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Estimation of Economic Parameters of U.S. Hydropower Resources

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Bechtel BWXT Idaho, LLC

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ABSTRACT

Tools for estimating the cost of developing and operating and maintaining hydropower resources in the form of regression curves were developed based on historical plant data. Development costs that were addressed included: licensing, construction, and five types of environmental mitigation. It was found that the data for each type of cost correlated well with plant capacity. A tool for estimating the annual and monthly electric generation of hydropower resources was also developed. Additional tools were developed to estimate the cost of upgrading a turbine or a generator. The development and operation and maintenance cost estimating tools, and the generation estimating tool were applied to 2,155 U.S. hydropower sites representing a total potential capacity of 43,036 MW. The sites included totally undeveloped sites, dams without a hydroelectric plant, and hydroelectric plants that could be expanded to achieve greater capacity. Site characteristics and estimated costs and generation for each site were assembled in a database in Excel format that is included on a compact disk at the back of the report.

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy and Energy Information Administration jointly funded the Idaho National Engineering and Environmental Laboratory (INEEL) to perform a study that would provide DOE, policy makers, and the public with documented and peer-reviewed contemporary estimates of potential, U.S. hydroelectricity supply from conventional sources, including quantities and associated costs. This study supports the DOE congressionally mandated mission to analyze and forecast U.S. energy supply and demand and provide information and assistance in the development of U.S. hydropower.

In order to meet DOE's informational needs, the technical objectives of the study were to develop tools for estimating the cost of developing, operating and maintaining, and upgrading hydroelectric plants and estimating their electric generating potential and applying these estimating tools to known hydropower resources to which they are applicable. A collection of sources of historical hydroelectric plant data was used to create data populations on which to base the estimating tools. Once it was determined that most of the various types of the historical cost data each correlated with plant capacity, tools in the form of least squares power curves were used to represent cost as a function of capacity.

Separate tools were developed for each component of development cost, including the costs of licensing, constructing, and responding to the possible need for five types of environmental mitigation. Operation and maintenance (O&M) cost estimating was addressed by two tools: one for fixed O&M costs and one for variable O&M costs. Separate tools were developed for estimating the cost of upgrading Francis, Kaplan, and bulb turbines and for upgrading a generator. These tools were found to require an additional variable besides capacity. In the case of turbines, the primary variable was hydraulic head and in the case of generators, it was rotational speed. A method for estimating annual and monthly electric generation was developed based on 30 years of generation history of a large number of U.S. hydroelectric plants. Based on the historical data, average plant factors were developed for each state. These plant factors could then be used to estimate generation based on the location of a hydropower resource of interest.

The data sources and technical approach used to develop the estimating tools are described. The equations for the resulting estimating tools are provided in the results section and are compared with the data from which they were derived in Appendix A. A distribution of the base data in the form of numbers of data points in various capacity ranges and the extremes of the data population is also presented in Appendix A for each of the tools except the upgrade tools. The development and O&M cost estimating tools were found to have R^2 values ranging from 0.56 to 0.99.

The development and O&M cost estimating tools and the generation estimating tool were applied to applicable resources in the Hydropower Evaluation Software (HES) database (Francfort et al. 2002). This database was the result of an extensive assessment of U.S. hydropower resources (Connor et al. 1998). Because the study was focused on making estimates for resources having capacities of 1 MW or greater that were not excluded from development by federal or state statutes or policies, estimates were made for 2,155 of the 5,677 resources in the database. These resources included undeveloped sites, dams without hydroelectric plants, and expansion of existing hydroelectric plants. The applicable resources constituted 43,036 of the 69,009 MW (62%) total capacity of the resources in the HES database. The cost and generation estimates were combined with resource characteristic information from the HES database to produce the INEEL Hydropower Resource Economics Database (IHRED). This database is provided in Excel format on a compact disk in a pocket on the back cover of this report. The database has 78 fields of information for the 2,155 sites. A data dictionary that describes each field is provided in Appendix B.

Estimated costs included in the database including licensing, construction, mitigation, and O&M were not developed by performing individual site analyses. They are general cost estimates based on a collection of historical experience for similar facilities. Therefore, the costs presented in this study should not be interpreted as precise engineering estimates. Actual costs for any specific site could vary significantly from these generalized estimates as indicated by the scatter in the data used to develop the estimating tools exhibited in the regression curve/data comparisons in Appendix A.

The extensive data generated by the study are summarized in the following table.

Type of Site	Number of Sites --- Percent of Total (2,155 sites)	Total Capacity (MW) --- Percent of Total (43,036 MW)	Median Unit Cost to Develop Sites (2002$/kW)	Median Unit Cost to Develop Site Capacity (2002$/kW)
Undeveloped	965 (45%)	17,369 (40%)	3,600	2,700
Dams w/o power	1,026 (48%)	20,749 (48%)	2,000	1,200
Dams w/ power	164 (8%)	4,917 (11%)	1,200	700
All	**2,155 (100%)**	**43,036 (100%)**	**2,600**	**1,600**

As shown by the data in this table, most of the hydropower potential is approximately evenly split between undeveloped sites and dams without power both in numbers of sites and total capacity. The expansion of existing hydroelectric plants constitutes approximately 10% in terms of number of sites and total capacity. While development costs ranged from less than $500 per kW to greater than $6,000 per kW in 2002 dollars, most of the plants had development costs less than $5,000 per kW.

The distribution of the number of plants and amount of capacity that could be developed as a function of unit cost were approximately symmetric for each type of site. If the sites of a particular type were ranked by unit cost, the median unit cost of developing the sites of that type (i.e., half the sites can be developed for unit costs less than this value and half for more) is listed in the table above as "Median Unit Cost to Develop Sites." The same ranking can be used to identify the median unit cost of developing the capacity represented by sites of a particular type (i.e., half the total capacity of the sites can be developed for unit costs less than this value and half for more) is listed in the table as "Median Unit Cost to Develop Site Capacity."

The overall median unit cost for developing capacity listed in the above table shows that half of the 43,036 MW of capacity can be developed for unit costs of $1,600 per kW or less, which is competitive with other sources of electricity. The median unit costs of developing power potential by adding a powerhouse to existing dams and expanding existing hydroelectric plants are $1,200 per kW and $700 per kW, respectively. These indications of competitive pricing are borne out in greater detail in the following table that shows numbers of plants and corresponding amounts of capacity by type of site that could be developed for unit costs within each of several unit cost ranges.

Total Development Cost/kW (2002$)	**Undeveloped**		**Dams Without Power**		**Dams With Power**		**Total**	
	No. of Sites	Capacity (MW)	No. of Sites	Capacity (MW)	No. of Sites	Capacity (MW)	No. of Sites	Capacity (MW)
≤ 500	0	0	0	0	3	1,514	3	1,514
500 to 1000	0	0	21	8,007	44	2,853	65	10,860
1000 to 1500	0	0	157	7,892	84	478	241	8,369
1500 to 2000	2	774	303	3,349	28	61	333	4,185
2000 to 2500	44	4,362	334	1,149	2	6	380	5,516
2500 to 3000	155	7,107	170	280	3	5	328	7,392
3000 to 4000	522	4,680	38	69	0	0	560	4,749
≥ $4,000	242	447	3	3	0	0	245	450
Total	**965**	**17,369**	**1,026**	**20,749**	**164**	**4,917**	**2155**	**43,036**

The median unit cost of developing the capacity associated with undeveloped sites is significantly higher at $2,700 per kW. However, while unit cost is a good indicator of total development costs, using it alone for comparison with other technologies penalizes projects like hydroelectric facilities that have high initial costs, long life, no fuel costs, and low operating costs. Hydropower also has significant economic advantages in terms of reliability, dispatchability, and peaking power supply, among others.

The principal conclusion of the study is that historical hydropower data, while exhibiting significant scatter, exhibit sufficient correlation with plant capacity to allow the production of estimating tools that can produce meaningful cost and generation estimates. Additional data and research are needed to refine these tools, particularly in the area of estimating the cost of water quality mitigation. The IHRED data were assembled, but analysis of this body of data was beyond the scope of the study. These data should be analyzed to determine the trends and patterns in the data. Such analysis may provide useful information for the prediction of future hydropower capacity and generation and for making decisions regarding hydropower development. The turbine and generator upgrade cost estimating tools could not be applied to specific sites, because no comprehensive assessment has been made of the potential increase in capacity and generation on a site-specific base. This assessment should be performed and the tools applied to estimate the investment cost and the potential return in increased capacity and generation.

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FIGURES

TABLES

ACRONYMS

BNI	Bechtel National, Incorporated
DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	DOE Energy Information Administration
FERC	Federal Energy Regulatory Commission
GIS	geographic information system A set of digital geographic information such as map layers and elevation data layers, that can be analyzed using both standardized data queries as well as spatial query techniques.
HES	Hydropower Evaluation Software
IHRED	INEEL Hydropower Resource Economics Database
INEEL	Idaho National Engineering and Environmental Laboratory
NPS	Nuclear Placement Services
O&M	operation and maintenance

NOMENCLATURE

Plant Age (A)	The date when a hydroelectric plant was completed or last upgraded
Capacity (C)	The design (nameplate) electric power generating capability of a hydroelectric power plant in kilowatts (kW) or megawatts (MW)
Capacity Factor (CF)	Another name for plant factor
Generation (G)	The electric energy generating capability of a hydroelectric power plant during a specified period of time in kilowatt-hours (kW-h) or megawatt-hours (MW-h)
Hydraulic head (H)	Usually the vertical distance from the water surface in the impoundment to the center of the turbine in feet
Plant Factor (PF)	The ratio of actual electricity generation during a specified period of time to the ideal generation during the period where the ideal generation is equal to plant capacity multiplied by the time during the period
Speed (S)	Generator rotational speed in rpm
R^2	A measure of goodness of fit of a regression curve equation to a population of data from which it is derived using the method of least squares; a value of 1.0 denotes that all data points coincide with points on the regression curve (Note: The least squares curve fits were determined using transformed versions of the power law equations that were linearized using logarithms. However, the reported R^2 values were determined for the un-transformed power law equations and were generally lower than the values for the linearized versions of the equations.)
δ	A factor such that $(1+\delta_{x\%,UB})$ times the equation of the regression curve defines an upper bounding curve and $(1-\delta_{x\%,LB})$ times the equation of the regression curve defines a lower bounding curve where the two bounding curves encompass x percent of the data points
η	Efficiency of a hydroelectric plant (water to wire)
ν	Degrees of freedom; equals (n – 2) for the power law estimating equations in this report where n is the number of data points

Estimation of Economic Parameters of U.S. Hydropower Resources

1. INTRODUCTION

The Idaho National Engineering and Environmental Laboratory (INEEL) performed an extensive assessment of potential U.S. hydropower resources for the U.S. Department of Energy (DOE) during the period from 1989 to 1998 (Connor et al. 1998). This assessment resulted in the identification of 5,677 sites having a hydropower potential in aggregate of approximately 70,000 MW of hydroelectric power. Although the assessment identified site attributes that would affect the cost of developing the site, estimates of development costs were not made. The assessment also did not address additional U.S. hydroelectric potential achievable by upgrading equipment at existing installations. There is growing public and policy maker interest in the extent to which hydropower can meet future U.S. electricity and environmental demands. These interests require that contemporary estimates of the cost and electricity generation capability of potential hydropower resources be made. The hydropower industry will also benefit from having initial estimates of the cost of developing, operating, and maintaining individual resources and their generation potential as a means of selecting sites for more extensive evaluations.

The purpose of the present study was to provide tools to estimate development costs, operating and maintenance costs, and electricity generation and apply these tools to the previously identified hydropower resources. This application resulted in a new database based on the original hydropower resources database (Hydropower Evaluation Software [HES] database—Francfort et al. 2002) that includes estimates of various categories of development costs (including contemporary environmental requirements), fixed and variable operating and maintenance costs, and plant factors and generation. In addition to providing and applying tools for estimating economic data to hydropower resources, the study has provided tools for estimating the cost of upgrading turbines and generators at existing plants.

The study was funded by the DOE Office of Energy Efficiency and Renewable Energy (EERE) and the DOE Energy Information Administration (EIA) Office of Integrated Analysis and Forecasting. It provides EIA with estimates needed to model conventional hydroelectricity supply using the Renewable Fuels Module, which provides summary information to the Electricity Market Module of the National Energy Modeling System. It will also support the mission of the EERE to provide information and assist in the development of U.S. hydropower.

This report provides a detailed description of how the cost and generation estimating tools were developed using hydropower industry historical data. It describes how the applicable tools were applied to hydropower resources in the HES database to create the INEEL Hydropower Resource Economics Database (IHRED). The new database contains resource characteristics and estimates of development costs, operation and maintenance (O&M) costs, and annual and monthly electric generation. The resulting estimating tools are presented in the body of the report and are shown graphically in Appendix A in which they are compared with the historical data from which they were derived. The data dictionary for the IHRED is presented in Appendix B. The database itself is provided in Excel format on a compact disk at the back of the report. The report concludes with conclusions from the study and recommendations for additional, related research.

2. TECHNICAL APPROACH

Tools were developed for estimating the development costs, O&M costs, and electricity generation for undeveloped sites, dams not having a hydroelectric plant, and the expansion of existing hydroelectric plants through the installation of an additional turbine-generator. These tools were developed using historical hydroelectric data from a number of sources. It was found early in the study that all types of cost data correlated as well or better with plant capacity or added plant capacity than with an independent variable incorporating capacity and head such as used in the study reported in Gordon 1983.

This section describes how the cost and generation estimating tools were developed and how they were applied to hydropower resource sites identified in hydropower resource assessment reported in Conner et al. 1998. It also describes how cost estimating tools were developed for estimating the upgrade of a turbine or a generator at an existing hydroelectric plant. These tools were not applied to specific sites, because unlike the resource assessment, no site-specific inventory of the upgrade potential of U.S. hydroelectric plants has been performed.

2.1 Cost Estimating Tools for Plant Development or Expansion

Hydropower site development cost comprises the costs for licensing, construction, and mitigation. Five types of mitigation costs that may apply to a site depending on its location and characteristics were addressed:

- Fish and wildlife mitigation
- Recreation mitigation
- Historical and archeological mitigation
- Water quality monitoring
- Fish passage.

It should be noted that water quality monitoring rather than water quality mitigation was addressed in defining a cost estimating tool. This limitation was necessary because no unique functional relationship between water quality mitigation cost and plant capacity could be found. Water quality mitigation costs were found to vary widely with location even within the same state. It should also be noted that the mitigation costs that were used to develop the cost estimating tools were the total costs that would occur over 30 years in 2002 dollars rather than levelized annual costs.

2.1.1 Data Sources

The sources of historical data for each type of development cost and the type of site to which they apply are shown in Table 1. The principal source of data for licensing costs and the only source of data for costs associated with the first four types of mitigation listed above were environmental assessments and relicensing documents obtained from the Federal Energy Regulatory Commission (FERC 2003). FERC documents associated with a total of 226 plants containing costs during the period from 1980 through 1997 were reviewed. A later set of FERC documents containing costs during the period from 1999 through 2001 were also reviewed at the suggestion of technical approach review panel members. Additional relicensing costs for the period 1993 through 1995 were taken from EPRI 1995.

Plant construction costs for undeveloped sites were taken from data provided by the EIA (EIA 2003a) for the period 1990 through 2000. These data included costs in the following categories:

- Land and land rights
- Structures and improvements
- Reservoirs, dams, and waterways
- Equipment
- Roads, railroads, and bridges.

Table 1. Number of data points for development cost historical data by data source as applicable to various cost types and types of sites.

Data Source	Licensing Cost			Construction Cost			Fish and Wildlife Mitigation Cost (1)			Recreation Mitigation Cost (2)			Historical and Archeological Mitigation Cost (3)			Water Quality Monitoring Cost (4)			Fish Passage Cost (5)	Fixed Operations and Maintenance Cost [3]	Variable Operations and Maintenance Cost [3]	Plant Factor & Generation [4]
	Undeveloped [1]	Dams w/o Power	Dams w/ Power	Undeveloped	Dams w/o Power	Dams w/ Power [2]	Undeveloped [1]	Dams w/o Power	Dams w/ Power	Undeveloped [1]	Dams w/o Power	Dams w/ Power	Undeveloped [1]	Dams w/o Power	Dams w/ Power	Undeveloped [1]	Dams w/o Power	Dams w/ Power	All	All	All	All
FERC Environmental Assessment and License Documents (1980 - 1997)	133						64			90			19			78						
FERC Environmental Assessment and License Documents (1999-2001)	6						10			11			3			11			3			
EIA data (1990-2000)				267	214	214														2319 474 384	2452 501 421	
EIA data (1970-2000, excluding 1983)																						18690 1157
EPRI TR-104858	23																					
Christensen 1986					12	12																
Francfort et al. 1994																			7			
Total	**162**			**267**	**226**	**226**	**74**			**101**			**22**			**89**			**10**	**2340** **475** **384**	2452 501 421	18690 1157

[1] Upper limit of 67% data range

[2] Lower limit of 67% data range

[3] Upper - total records; middle - avg. cost values; lower - no. of plants

[4] Upper - total records; lower - no. of plants

The same data source was used for costs of power house construction and expansion of an existing hydroelectric plant, except in this case only costs in the "structures and improvements" and "equipment" categories were used. Several points were also taken from Christensen 1986.

