0.2743)
Hd60	0.3317	0.4705	0.1252	0.2493
(30 ft < Head ≤ 60 ft)	(0.3265)	(0.3947)	(0.299)	(0.255)
Hd100	0.1567	-0.103	0.2341	-0.4235
(60 ft < Head ≤ 100 ft)	(0.3036)	(0.3265)	(0.2543)	(0.2709)
Cap1	1.363 **	1.3252 **	1.3668 **	0.8013
(capacity ≤ 1 MW)	(0.6212)	(0.6308)	(0.5364)	(0.484)
Cap10	0.7654 *	0.8882 **	0.9141 ***	0.7131 **
(1 MW < capacity ≤ 10 MW)	(0.3862)	(0.4059)	(0.3298)	(0.2783)
Cap30	0.5908 **	0.7205 **	0.6845 ***	0.5756 ***
(10 MW < capacity ≤ 30 MW)	(0.2627)	(0.2694)	(0.2222)	(0.1871)
y40	-0.0339	-0.5351	-5e-04	0.0096
	(0.2241)	(0.3817)	(0.1866)	(0.1518)
y40x	0.9509 ***		0.9057 ***	0.5595 ***
	(0.1933)		(0.1727)	(0.1666)
bias correction	1.5381	1.2357	1.3697	1.0664
R^2	0.9053	0.9263	0.9348	0.9552
Adjusted R^2	0.8908	0.9104	0.9239	0.9465
N	91	63	85	75
Model Data Scope				
Plants reported after year 2000		X		
Plants with per kW cost ≤ $15,000			X	
Plants with per kW cost ≤ $10,000				X
Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.				

CANAL/CONDUITS

Table 18. ICC model estimates (Canal, alternative models).

Variable	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Intercept	3.5123 ***	3.3443 **	2.1176 *	1.4529
	(1.1839)	(1.5683)	(1.0722)	(0.9545)
ln(Flow)	0.7222 ***	0.6885 ***	0.8252 ***	0.8912 ***
	(0.0708)	(0.103)	(0.0646)	(0.0601)
ln(Head)	0.7352 ***	0.5773 ***	0.8294 ***	0.8434 ***
	(0.1118)	(0.1701)	(0.1022)	(0.0887)
Construction Stage	-0.1525	-0.5452	-0.112	0.0751
	(0.2294)	(0.3673)	(0.2009)	(0.1857)
Engineering Stage	0.0052	-0.4128	-0.1708	-0.1174
	(0.2331)	(0.3609)	(0.2073)	(0.1932)
Hd30	0.2758	0.2501	0.2385	-0.0305
(Head ≤ 30 ft)	(0.34)	(0.4811)	(0.2995)	(0.2681)
Hd60	-0.0411	-0.0145	0.0615	-0.0837
(30 ft < Head ≤ 60 ft)	(0.2771)	(0.4156)	(0.2458)	(0.2217)
Hd100	0.3579	0.4966	0.3703 *	0.1453
(60 ft < Head ≤ 100 ft)	(0.229)	(0.3274)	(0.2085)	(0.1914)
Cap1	-2.0663 ***	-0.7319	-1.4913 **	-1.2561 **
(capacity ≤ 1 MW)	(0.7596)	(0.8456)	(0.671)	(0.5821)
Cap10	-1.9643 ***	-0.5643	-1.6039 **	-1.532 ***
(1 MW < capacity ≤ 10 MW)	(0.7007)	(0.7399)	(0.6156)	(0.5317)
Cap30	-1.5911 **		-1.4403 **	-1.4847 **
(10 MW < capacity ≤ 30 MW)	(0.7834)		(0.6838)	(0.5857)
y40	0.0751		0.0314	0.0658
	(0.2508)		(0.219)	(0.1881)
y40x	0.2619		0.1839	0.4037 **
	(0.2164)		(0.1923)	(0.1799)
Model Data Scope				
Plants reported after year 2000		X		
Plants with per kW cost ≤ $15,000			X	
Plants with per kW cost ≤ $10,000				X
bias correction	1.0008	0.9284	1.0008	1.0007
R^2	0.8525	0.7843	0.8936	0.9278
Adjusted R^2	0.8321	0.743	0.8775	0.9151
N	100	57	92	81

Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.