Fish passage construction cost was limited to those projects that installed bi-directional fish passage as opposed to uni-directional passage or screens. The majority of the cost data came from Francfort et al.'s review of fish passage projects (Francfort et al. 1994). Three data points were also obtained from FERC relicensing applications with costs in the 1999 through 2001 period.

2.1.2 General Method

The sets of historical data were assembled in the form of Excel spreadsheets, and each contained plant identifiers, costs, capacity, and other plant data. For each dataset, the following operations were performed to determine an estimating tool:

1. Each cost was escalated to 2002 dollars using one of the two escalation curves discussed below.

2. Escalated costs were plotted as a function of plant capacity in the case of undeveloped sites and dams without power or as a function of added capacity for plant expansions at dams with power.

3. A least squares curve fit was performed on the data in each plot to determine a best fit mathematical function providing cost in 2002 dollars as a function of plant capacity. The derived function could then be used as a tool to estimate costs of this type for hydropower sites. In addition to the function, the least squares curve fitting also provided a root-mean-square (RMS) goodness of fit value.

Costs for labor intensive work were escalated using the consumer price index (CPI) with 1970 as the base year (EHR 2002). The escalation values are listed in the second column of Table 2 and are shown graphically in Figure 1. Escalation factors represented by this curve were applied to licensing costs and all mitigation costs except fish passage, which has a large construction component.

Plant and fish passage construction costs were escalated using the escalation data listed in the first column of Table 2, and are shown graphically in Figure 2. These data use 1940 as the reference year. Prior to 1969, escalation values are from the Engineering News Record (ENR 2002). For 1969 and later, the values are from the U.S. Bureau of Reclamation (USBR 2002).

In order to escalate a cost from its year of occurrence to 2002, an escalation ratio was calculated by dividing the 2002 escalation factor value by the escalation factor value for the year of cost occurrence. The escalation ratio was then applied to the cost to escalate it to the cost in 2002 dollars.

2.1.3 Data Screening

The dataset containing construction costs (EIA 2003a) included data for 909 plants. Ninety plants were eliminated by one or more of the following three criteria:

1. Capacity less than 1 MW
2. Capacity greater than 1300 MW
3. Pumped storage plant.

Prior to determining the construction cost estimating tools, the data for the remaining 819 plants were screened to identify unusable or unrealistic records. For the undeveloped site construction cost estimating tool, the following data screens were made:

1. Any records containing a zero value for total cost of plant were considered unusable (2% of plants removed).

2. Records for plants constructed prior to 1940 were not used because even though the costs could be escalated, it was judged that the escalated costs would be unrealistically low relative to current costs because of the low labor rates that existed prior to 1940 (88% of plants removed).

Table 2. Escalation factors for construction costs, labor intensive costs, and turbine replacement costs.

Year	Construction[a]	Inflation[b]	Turbine [c]
2002	18.2490	4.8362	2.53
2001	17.9767	4.7017	2.48
2000	17.6654	4.5480	2.42
1999	17.1206	4.4497	2.39
1998	16.7315	4.3835	2.35
1997	16.2646	4.2829	2.28
1996	15.6420	4.1597	2.28
1995	15.5642	4.0480	2.28
1994	15.0195	3.9454	2.26
1993	14.7860	3.8312	2.21
1992	14.3969	3.7193	2.16
1991	14.3191	3.5687	2.08
1990	13.8521	3.3862	1.95
1989	13.3852	3.2308	1.85
1988	12.7626	3.1029	1.79
1987	12.4514	2.9934	1.74
1986	12.2957	2.9387	1.69
1985	12.1595	2.8382	1.66
1984	12.1595	2.7194	1.63
1983	11.7899	2.6348	1.58
1982	11.6732	2.4819	1.50
1981	11.0895	2.2490	1.43
1980	10.2140	1.9818	1.31
1979	9.1440	1.7809	1.18
1978	8.3658	1.6553	1.08
1977	7.7821	1.5525	1.00
1976	7.4903	1.4681	
1975	7.1012	1.3471	
1974	6.4202	1.2124	
1973	5.4475	1.1416	
1972	5.0584	1.1051	
1971	4.8638	1.0594	
1970	4.4747	1.0000	

Year	Construction[a]	Inflation[b]	Turbine
1969	3.8911		
1968	3.5525		
1967	3.3307		
1966	3.2023		
1965	3.0895		
1964	3.0156		
1963	2.9261		
1962	2.8560		
1961	2.7977		
1960	2.7549		
1959	2.7004		
1958	2.5875		
1957	2.5058		
1956	2.4202		
1955	2.3113		
1954	2.1984		
1953	2.1245		
1952	2.0506		
1951	1.9767		
1950	1.8482		
1949	1.7354		
1948	1.6809		
1947	1.5409		
1946	1.2918		
1945	1.1790		
1944	1.1556		
1943	1.1284		
1942	1.0934		
1941	1.0389		
1940	1.0000		

a. ENR 2002 and USBR 2002.

b. EHR 2002.

c. USBR 2002.

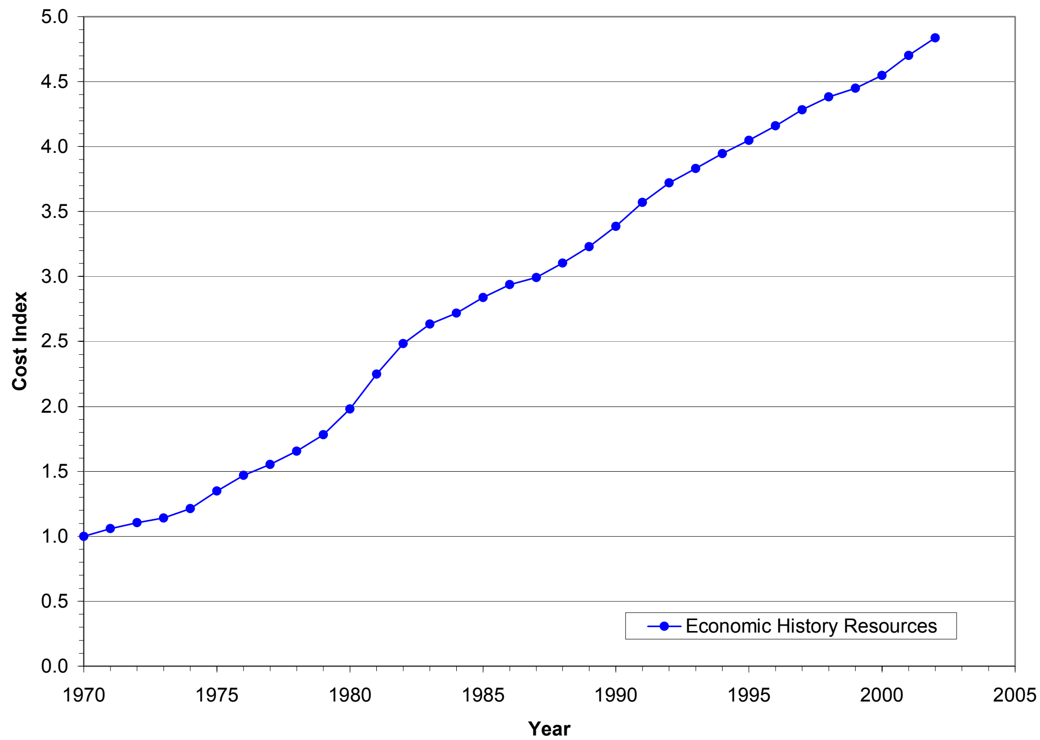

Figure 1. Escalation for licensing costs, mitigation costs except fish passage, and operating and maintenance costs.

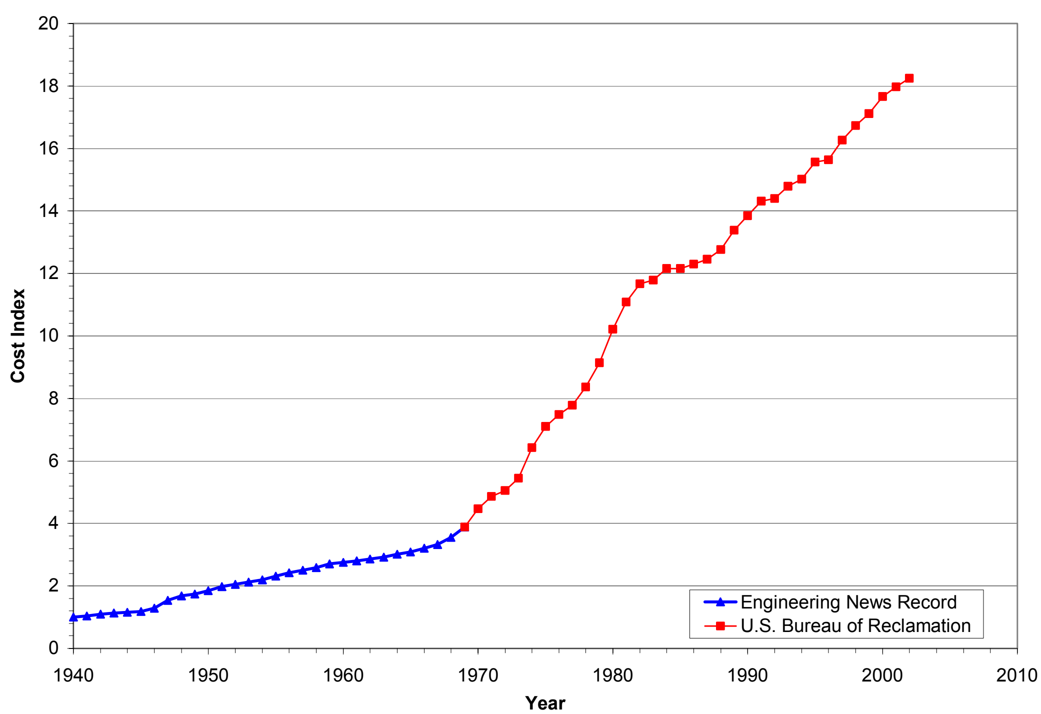

Figure 2. Escalation for construction costs and fish passage costs.

3. Any construction cost less than $700/kW or greater than $5,000/kW was considered to be atypical and was not used (9% of plants removed).

4. A history of construction cost for a specific plant that decreased rather than increased in successive years was reviewed to select the most realistic value or marked as unusable if a best value could not be identified (1% of plants removed).

The data screening process prior to determining the construction cost estimating tools for power house addition to a dam or expansion of a hydroelectric plant was the same except for the zero data screen. If either the cost for "structures and improvements" or the cost for "equipment" was zero, the record was considered to be unusable. Most of the plants removed by screening were removed because they were constructed prior to 1940 (80% of plants removed). The zero cost criteria and the unit cost criteria accounted for 10% and 9% of the plants removed, respectively with an additional 1% of the plants removed being the result of difficult to interpret cost trends.

Data screening resulted in data for 267 plants being used to determine the construction cost estimating tool for undeveloped sites. Screening also resulted in data for 214 plants being used to determine the construction cost estimating tool for power house addition and plant expansion. Since the construction cost values for a given plant were reported as a cumulative cost and therefore increased each year, the actual cost data point for a specific plant was the construction cost value for the earliest year in the dataset in nearly all cases.

2.1.4 Accounting for Cost Variations by Type of Site

The cost data for licensing, fish and wildlife mitigation, recreation mitigation, historical and archeological mitigation, and water quality monitoring were taken from environmental assessment and relicensing documents for existing hydroelectric plants rather than from new FERC license applications. Since these costs would be higher for new development, it was decided to include a premium for these costs associated with undeveloped sites and dams without power. It was reasoned that these costs for dams without power would be higher than for existing hydroelectric plants (dams with power) and would be higher still for undeveloped sites.

These premiums were defined by taking the upper bound of envelopes that encompassed two-thirds or 98% of the data points in analogy to plus or minus one and two sigma bands. The upper and lower bounds of each envelope were determined by selecting values of a data band parameter, δ such that the curves defined by $(1 \pm \delta)$ times the regression curve equation encompassed either two-thirds or 98% of the data points. A different value of δ was used to encompass the designated fraction of the points above the regression curve than was used to encompass this fraction of points below the curve.

For licensing and the four types of mitigation, the regression curve itself was used as the estimating tool for a plant expansion. The 67% upper bound [$(1+\delta_{67\%,UB})$ times the regression curve equation] was used as the estimating tool for addition of a powerhouse to a dam without power. The 98% upper bound [$(1+\delta_{98\%,UB})$ times the regression curve equation] was used as the estimating tool for an undeveloped site.

No premium for fish passage cost was used. This is because it was judged that the installation cost of fish passage would not be affected by the extent of previous development at the site. Fish passage was thus treated as an incremental cost in all cases rather than as an integrated cost that would differ depending on the type of site at which it was installed.

A bounding curve was also used at the estimating tool for estimating the construction cost of a plant expansion. Because the available data were the costs associated with the addition of a powerhouse, it was judged that these costs were too high when estimating the cost of a plant expansion. For this reason, the equation for the 67% lower bound of the cost data for construction of a powerhouse [$(1-\delta_{67\%,LB})$ times the regression curve equation] was used as the estimating equation for the construction cost of a plant expansion.

2.2 Cost Estimating Tools for Plant Operation and Maintenance

Separate cost estimating tools were developed for fixed and variable O&M costs. The data on which these tools were based was EIA data (EIA 2003a) for the period 1990 through 2001. The following costs were considered to be fixed O&M costs:

- Operation supervision and engineering
- Maintenance supervision and engineering
- Maintenance of structures
- Maintenance of reservoirs, dams, and waterways
- Maintenance of electric plant
- Maintenance of miscellaneous hydraulic plant.

In contrast, the following costs were considered to be variable O&M costs:

- Water for power
- Hydraulic expenses
- Electric expenses
- Miscellaneous hydraulic power expenses
- Rents.

Prior to performing the process to determine the cost estimating tool, screening operations were performed on the dataset. Of the 909 plants represented in the dataset, 90 were eliminated by one or more of the following three criteria:

1. Capacity less than 1 MW
2. Capacity greater than 1300 MW
3. Pumped storage plant.

For the fixed O&M cost estimating tool, the following data screens were made:

1. Any record containing a zero or negative value for any of the fixed O&M component costs listed above or zero electicity generation was considered to be unusable (93% of plants removed).
2. Any record containing a total fixed O&M cost that was less than 0.5 mills/kW-h or greater than 5.5 mills/kW-h was considered to be unusable (7% of plants removed).

Plants for which there was more than one capacity listed were treated as separate plants at the respective capacities.

For the variable O&M cost estimating tool, the following data screens were made:

1. Any record containing a negative value for any of the variable O&M component costs listed above was considered to be unusable (1% of plants removed).
2. Any record containing zero values for all the variable O&M component costs listed above except water for power was considered to be unusable (78% of plants removed).
3. Any record containing a total variable O&M cost that was less than 1.5 mills/kW-h or greater than 8.0 mills/kW-h was considered to be unusable (21% of plants removed).

Plants for which there was more than one capacity listed were treated as separate plants at the respective capacities.

These screening operations resulted in significant reductions in the numbers of plants that actually contributed to the determination of the estimating tools. Of the original 819 plants of interest, data for 384 plants was used to determine the fixed O&M cost estimating tool while data for 421 plants was used to determine the variable O&M cost estimating tool. Because some plants had more than one capacity listed for the same plant, 474 data points were used to determine the fixed O&M cost estimating tool, and 501 data points were used to determine the variable O&M cost estimating tool

Both of the O&M cost estimating tools were determined using a process similar to that described above for development costs:

(1) escalating costs to 2002 dollars using the escalation data shown in Figure 1, (2) time averaging the data for each plant-capacity combination to obtain an average annual cost, (3) plotting the average values as a function of plant capacity or added capacity, and (4) performing a least squares curve fit to determine the equation to be used as the estimating tool.

2.3 Cost Estimating Tools for Turbine and Generator Upgrade

The cost estimating tools for upgrading three types of turbines: Francis, Kaplan, and bulb were produced using data from EPRI 1989. Cost data points were taken from working plots of cost as a function of hydraulic head for various plant capacities. These costs were escalated to 2002 dollars using the cost escalation data in the third column of Table 2, which is shown graphically in Figure 3 (USBR 2002). Iterative analysis was performed on the data for each type of turbine to obtain a mathematical expression of cost as a function of capacity and hydraulic head that closely matched the escalated data.

The cost estimating tool for upgrading generators is based on data obtained from a hydropower industry source (Hunt 2003). These data are in the form of generator cost as a function of rotational speed for various capacities. Iterative analysis was performed on the data to obtain a mathematical expression of cost as a function of capacity and rotational speed that closely matched the data.