PUMPED STORAGE HYDROPOWER (PSH)

Table 19. ICC model estimates (PSH, alternative models).

Variable	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Intercept	0.3585	1.0088	0.3585	-0.3076
	(0.9867)	(1.1008)	(0.9867)	(0.9503)
ln(Flow)	0.7888 ***	0.7722 ***	0.7888 ***	0.8304 ***
	(0.0677)	(0.0739)	(0.0677)	(0.065)
ln(Head)	0.9332 ***	0.8569 ***	0.9332 ***	0.9734 ***
	(0.0798)	(0.0951)	(0.0798)	(0.0762)
Construction Stage	-0.4084 ***	-0.1526	-0.4084 ***	-0.3955 ***
	(0.1337)	(0.1621)	(0.1337)	(0.1265)
Engineering Stage	0.0367	0.0457	0.0367	0.0427
	(0.1748)	(0.1892)	(0.1748)	(0.1653)
y40	0.2463 *		0.2463 *	0.2398 *
	(0.1457)		(0.1457)	(0.1378)
Model Data Scope				
Plants reported after year 2000		X		
Plants with per kW cost ≤ $15,000			X	
Plants with per kW cost ≤ $10,000				X
bias correction	1.2205	1.209	1.2205	1.2071
R^2	0.6525	0.6086	0.6525	0.6911
Adjusted R^2	0.6365	0.591	0.6365	0.6768
N	115	94	115	114

Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.

CAPACITY EXPANSION

Table 20. ICC model estimates (Capacity Expansion, alternative models).

Variable	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Intercept	11.4931 ***	12.0767 ***	11.4931 ***	11.2406 ***
	(1.3017)	(1.8821)	(1.3017)	(1.3549)
ln(Added Capacity)	0.4161 *	0.3988	0.4161 *	0.4618 **
	(0.2137)	(0.3111)	(0.2137)	(0.2239)
ln(Head)	-0.3752 *	-0.462 *	-0.3752 *	-0.3637 *
	(0.1917)	(0.2282)	(0.1917)	(0.1936)
Construction Stage	0.5681 *	0.4507	0.5681 *	0.5674 *
	(0.2925)	(0.3019)	(0.2925)	(0.2944)
Engineering Stage	-0.2519	0.0098	-0.2519	-0.2494
	(0.3636)	(0.3819)	(0.3636)	(0.366)
Hd30	-0.6541	-1.3849 *	-0.6541	-0.6245
(Head ≤ 30 ft)	(0.5088)	(0.7589)	(0.5088)	(0.5137)
Hd60	0.2536	0.2004	0.2536	0.2694
(30 ft < Head ≤ 60 ft)	(0.3667)	(0.5107)	(0.3667)	(0.3697)
AddCap1	-1.4701		-1.4701	-1.3563
(Added Capacity ≤ 1 MW)	(0.9553)		(0.9553)	(0.974)
AddCap10	-0.6695	-0.7601	-0.6695	-0.5589
(1 MW < Added Capacity ≤ 10 MW)	(0.636)	(0.8046)	(0.636)	(0.6578)
AddCap30	-0.4292	-0.3806	-0.4292	-0.3704
(10 MW < Added Capacity ≤ 30 MW)	(0.535)	(0.5883)	(0.535)	(0.5444)
y40	0.0124	-1.3441	0.0124	0.0112
	(0.5054)	(0.7872)	(0.5054)	(0.5087)
y40x	-0.4227		-0.4227	-0.367 (0.414)
	(0.4043)		(0.4043)	
bias correction	1.4762	1.4064	1.4762	1.4551
R^2	0.8427	0.7641	0.8427	0.8361
Adjusted R^2	0.7946	0.663	0.7946	0.7846
N	48	31	48	47
Model Data Scope				
Plants reported after year 2000		X		
Plants with per kW cost ≤ $15,000			X	
Plants with per kW cost ≤ $10,000				X
Standard errors in parentheses; p-value indicators: *** p < 0.01, ** p < 0.05, * p < 0.1.				