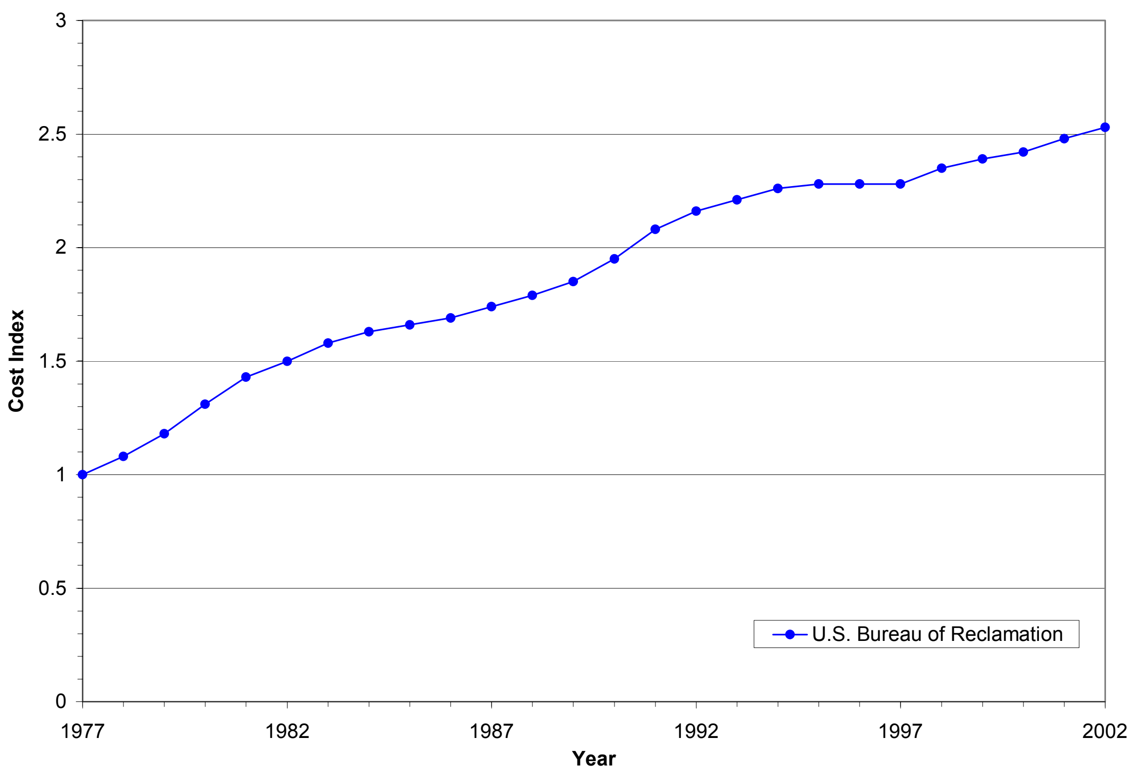

Figure 3. Escalation for turbine replacement costs.

2.4 Estimating Plant Electric Generation

The EIA provided both annual and monthly plant generation data for the period 1970 through 2000 (EIA 2003b). The generation data were converted to plant factors (PF) using the equation

$$PF_{Time\ Period} = \frac{Generation_{TimePeriod}(MW - h)}{Capacity(MW)\ x\ Time(hours)}$$

where

Time = annual or monthly hours.

The plant factor data were grouped by the state in which the plant is located. The plant factors for each time period (Annual, January, February, etc.) associated with each state regardless of year or location of occurrence were used to obtain an unweighted, average plant factor for each time period for each state. Annual plant factors less than 0.25 or greater than 0.85 were judged to be unrealistic and were not included in the average.

The plant factors for a given state were used to estimate either the total or incremental (for plant expansions) potential generation of hydropower resource sites within the state using the inverse of the above equation:

$$G_{State, Time\ Period} = (PF_{State,\ Time\ Period}) * (C) * (Time)$$

where

$G_{State,\ Time\ Period}$	=	generation during a specified time period in MW-h
$PF_{State, Time\ Period}$	=	average state plant factor for a specified period of time
C	=	plant capacity or added capacity in MW
Time	=	time period in hours

2.5 FERC Annual Charge

For plants with a capacity greater than 1.5 MW, FERC charges plant owners an annual fee based on plant capacity and annual generation (FERC 1999). In order to have a complete estimate of plant costs, the following formula was applied once the plant annual generation or added generation was estimated as described in the previous section.

$$\text{Cost (2002\$)} = (0.17238 * G) + (1.53227 * C)$$

where

G = annual generation in MW-h

C = capacity in kW

2.6 Application of Estimating Tools to Hydropower Resources

The cost and generation estimating tools that were developed as described above were applied to the hydropower resources identified in the resource assessment reported in Connor et al. 1998. Characteristic information about the hydropower resources was assembled in the HES database (Francfort et al. 2002). The database was screened to identify sites to which the estimating tools were applicable using the following criteria to identify nonapplicable sites:

- Sites having capacity potentials less than 1 MW
- Sites that were excluded from development by federal statutes and policies
- Sites that were excluded from development by state and municipal statutes and policies
- Sites that have been developed since the assessment was performed
- Sites that are pumped storage plants.

Sites that were excluded from development by federal statutes and policies were identified by using geographic information system (GIS) tools to intersect the geographic location of resources in the HES database with a GIS data layer containing all federally excluded areas including:

- National battlefields
- National historic parks
- National parks
- National parkways
- National monuments
- National preserves
- National wildlife refuges
- Wildlife management areas
- National wilderness areas
- Wild and scenic rivers.

The HES database also contained information about whether the resource is sited at the upstream or downstream end of a wild and scenic stream reach (W_S_PROT) or on a tributary (W_S_TRIB) of a stream designated as wild and scenic. It also contained information about whether a site is located in a federally designated exclusion zone: FED103_C and FED106_C. Those sites that were designated as meeting any of these criteria or were identified as being in an exclusion zone via the use of the GIS layer were eliminated from the list of resources to which the estimating tools were applied.

Of the 5,677 resources in the HES database, 3,522 were found to be unsuitable for application of the estimating tools for one or more of the reasons stated above leaving 2,155 applicable sites. Figure 4 shows the distribution of the resources in the HES database based on the applicability of the estimating tools and the various reasons for nonapplicability. (Applicable sites are designated as "IHRED sites.") Most of sites (2,311 sites or 41%) were eliminated, because they had a capacity of less than 1 MW.

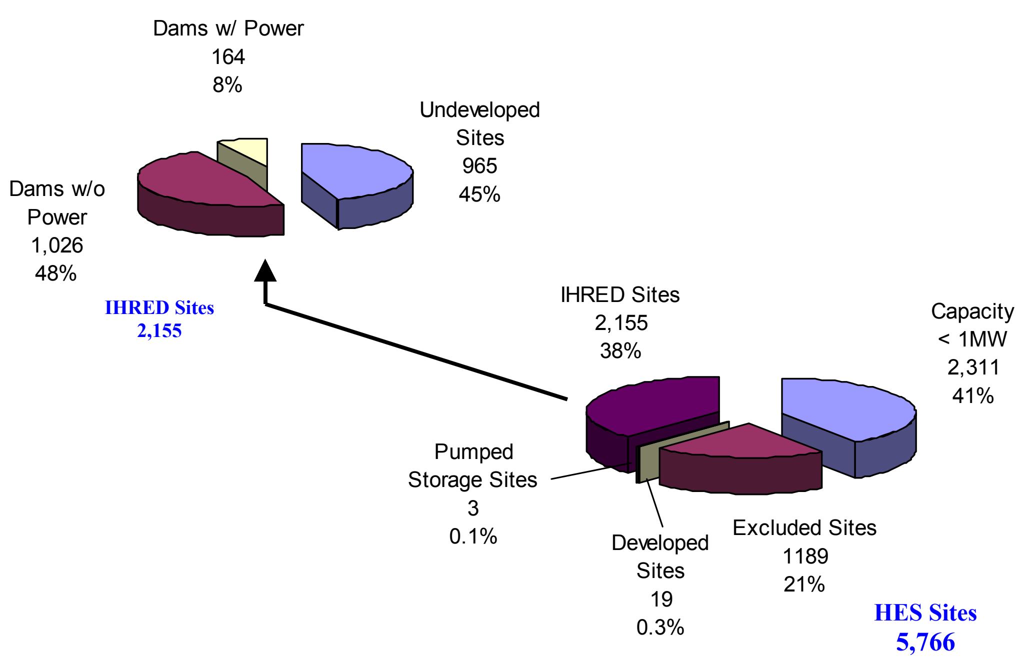

Figure 4. Distribution of the hydropower resource sites in the HES database based on numbers of sites.

A counterpart to the distribution shown in Figure 4 in terms of the total amount of power represented by applicable resources and the various classes of nonapplicable resources is shown in Figure 5. This figure shows that while the resources having a capacity of 1 MW or less represented 41% of the HES sites in number, they collectively represented only 1% of the total capacity of all the sites in the HES database.

The cost estimating tools were applied to the applicable sites in the HES database based on the listed capacity of the site. The potential generation (annual and monthly) of the resource was estimated using the average plant factors for the state in which the resource is located. The application of the mitigation cost estimating tools was dependent on site characteristics in the HES database. The cost of fish and wildlife mitigation was estimated if any of the FISH_C, WILDLF_C, or T_E_W_C (indicates the presence of threatened or endangered wildlife) fields contained a "Y" value. The cost of recreation mitigation was estimated if either of the following parameters had a "Y" value: REC_C or SCENIC_C. The cost of historical and archeological mitigation was estimated if either of the following parameters had a "Y" value: CULTUR_C or HISTORY_C. The cost of fish passage mitigation was estimated if the T_E_F_C parameter (indicates the presence of threatened or endangered fish) had a "Y" value. The cost of water quality monitoring was estimated for all sites.

The basic site characteristic data from the HES database was combined with the cost and generation data produced using the estimating tools to create a new database named the INEEL Hydropower Resource Economics Database (IHRED). Because the HES database did not identify plants that could be upgraded by installing new turbines or generators, the tools for estimating these costs were not applied to any of the resources listed in the database.

The distribution of the 2,511 sites in the IHRED in terms of the types of sites is shown in Figure 4. Of these sites, the sites that were either totally undeveloped or were a dam without a hydroelectric installation represented 45 and 48% of the applicable sites, respectively. Sites with hydroelectric installations that could be expanded were 8% of the applicable sites.

Viewed from a total capacity perspective, Figure 5 shows a nearly equal portion for totally undeveloped sites and dams without a hydroelectric installation being 40 and 48% of the total capacity of the IHRED sites, respectively. Sites with hydroelectric installations that could be expanded represent 11% of the total capacity.

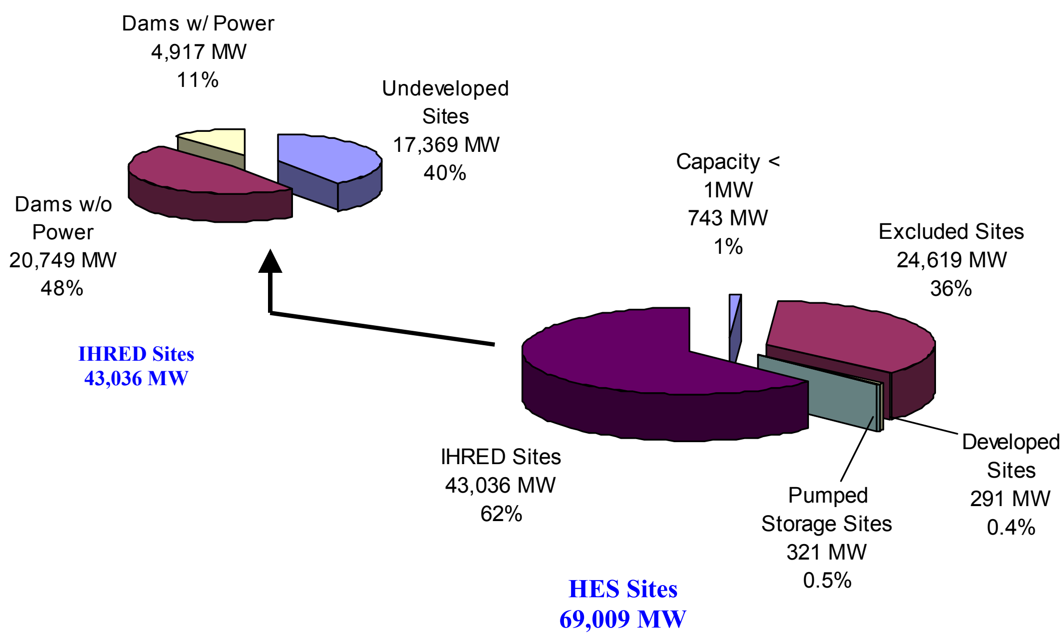

Figure 5. Distribution of hydropower resource sites in the HES database based on total capacity.

3. RESULTS

The technical approach to developing cost and generation estimating was executed using the various sources of historical data listed in Table 1. The resulting tools for estimation are described in this section. The application of these tools to applicable hydropower resources in the HES database that resulted in the production of the IHRED is also described.

3.1 Cost Estimating Tools for Plant Development or Expansion

The historical data for licensing costs, construction costs, and five types of mitigation costs were found to correlate well with plant capacity or added capacity. Plots of the basic data that were used to develop each cost estimating tool are presented in Appendix A along with the resulting regression curve and data bands encompassing 67 and 98% of the data points. In addition, the population of each basic dataset based on capacity ranges accompanies each basic plot in the appendix. These distribution charts are accompanied by a thumbnail plot listing the minimum and maximum values of cost and capacity included in the dataset.

A least squares curve fit showed that a power curve best represented the data in each dataset. The equation for each cost estimating tool is listed in Table 3, which gives the coefficient and exponent for the power curve, the data band parameter values, and the R^2 value indicating the goodness of the fit. The equations of the upper and lower bounds of the data band encompass either 67 or 98% of the data points. They are the same as the basic curve fit equation, except the coefficient is multiplied by $(1 + \delta_{x\%,UB})$ for the upper bound or multiplied by $(1 - \delta_{x\%,LB})$ for the lower bound where x is either 67 or 98. No value is listed for the data band parameter and no R^2 is listed in the table for tools that are the upper or lower bound of a dataset.

In order to gain confidence that cost has a power law relationship with capacity for each of the elements of development costs, tests of significance were performed on the exponents in each of the cost estimating equations. These tests showed that the exponents are statistically significantly different than zero with greater than 99% confidence providing confidence that cost increases with capacity rather than there being a significant probability that cost does not vary with capacity (exponent equals zero). The values of the t statistic for each of the exponents is compared with the t statistic value for a one-tailed, 99.9% significance test in Table 4.

3.2 Cost Estimating Tools for Plant Operation and Maintenance

The historical data for fixed and variable O&M costs were also found to correlate well with plant capacity or added capacity. Plots of the basic data that were used to develop each cost estimating tool are presented in Appendix A along with the resulting regression curve and data bands encompassing 67% of the data points. In addition, the population of each basic dataset based on capacity ranges along with a thumbnail plot listing the minimum and maximum values of cost and capacity included in the dataset accompanies each basic plot in the appendix .

A least squares curve fit showed that a power curve best represented the data in each dataset. The equation for each cost estimating tool is listed in Table 5, which gives the coefficient and exponent for the power curve, the data band parameter values, and the R^2 value indicating the goodness of the fit.

The results of tests of significance on the exponents of the two O&M cost estimating tools are presented in Table 6. These results show with greater than 99.9% confidence that cost increases with capacity.

Table 3. Cost estimating equations for licensing, construction, and five types of mitigation.

Cost (2002$) = A * [Capacity (MW)] ^{B}							
Estimating Tool Application	**Coefficient (A)**	**Exponent (B)**	**Data Band Parameter ($\delta_{98\%,UB}$)**	**Data Band Parameter ($\delta_{67\%,UB}$)**	**Data Band Parameter ($\delta_{67\%,LB}$)**	**Data Band Parameter ($\delta_{98\%,LB}$)**	**R^2**
Licensing - Undeveloped Sites	6.1E+05	0.70	-	-	-	-	N/A
Licensing - Dams w/o Power	3.1E+05	0.70	-	-	-	-	N/A
Licensing – Dams w/ Power	2.1E+05	0.70	1.90	.46	.39	.63	0.74
Construction - Undeveloped Sites	3.3E+06	0.90	1.26	.49	.35	.67	0.81
Construction - Dams w/o Power	2.2E+06	0.81	2.50	.67	.38	.74	0.74
Construction - Dams w/ Power	1.4E+06	0.81	-	-	-	-	N/A
Fish & Wildlife Mitigation - Undeveloped Sites	3.1E+05	0.96	-	-	-	-	N/A
Fish & Wildlife Mitigation - Dams w/o Power	2.0E+05	0.96	-	-	-	-	N/A
Fish & Wildlife Mitigation - Dams w/ Power	8.3E+04	0.96	2.78	1.38	.39	.77	0.70
Recreation Mitigation - Undeveloped Sites	2.4E+05	0.97	-	-	-	-	N/A
Recreation Mitigation - Dams w/o Power	1.7E+05	0.97	-	-	-	-	N/A
Recreation Mitigation - Dams w/ w/o Power	6.3E+04	0.97	2.82	1.66	.54	.92	0.87
Historical & Archeological Mitigation - Undeveloped Sites	1.0E+05	0.72	-	-	-	-	N/A
Historical & Archeological Mitigation - Dams w/o Power	8.5E+04	0.72	-	-	-	-	N/A
Historical & Archeological Mitigation - Dams w/ w/o Power	6.3E+04	0.72	.65	.35	.43	.50	0.94
Water Quality Monitoring - Undeveloped Sites	4.0E+05	0.44	-	-	-	-	N/A
Water Quality Monitoring - Dams w/o Power	2.0E+05	0.44	-	-	-	-	N/A
Water Quality Monitoring - Dams w/ w/o Power	7.E+04	0.44	5.13	2.13	.59	.93	0.56
Fish Passage Mitigation	1.3E+06	0.56	.79	.09	.18	.31	0.99

Table 4. Significance test results for development cost estimating equation exponents.

Estimating Tool	Exponent Standard Error	t Statistic Value	$t_{(\nu, 0.001)}$
Licensing – Dams w/o Power	.02806	24.854	3.142
Construction – Undeveloped Sites	.01781	50.378	3.121
Construction – Dams w/o Power	.02706	29.825	3.127
Fish & Wildlife Mitigation	.05587	17.142	3.207
Recreation Mitigation	.06534	14.835	3.175
Hist. & Arch. Mitigation	.05753	12.440	3.552
Water Quality Mitigation	.07837	5.559	3.187
Fish Passage Mitigation	.03827	14.571	4.501

Table 5. Cost estimating equations for fixed and variable operation and maintenance.

Cost (2002$) = A ∗ [Capacity (MW)] ^{B}							
Estimating Tool Application	**Coefficient (A)**	**Exponent (B)**	**Data Band Parameter ($\delta_{98\%,UB}$)**	**Data Band Parameter ($\delta_{67\%,UB}$)**	**Data Band Parameter ($\delta_{67\%,LB}$)**	**Data Band Parameter ($\delta_{98\%,LB}$)**	**R^2**
Fixed Operation and Maintenance	2.4E4	0.75	1.92	.67	.46	.74	0.60
Variable Operation and Maintenance	2.4E4	0.80	2.55	.77	.39	.74	0.67

Table 6. Significance test results for O&M cost estimating equation exponents.

Estimating Tool	Exponent Standard Error	t Statistic Value	$t_{(\nu, 0.001)}$
Fixed Operation and Maintenance	.02127	35.400	3.108
Variable Operation and Maintenance	.02198	36.295	3.107

Table 7. Cost estimating equations for turbine and generator upgrades.

Turbines: Cost (2002$) = A ∗ [Capacity (MW)] ^{B} ***∗ [Head(ft)]*** ^{C}			
Estimating Tool Application	**Coefficient (A)**	**Exponent (B)**	**Exponent (C)**
Francis Turbines	3.E6	0.71	-0.42
Kaplan Turbines	4.E6	0.72	-0.38
Bulb Turbines	6.E6	0.86	-0.63
Generators: Cost (2002$) = A ∗ [Capacity (MW)] ^{B} ***∗ [Speed(rpm)]*** ^{C}			
Generators	3.E6	0.65	-0.38

3.3 Cost Estimating Tools for Turbine and Generator Upgrade

Development of the cost estimating tools for turbine and generator upgrades resulted in power equations in which the coefficient is a function of the capacity of the turbine or generator being replaced. The equations for these tools are listed in Table 7. The tools are shown graphically in Appendix A.

3.4 Estimating Plant Electric Generation

Annual and monthly plant factors were determined for each state. The resulting plant factors are listed in Table 8.

3.5 Estimated Economic Parameters for Hydropower Resources

The development and O&M cost estimating tools listed in Tables 3 and 5 and the plant factors listed in Table 8 were applied to 2,155 U.S. hydropower resources from the HES database to build the IHRED. Resource characteristic data in the HES database were retained in the IHRED, and cost and generation data were added to assemble the 78 fields of data for each resource. The IHRED data dictionary, which provides field names and descriptions is listed in Appendix B. The database in Excel format is provided on a compact disk as part of Appendix B and is included in a pocket on the back cover of this document.

The distribution of the hydropower resources in the IHRED, which is based on the number of resources having capacities or capacity additions within various capacity ranges, is shown in Figure 6. This figure shows that 1,461 of the 2,155 resources in the IHRED (68%) had capacities or capacity additions in the 1 to 10 MW range. Ninety-two percent of the resources had capacities or capacity additions of 50 MW or less. A comparison of Figure 6 with similar distributions for the data populations on which the cost estimating tools are based (Appendix A) reveals that the distributions are similar. Thus, the vast majority of cost estimates that were made for resources in the IHRED were based on historical data from plants in the same capacity range.

A related distribution of the IHRED resources is shown in Figure 7. In this figure, the total capacity represented by the resources having capacities or capacity additions in each capacity range is shown. This figure shows that the 1,461 resources (68% of the sites) having capacities or capacity additions in the 1 to 10 MW range represent only 12% of the total 43,036 MW of the IHRED resources. The 92% of the IHRED resources having capacities or capacity additions of 50 MW or less constitute 41% of the total capacity of the resources. Another 44% of the total capacity is contributed by resources having capacities or capacity additions of 100 MW or greater with 24% of the total capacity being contributed by the 21 sites having capacities or added capacities greater than 250 MW.

All the cost estimating tools are based on data populations that include data for plants having capacities greater than 100 MW. But, the number of points is less than at the other end of the capacity scale. The data populations on which construction and O&M cost estimating tools are based have the best representations at the high end of the capacity range. The thumbnail plot on each of the source data distributions in Appendix A provides the minimum and maximum capacity and cost of the source data.

The distributions of the IHRED sites, which are given in capacity ranges in Figures 6 and 7, are presented in ranges of unit development cost in Figures 8 and 9. Unit development cost is the sum of the estimated costs of licensing, construction, and any required mitigation divided by the capacity or added capacity of the site. The distribution of the number of undeveloped sites that could be developed for various unit costs is shown by the blue bar segments in Figure 8. This is an approximately symmetric distribution with the maximum number of this type of site being developed for $3,500 to $4,000 per kW. Likewise, the distribution of dams without power sites shown by the red bar segments is approximately symmetric with the maximum number of this type of site being developed for $2,000 to $2,500 per kW. The distribution of the dams with power or plant expansions shown by the white bar segments is also approximately symmetric with the

Table 8. Annual and monthly plant factors by state.

State	Abbr.	Annual	January	February	March	April	May	June	July	August	September	October	November	December
ALASKA	AK	0.5021	0.4876	0.4819	0.4512	0.4547	0.4767	0.5393	0.5500	0.5350	0.5119	0.5255	0.5183	0.4913
ALABAMA	AL	0.4378	0.6489	0.6718	0.6707	0.5330	0.4145	0.3464	0.3093	0.2818	0.2485	0.2686	0.3642	0.5108
ARKANSAS	AR	0.4208	0.4725	0.5037	0.5317	0.5319	0.4773	0.4441	0.4069	0.3438	0.2760	0.2717	0.3322	0.4630
ARIZONA	AZ	0.4860	0.3438	0.3812	0.4679	0.5759	0.5943	0.6538	0.6510	0.6250	0.4859	0.3570	0.3379	0.3511
CALIFORNIA	CA	0.5487	0.4931	0.5327	0.5935	0.6149	0.6462	0.6396	0.6067	0.5779	0.5142	0.4476	0.4422	0.4748
COLORADO	CO	0.4946	0.4514	0.4430	0.4233	0.4226	0.5743	0.6686	0.6528	0.5547	0.4983	0.4259	0.3858	0.4290
CONNECTICUT	CT	0.4672	0.5576	0.6018	0.7414	0.7574	0.6209	0.3994	0.2340	0.1927	0.1878	0.3089	0.4478	0.5670
FLORIDA	FL	0.4316	0.4622	0.5304	0.5875	0.5232	0.3985	0.4180	0.4397	0.4674	0.3660	0.2626	0.3277	0.4030
GEORGIA	GA	0.4378	0.5166	0.5343	0.5414	0.5251	0.4563	0.4142	0.3752	0.3788	0.3340	0.3446	0.3925	0.4472
HAWAII	HI	0.6111	0.5876	0.5655	0.6429	0.7861	0.7110	0.5799	0.5666	0.5572	0.5183	0.5620	0.6526	0.6015
IOWA	IA	0.5549	0.4745	0.5169	0.6212	0.6221	0.6163	0.5996	0.5680	0.5218	0.5017	0.4851	0.5738	0.5565
IDAHO	ID	0.6037	0.6042	0.5955	0.6129	0.6402	0.6619	0.6675	0.6262	0.5837	0.5647	0.5354	0.5586	0.5930
ILLINOIS	IL	0.5145	0.4649	0.4862	0.4980	0.4980	0.4978	0.5105	0.5266	0.5439	0.5318	0.5346	0.5672	0.5139
INDIANA	IN	0.4982	0.4985	0.5219	0.5715	0.6232	0.6107	0.5497	0.4458	0.3833	0.3837	0.3846	0.4792	0.5306
KANSAS	KS	0.4083	0.3470	0.3956	0.4382	0.3919	0.4057	0.3933	0.3869	0.4029	0.4389	0.3806	0.4579	0.4616
KENTUCKY	KY	0.5309	0.5786	0.5401	0.4974	0.4948	0.5522	0.5652	0.5533	0.5207	0.4826	0.4841	0.5352	0.5655
LOUISIANA*	LA	0.4208	0.4725	0.5037	0.5317	0.5319	0.4773	0.4441	0.4069	0.3438	0.2760	0.2717	0.3322	0.4630
MASSACHUSETTS	MA	0.4840	0.5478	0.5567	0.6323	0.6284	0.5800	0.4386	0.3254	0.3251	0.3094	0.4032	0.5011	0.5646
MARYLAND	MD	0.4251	0.4507	0.5409	0.7230	0.7349	0.5427	0.3296	0.2448	0.1753	0.1898	0.2650	0.3911	0.5232
MAINE	ME	0.5824	0.5815	0.5975	0.6618	0.7114	0.7023	0.6119	0.4918	0.4448	0.4603	0.5273	0.6001	0.6007
MICHIGAN	MI	0.4830	0.4720	0.4842	0.5523	0.6556	0.5808	0.4896	0.3977	0.3633	0.3905	0.4260	0.4820	0.5052
MINNESOTA	MN	0.6054	0.5247	0.5346	0.5927	0.7256	0.7216	0.6882	0.6184	0.4920	0.5275	0.5755	0.6720	0.5914
MISSISSIPPI*	MS	0.4208	0.4725	0.5037	0.5317	0.5319	0.4773	0.4441	0.4069	0.3438	0.2760	0.2717	0.3322	0.4630
MISSOURI	MO	0.4107	0.4300	0.4663	0.5651	0.5668	0.4890	0.4205	0.3607	0.3186	0.2658	0.2633	0.3550	0.4321
MONTANA	MT	0.6114	0.6125	0.5951	0.5761	0.6088	0.6463	0.7059	0.6616	0.5897	0.5570	0.5768	0.6111	0.5960
NORTH CAROLINA	NC	0.4555	0.5545	0.5772	0.5896	0.5321	0.4863	0.4410	0.3768	0.3824	0.3448	0.3427	0.3763	0.4699
NORTH DAKOTA	ND	0.5474	0.6104	0.6300	0.4981	0.4679	0.5173	0.5854	0.6091	0.6104	0.5267	0.4856	0.5110	0.5220
NEBRASKA	NE	0.4700	0.3989	0.4822	0.5014	0.5072	0.4905	0.5113	0.5273	0.4948	0.4362	0.4526	0.4515	0.3880
NEW HAMPSHIRE	NH	0.5524	0.5381	0.5579	0.6556	0.7584	0.7165	0.5561	0.4081	0.3811	0.3725	0.4937	0.6042	0.5896
NEW JERSEY	NJ	0.3310	0.3245	0.3719	0.5082	0.4571	0.4178	0.3115	0.2431	0.1707	0.2596	0.2882	0.2858	0.3372
NEW MEXICO	NM	0.4796	0.3652	0.3899	0.5137	0.6029	0.5825	0.5497	0.5551	0.4771	0.4776	0.4424	0.3806	0.4131
NEVADA	NV	0.5410	0.4312	0.4996	0.5414	0.6409	0.6542	0.6103	0.5931	0.5794	0.5529	0.4979	0.4317	0.4580
NEW YORK	NY	0.5354	0.5519	0.5667	0.6301	0.7009	0.6425	0.5094	0.4088	0.3700	0.3933	0.4763	0.5768	0.6027
OHIO	OH	0.4681	0.4524	0.4352	0.4403	0.5141	0.5315	0.5319	0.5082	0.4268	0.4148	0.4245	0.4465	0.4886
OKLAHOMA	OK	0.4605	0.4242	0.4525	0.5970	0.6085	0.6262	0.6424	0.4826	0.3137	0.2581	0.2561	0.4078	0.4585
OREGON	OR	0.5669	0.6551	0.6488	0.6478	0.6274	0.6254	0.5721	0.4558	0.4211	0.4494	0.4733	0.5784	0.6552
PENNSYLVANIA	PA	0.4995	0.5224	0.5609	0.6931	0.7016	0.6139	0.5045	0.3931	0.2977	0.2932	0.3548	0.4727	0.5910
RHODE ISLAND	RI	0.3052	0.3785	0.6043	0.6396	0.5104	0.3676	0.1644	0.0979	0.0524	0.0636	0.0841	0.2574	0.4636
SOUTH CAROLINA	SC	0.4691	0.5875	0.6200	0.6191	0.5735	0.5103	0.4485	0.3623	0.3585	0.3227	0.3528	0.3978	0.4860
SOUTH DAKOTA	SD	0.5064	0.3835	0.3532	0.3836	0.4706	0.5240	0.5707	0.6291	0.6546	0.6319	0.5656	0.5056	0.3952
TENNESSEE	TN	0.5055	0.6158	0.6057	0.5671	0.4868	0.4611	0.4836	0.4749	0.5038	0.4437	0.4252	0.4553	0.5475
TEXAS	TX	0.5053	0.4893	0.5144	0.5404	0.5441	0.5814	0.6325	0.5176	0.4754	0.4607	0.4309	0.4480	0.4318
UTAH	UT	0.5127	0.3949	0.4286	0.4481	0.5577	0.6849	0.6833	0.6088	0.5760	0.5077	0.4278	0.4163	0.4139
VIRGINIA	VA	0.4429	0.5144	0.5783	0.6306	0.6127	0.5781	0.4653	0.3381	0.2961	0.2692	0.2818	0.3381	0.4221
VERMONT	VT	0.4976	0.4905	0.4974	0.5767	0.7418	0.6618	0.4687	0.3192	0.3051	0.3268	0.4570	0.5739	0.5567
WASHINGTON	WA	0.5312	0.6069	0.6096	0.5597	0.5488	0.5795	0.5959	0.5084	0.4000	0.4007	0.4256	0.5385	0.6066
WISCONSIN	WI	0.5559	0.4863	0.4944	0.5931	0.7286	0.6675	0.5861	0.4837	0.4526	0.5042	0.5359	0.5968	0.5423
WEST VIRGINIA	WV	0.5609	0.6136	0.6743	0.7019	0.7047	0.6851	0.5880	0.4774	0.4265	0.3806	0.3920	0.4944	0.6009
WYOMING	WY	0.5034	0.4149	0.4053	0.4354	0.5054	0.5789	0.6720	0.6922	0.6361	0.4867	0.3983	0.3997	0.4081

* Louisiana and Mississippi values were estimated using Arkansas plant factors.

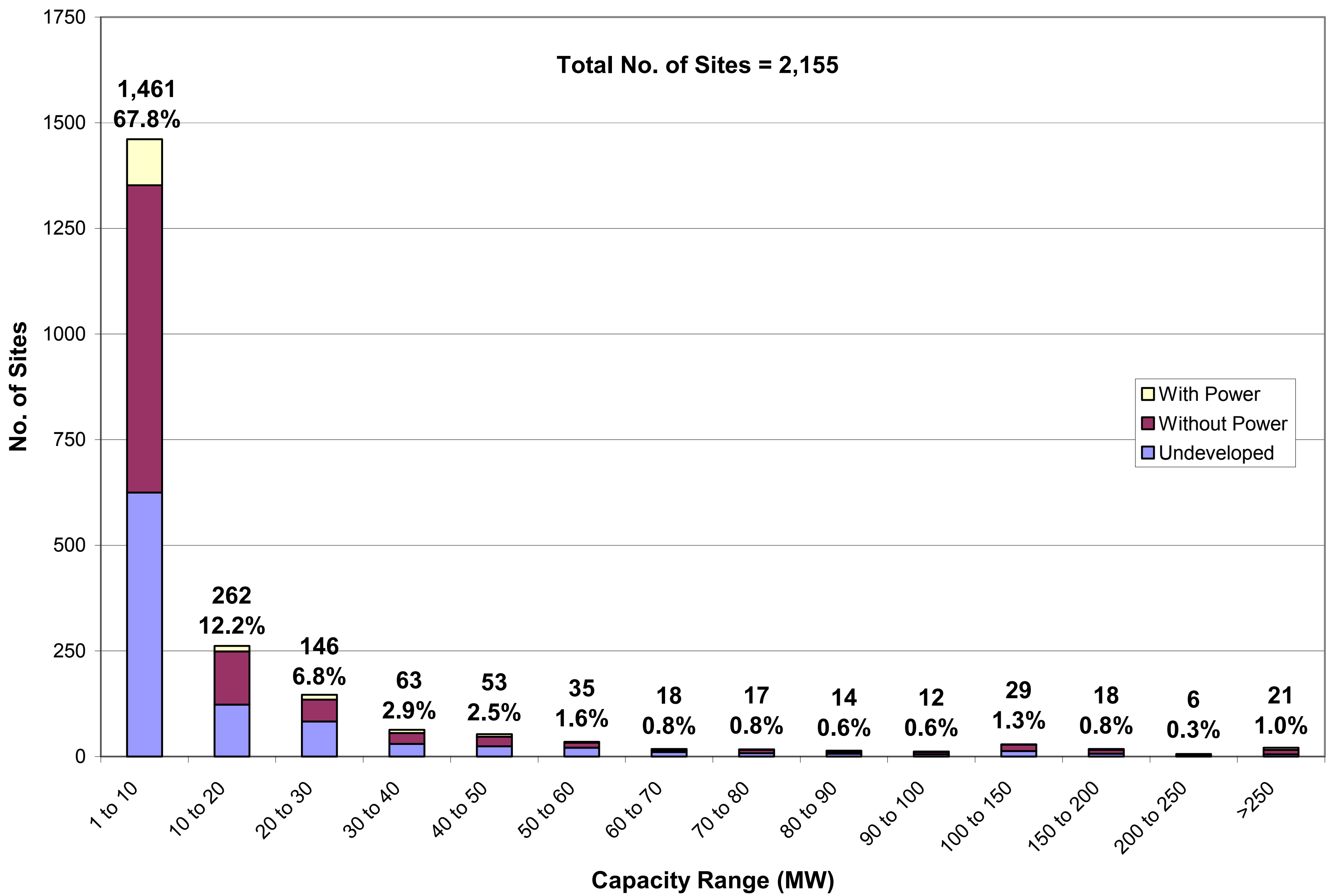

Figure 6. Number of IHRED resources having capacities or capacity additions within various capacity ranges.

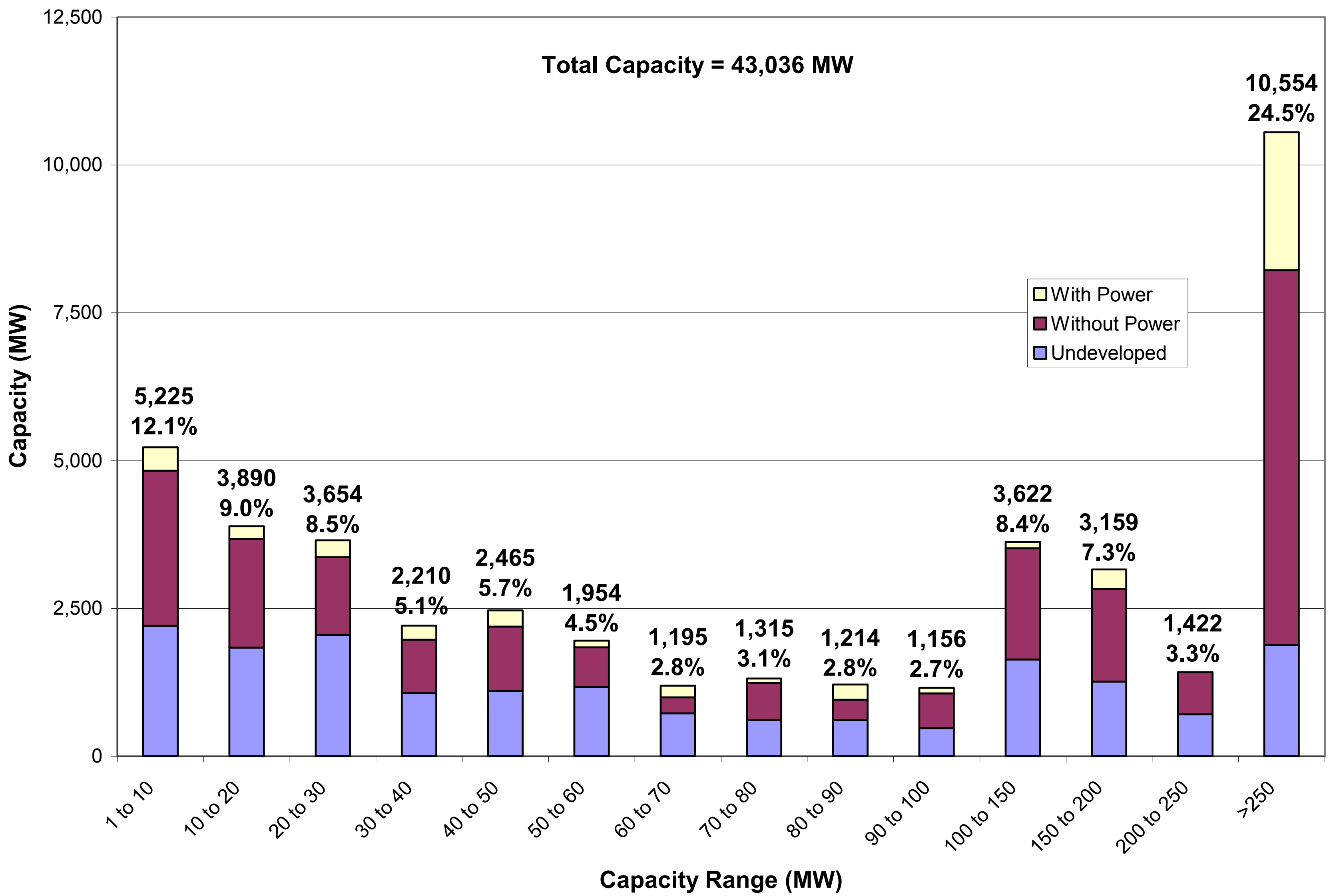

Figure 7. Total capacity of IHRED resources having capacities or capacity additions within various capacity ranges.

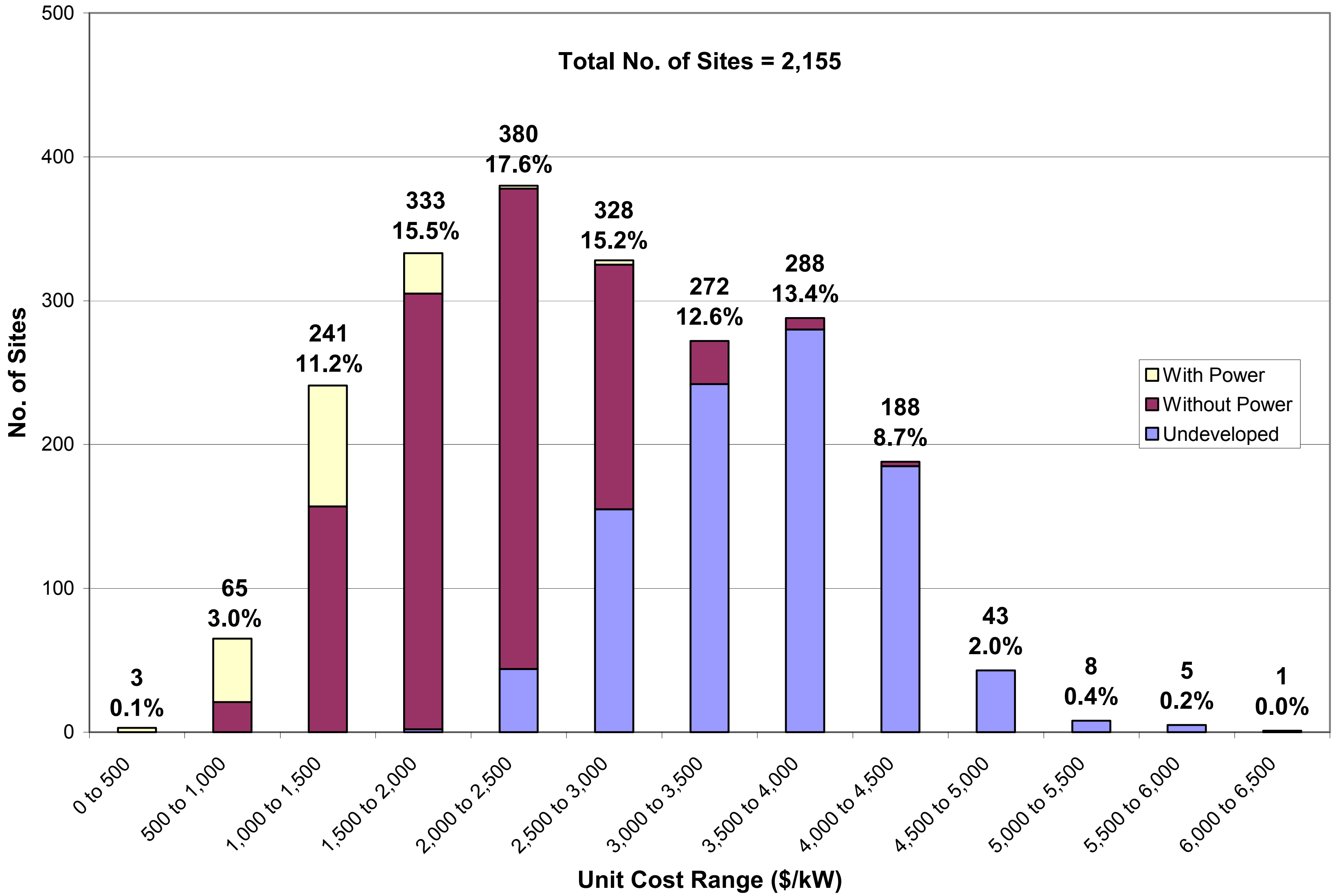

Figure 8. Number of IHRED resources having unit cost (total development) within various unit cost ranges.

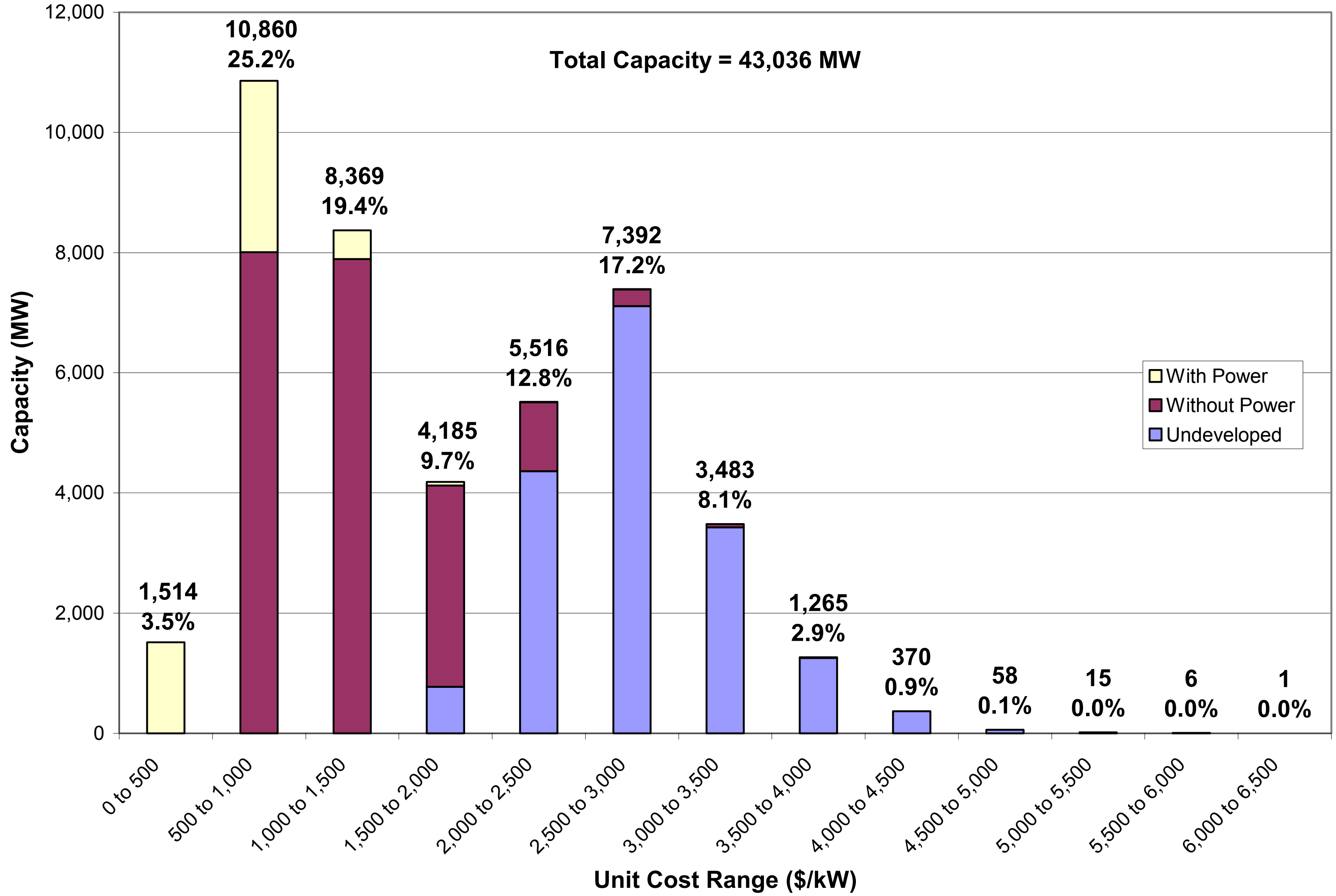

Figure 9. Total capacity of IHRED resources having unit cost (total development) within various unit cost ranges.

maximum number of this type of site being developed for $1,000 to $1,500 per kW. These maximum points of the respective distributions shift downward in unit cost from the perspective of developing the maximum capacity as shown in Figure 9. The maximum total capacity from undeveloped sites is obtained for $2,500 to $3,000 per kW, while the maximum total capacity is obtained from adding a powerhouse to dams without power for $500 to $1,500 per kW. The maximum total capacity from plant expansions is obtained for $500 to $1,000 per kW. Viewed as a whole, the results indicate that over 20,000 MW of capacity could be developed at unit costs of $1,500 per kW or less.

When considering new generating plants, long-standing energy industry practice has been to use unit costs ($/kW) of various facilities as a comparison tool to make development decisions. While the unit cost parameter is a good indicator of total development costs, using it alone for comparison with other technologies penalizes projects like hydroelectric facilities that have high initial costs, long life, no fuel costs, and low operating costs.

The chart showing amounts of capacity (MW) falling within various unit cost ranges (Figure 9) is presented for information as a relative cost indicator for the available hydropower resources analyzed in this study. It is not intended to imply an endorsement of the unit cost method to compare various technologies and make development decisions.

3.6 Likelihood of Development

In order to provide the IHRED user with some measure of the likelihood that a particular site will be developed, the SITEPROB field and the associated values from the HES database were included in the IHRED as field number 36. This parameter ranges from 0.10, which indicates the least likely sites to be developed, to 0.90, which indicates the most likely sites. The researchers reasoned that no site has a 0% probability of development just as no site can be predicted to have a 100% probability of development.

As described in Francfort et al. 2002, the value of the SITEPROB variable is a composite of the values of "suitability factors" that were determined to apply to a site during the hydropower resource assessment reported in Connor et al. 1998. Dependent upon the type of site (undeveloped, dam w/o power, or dam w/ power) suitability factor values were assigned to each of 12 environmental attributes and seven federally designated land uses. The suitability factor values (0.10, 0.25, 0.50, 0.75, 0.90) reflect: a) the probability that the attribute or land use will make a project unacceptable, prohibiting its development; and b) the degree to which associated licensing and mitigation costs would reduce the economic viability of the project. The lowest value indicates that the attribute would tend to prohibit development or make it highly unlikely and the highest value indicates that the attribute will have little effect on the likelihood of development. The SITEPROB value is either the single lowest suitability factor associated with the site or the next lowest value when there is more than one occurrence of the lowest value.

4. CONCLUSIONS AND RECOMMENDATIONS

Analysis of historical hydropower data has shown that the costs of licensing, construction, five types of mitigation, and fixed and variable O&M costs correlate with plant capacity. As a result, least squares power curve fits of cost as a function of capacity were defined that have R^2 values ranging from 0.56 to 0.99. These power equations can be used to estimate costs in 2002 dollars for hydropower resources including undeveloped sites, addition of a power house to a dam, and expansion of an existing hydroelectric plant. Functional relationships were also developed that can be used to estimate the cost in 2002 dollars of upgrading three types of turbines (Francis, Kaplan, and bulb) and upgrading generators.

In addition to the cost estimating tools, a method for estimating resource annual and monthly electric generation was developed. This method, which is based on 30 years of generation data, can be used to determine generation based on average generation values for the state in which the resource is located.

The HES database that contains 5,677 hydropower resources and has a total capacity of 69,009 MW was evaluated and found to contain 2,155 resources having a total capacity of 43,036 MW to which the cost and generation estimating tools were applicable. Application of the tools resulted in cost and generation data, which was assembled to produce the IHRED that included these data and site characteristic information for each of the 2,155 resources. This database will be useful both in predicting future hydroelectric supply and as a preliminary indication of the feasibility of realizing the potential of hydropower resources.

The estimated costs of developing the 2,155 sites in the IHRED indicate that over 20,000 MW of new capacity could be developed for $1,500 per kW or less. These sites are existing dams to which a powerhouse could be added or existing hydroelectric plants that could be expanded. The development of undeveloped sites is significantly more expensive with a median unit cost of $2,700 per kW. While the unit cost is relatively high in comparison with other technologies, it should be considered that hydroelectric facilities offer attractive characteristics that offset the high initial cost such as long life, no fuel costs, and low operating costs as well as reliability, dispatchability, and peaking power supply, among others.

This study was constrained to use only data sources that were readily available; generally in electronic form. In addition, questionable or incomplete data could not be evaluated and had to be treated as unusable. The data populations on which the cost estimating tools are based could be expanded with greater research and the purchase of private data collections. Some of the data that was not used, because it appeared questionable or incomplete, could possibly be used if it were further researched. The larger data populations obtained from these efforts would refine the cost estimating tools.

The majority of the estimating tools had R^2 values in the 60 and 70 percentiles, indicating significant scatter in the data. Additional data may increase these R^2 values. However, this scatter may be indicative of dependence on another variable or other variables in addition to plant capacity. Alternate functional relationships that may better correlate the data should be investigated.

A tool for estimating water quality mitigation could not be produced within the constraints of the study, because of the limited data that was readily available and the lack of correlation with a single parameter like plant capacity. Greater research would probably add additional data and may result in a method of estimating this parameter. The estimating tool for the cost of water quality monitoring, which had an R^2 value of 0.56, would no doubt benefit from additional research. Such research may well show that dependence on a single variable like plant capacity is not sufficient for estimating this cost.

The tools that were developed for estimating the cost of upgrading turbines and generators could not be applied to specific sites to evaluate the potential for capacity increase, resulting from these types of upgrades. An evaluation of U.S. hydroelectric plants from the perspective of upgrade potential should be performed to create a counterpart to the IHRED containing plant characteristics; the estimated cost of the plant upgrade; estimated, associated licensing and mitigation costs, if any; estimated, incremental O&M costs; and added capacity and generation.

The method of estimating plant generation should be reviewed to determine whether a more mechanistic model can be developed. Use of 30 years of historical data is a good first step, but the resulting predictors could probably benefit from refinement based on climatic prediction models. Also, using state boundaries as the arbiter of what average plant factor applies to a particular location is probably not optimally accurate. Plant factors based on hydrography would probably provide better predictors. This approach should be investigated.

The present study produced a large volume of data associated with a significant number of hydropower resources. It was not within the scope of the study to analyze this data extensively and draw conclusions or make recommendations based on such analysis. Greater value could be obtained from the useful product that has been produced if the IHRED data were analyzed to determine the trends and patterns that they contain. This analysis should be performed for the benefit of both those who will use the data for predicting future hydroelectric supply and those who are decision makers regarding hydropower development.

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Appendix A

Cost Estimating Tools

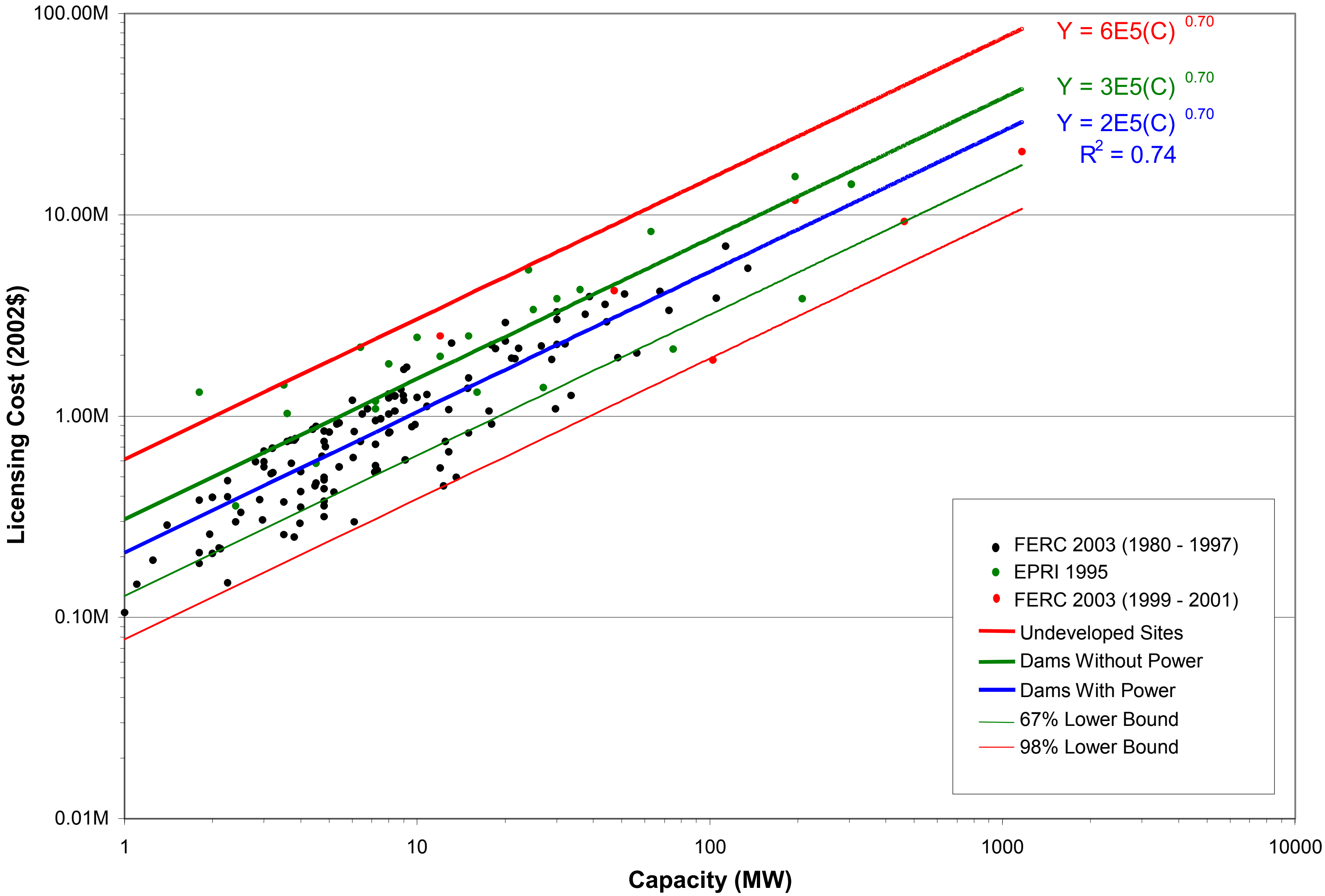
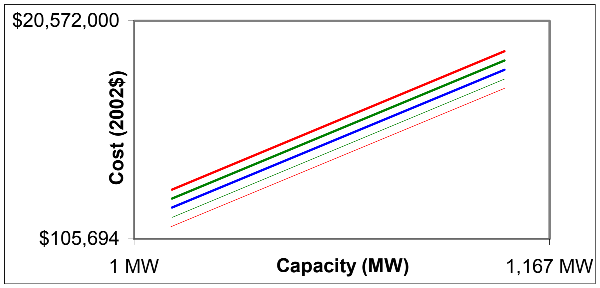


Figure A.1A. Licensing cost as a function of plant capacity for an undeveloped site and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.



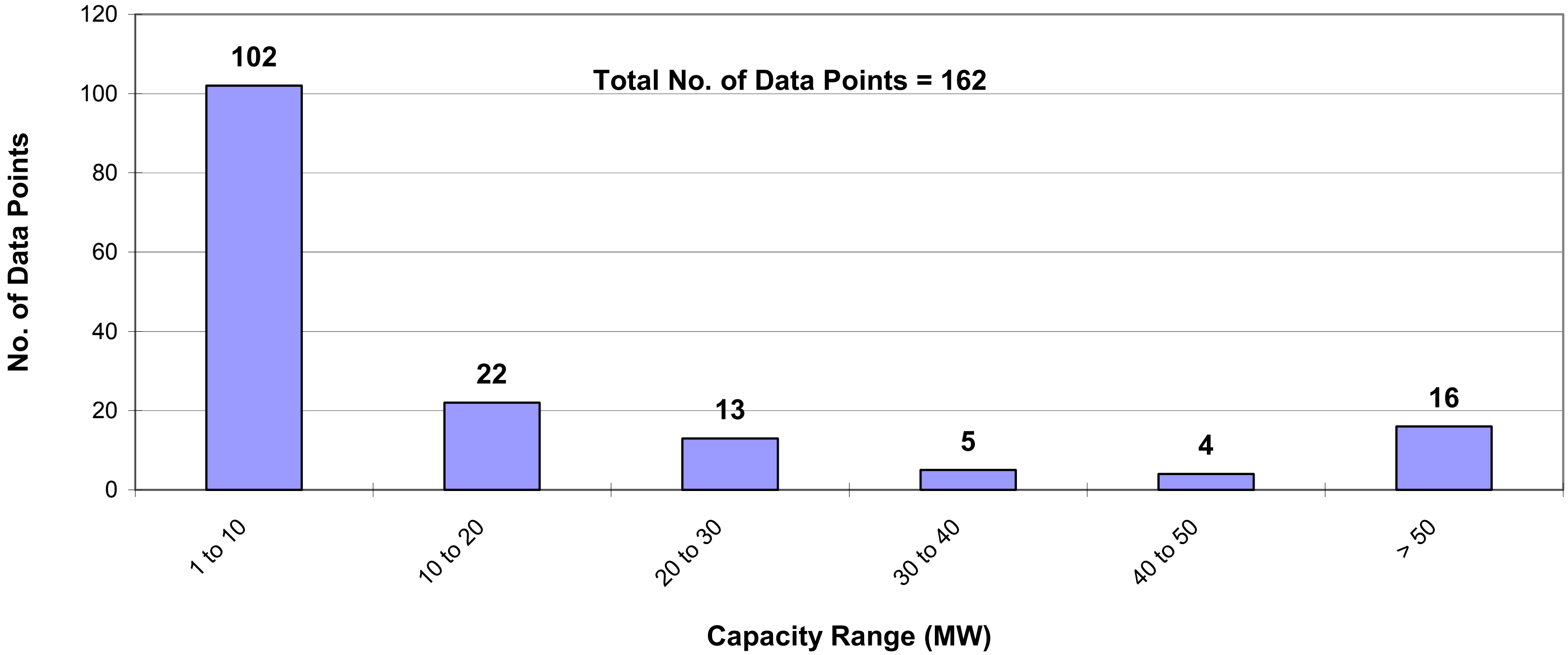


Figure A-1B. Number of licensing cost data points for various plant capacity ranges.

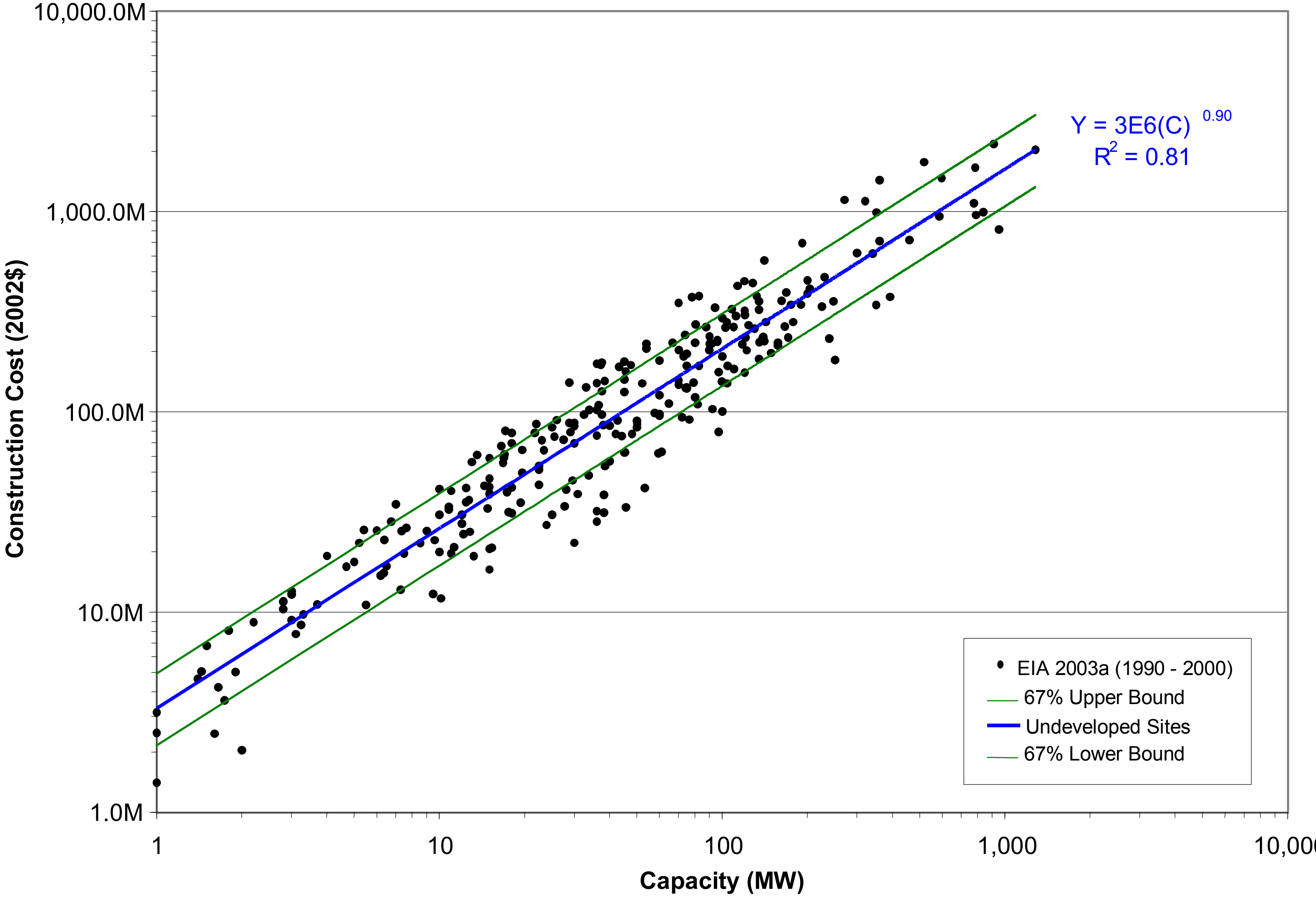


Figure A-2A. Plant construction cost as a function of plant capacity for undeveloped sites.

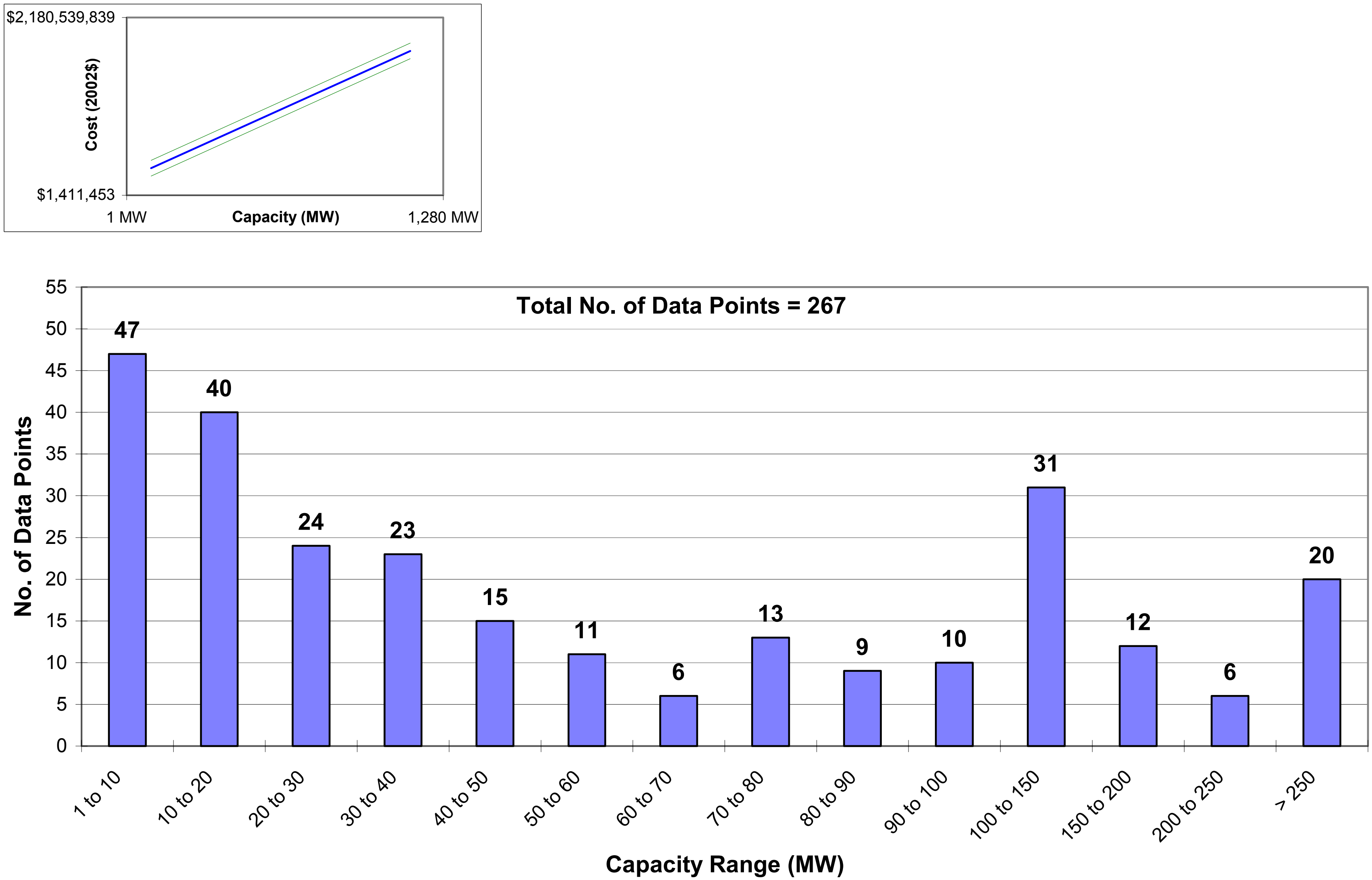


Figure A-2B. Number of undeveloped site construction cost data points for various plant capacity ranges.

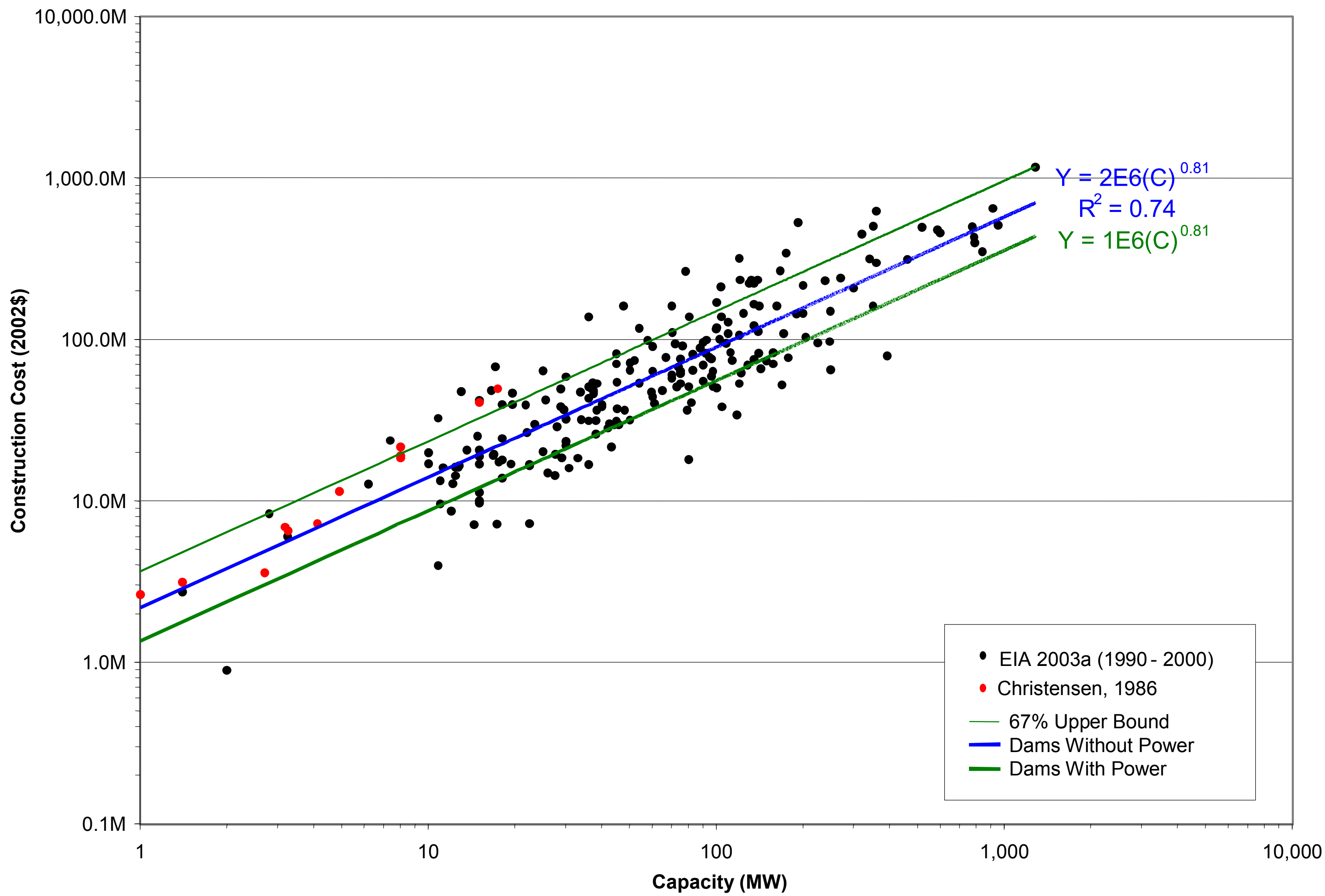


Figure A-3A. Construction cost as a function of plant capacity for a powerhouse installation at a dam without power or as a function of added capacity for a plant expansion.

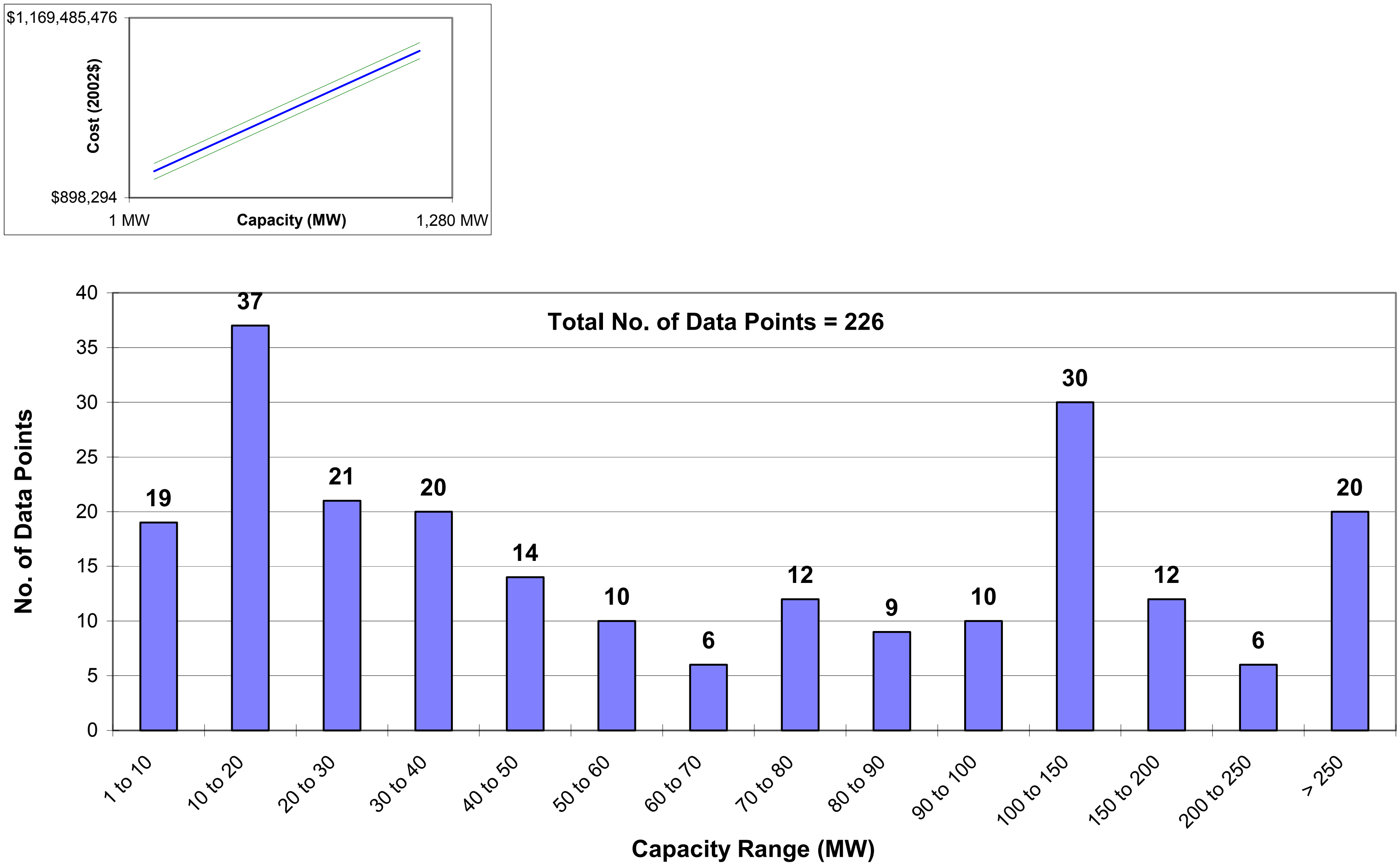


Figure A-3B. Number of powerhouse construction cost data points for various plant capacity ranges.

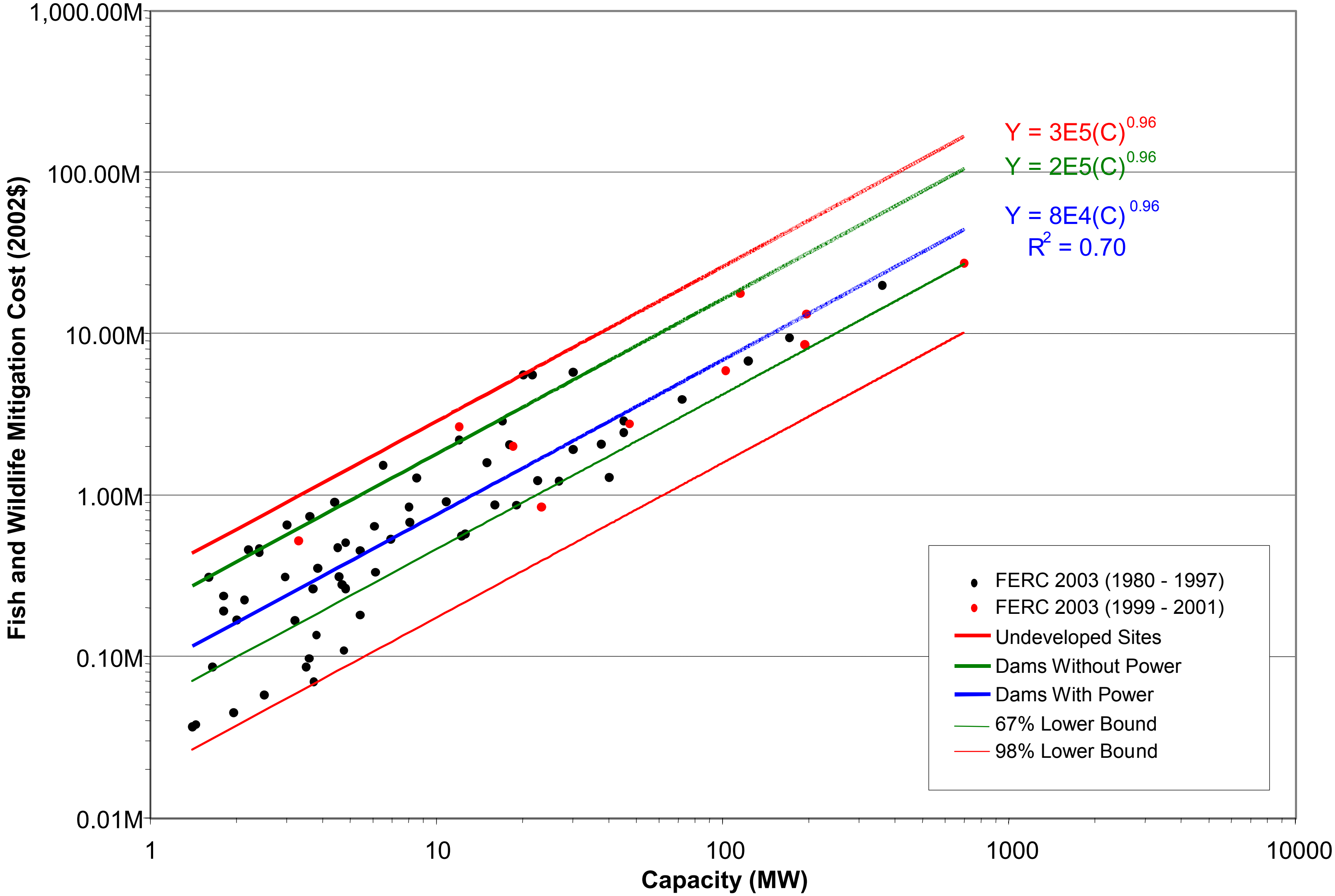


Figure A-4A. Fish and wildlife mitigation cost as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.

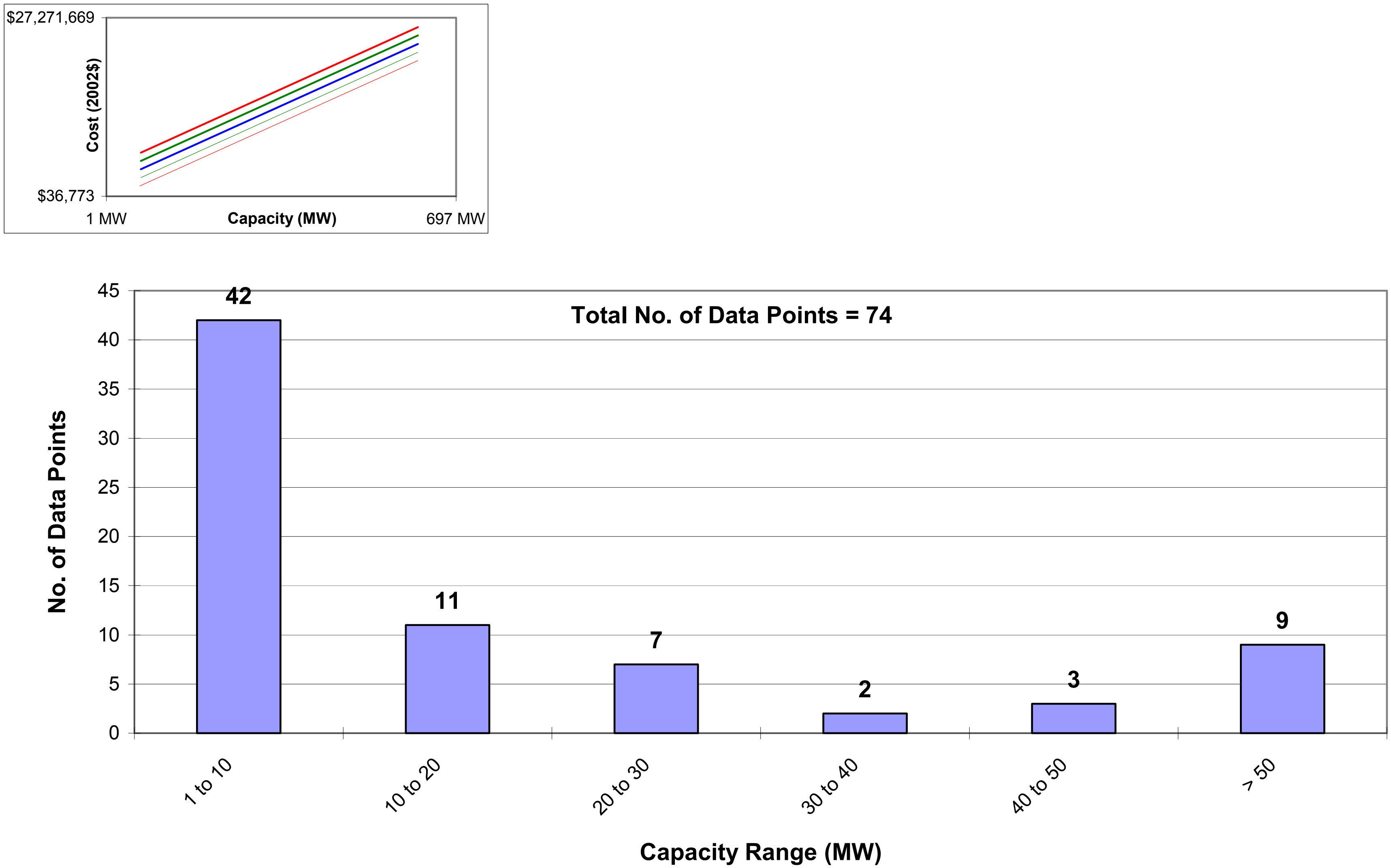


Figure A-4B. Number of fish and wildlife mitigation cost data points for various plant capacity ranges.

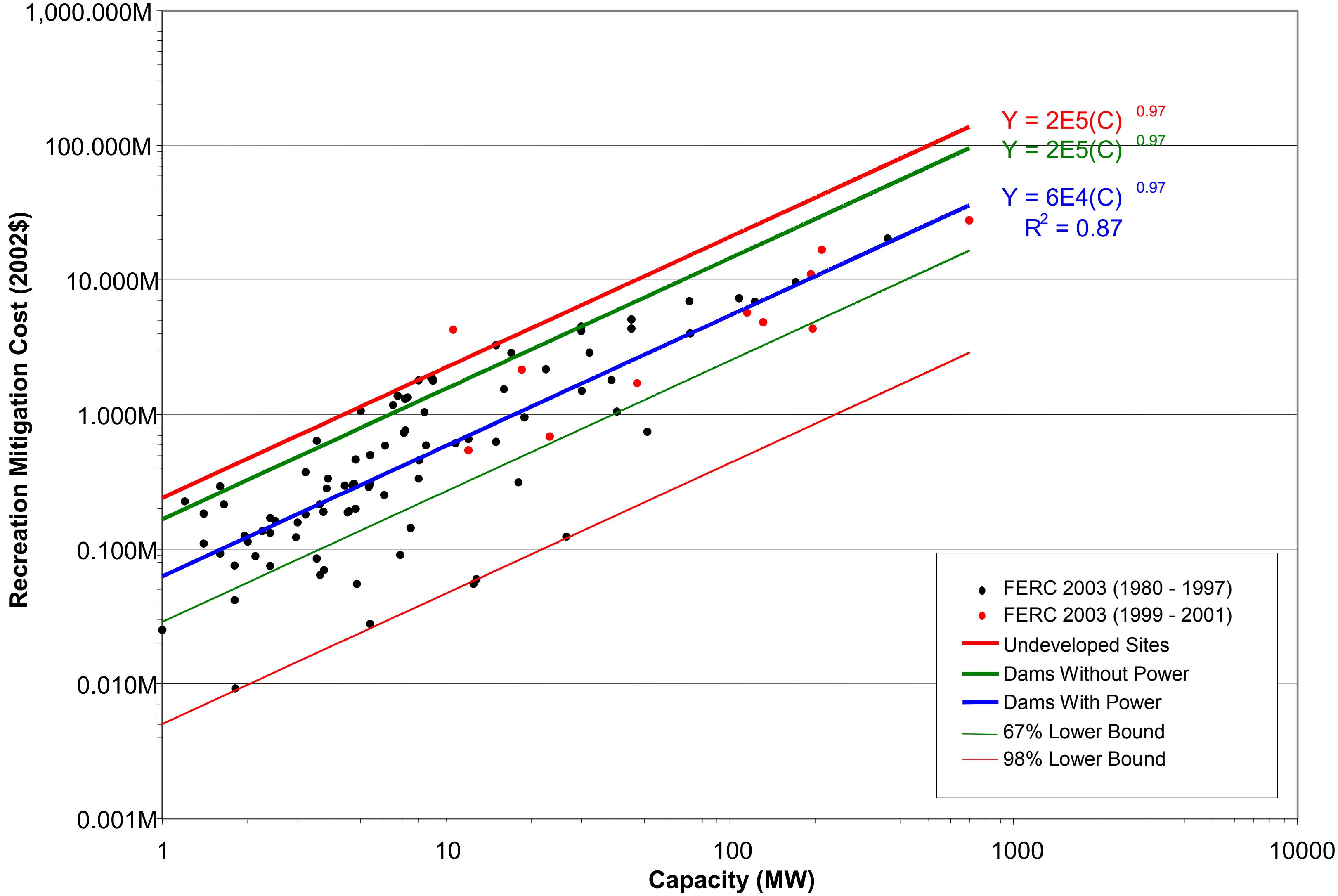


Figure A-5A. Recreation mitigation cost as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.

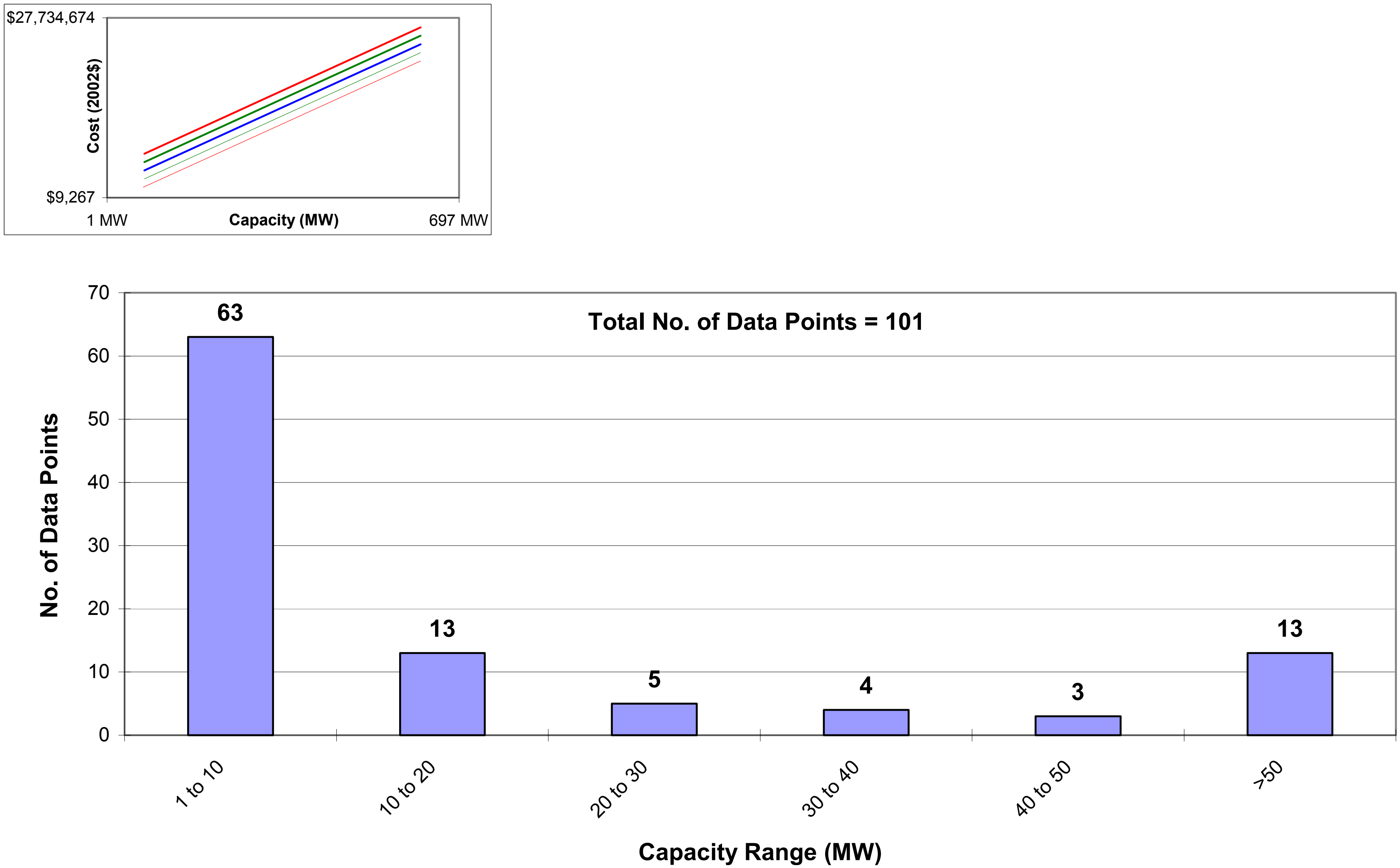


Figure A-5B. Number of recreation mitigation cost data points for various plant capacity ranges.

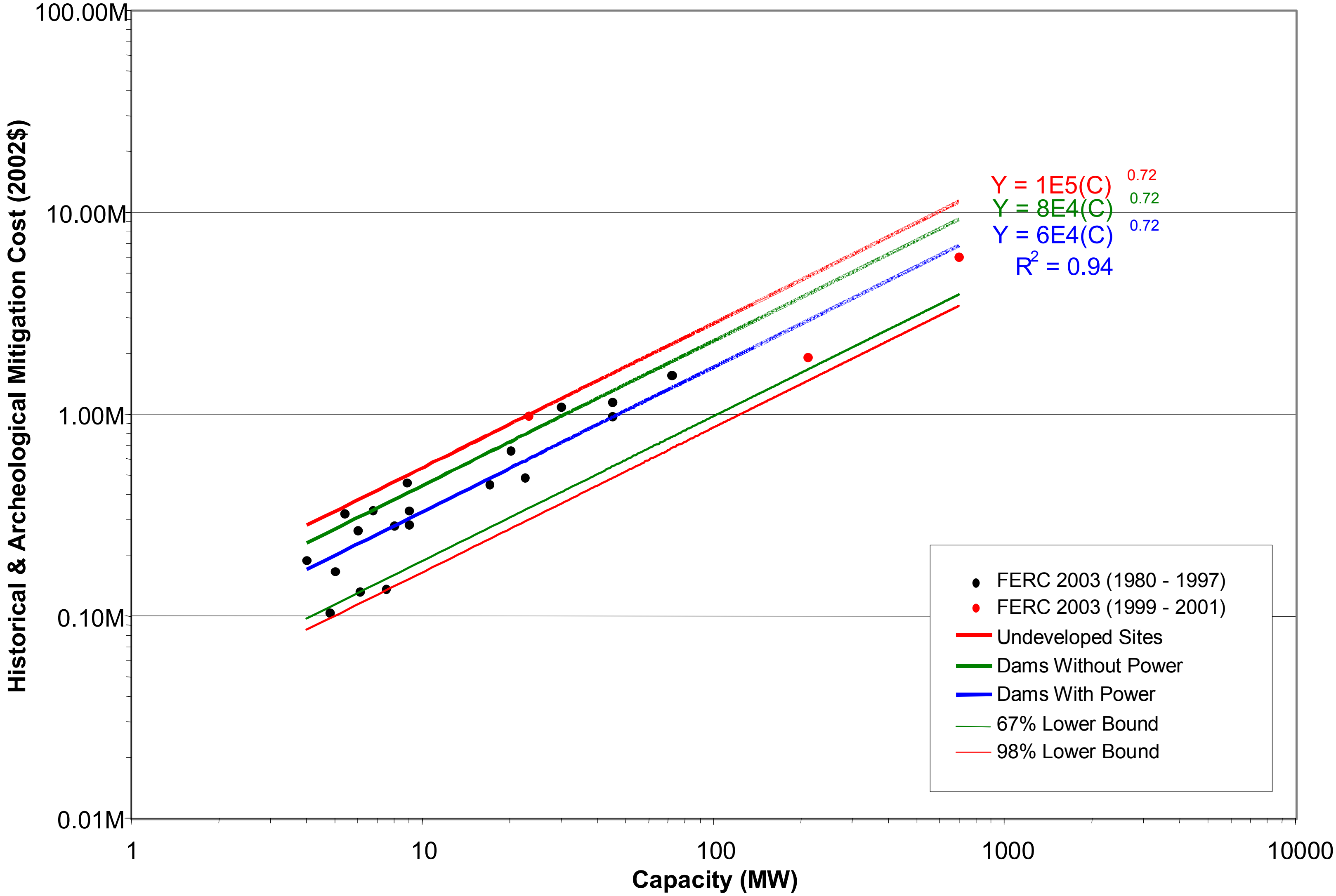
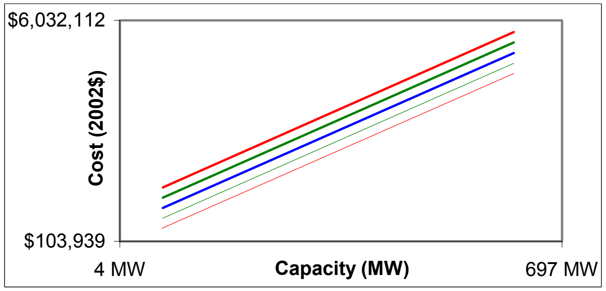


Figure A-6A. Historical and archeological mitigation cost as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.



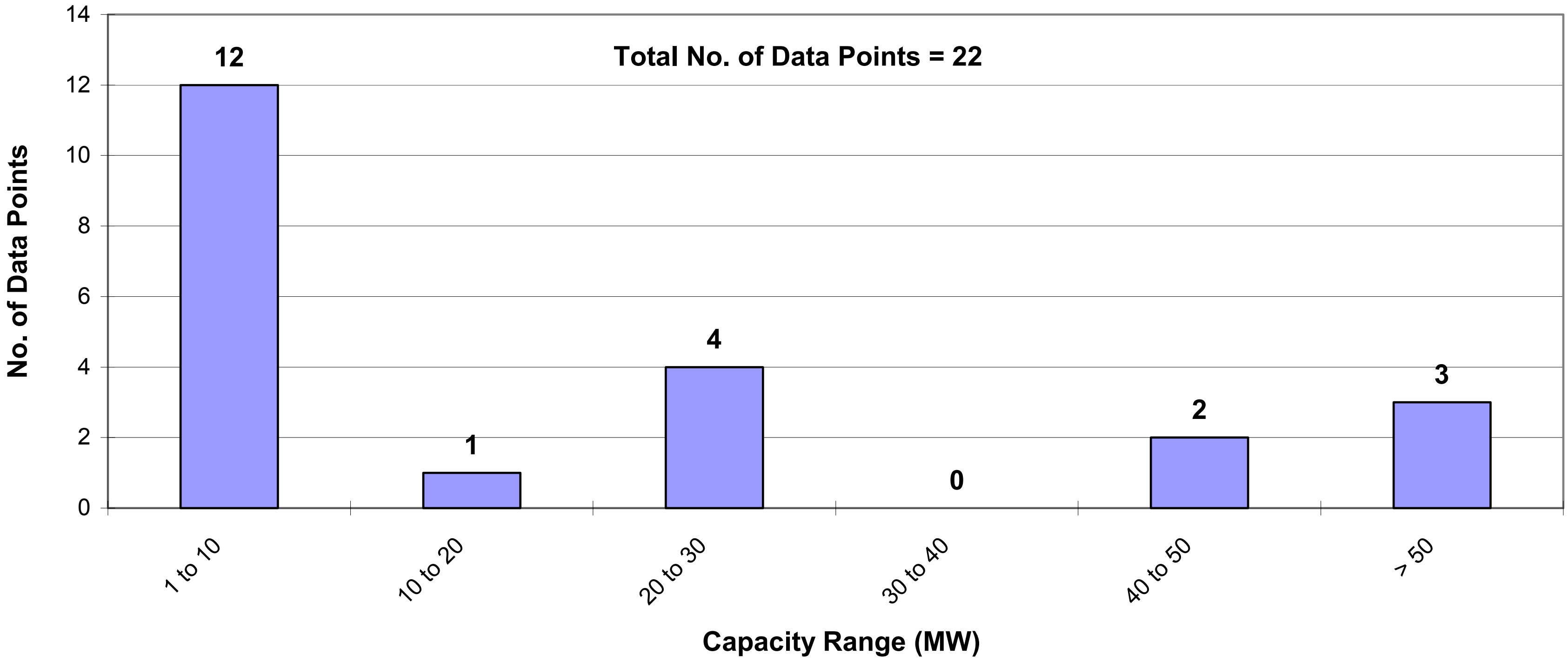


Figure A-6B. Number of historical and archeological mitigation cost data points for various plant capacity ranges.

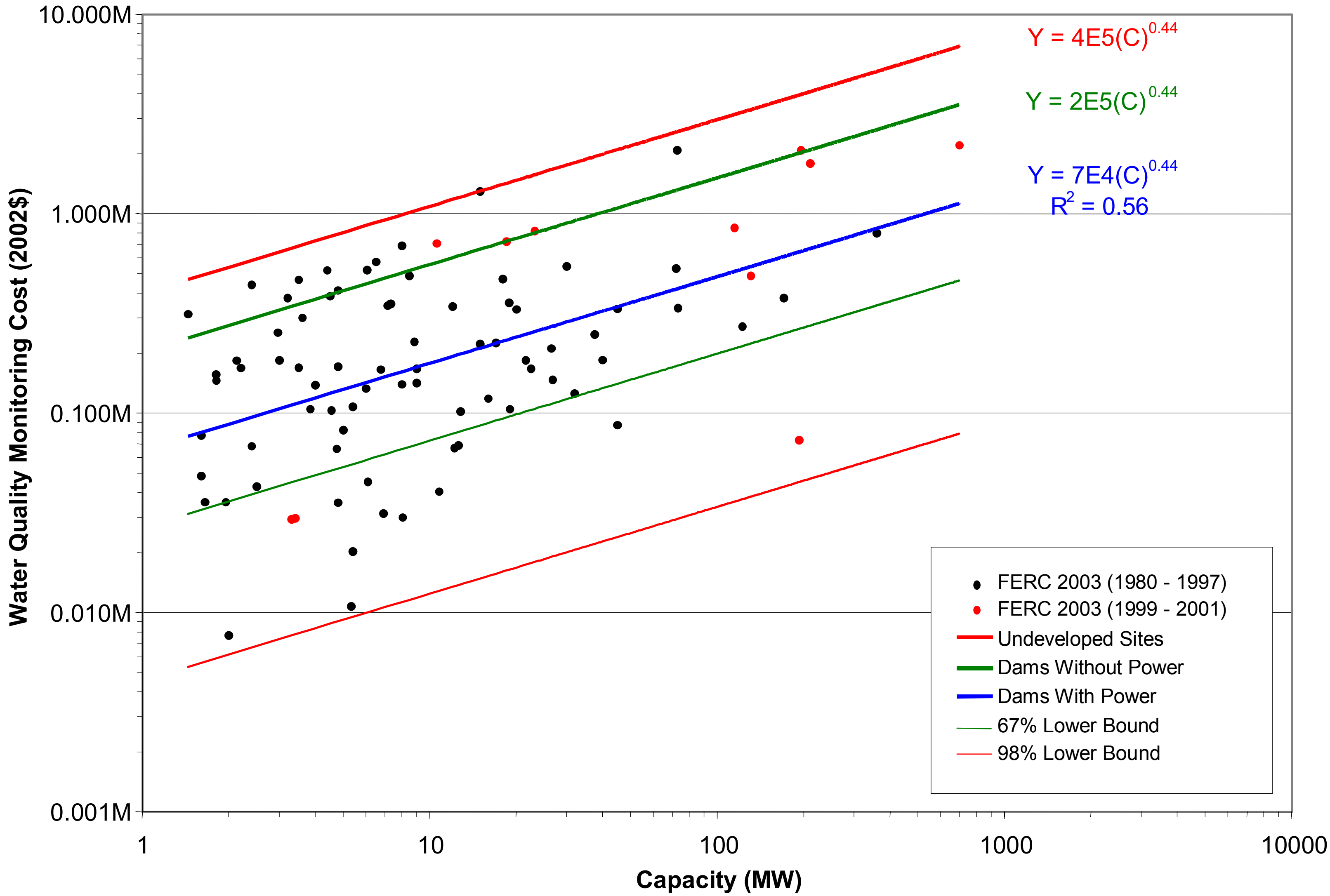
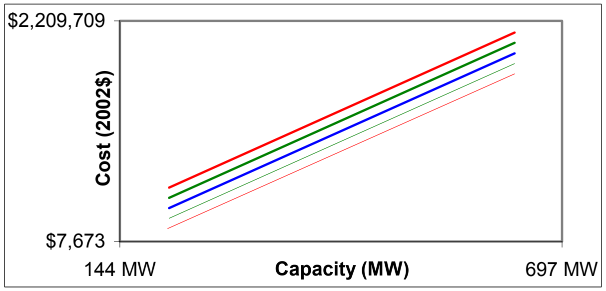


Figure A-7A. Water quality monitoring cost as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.



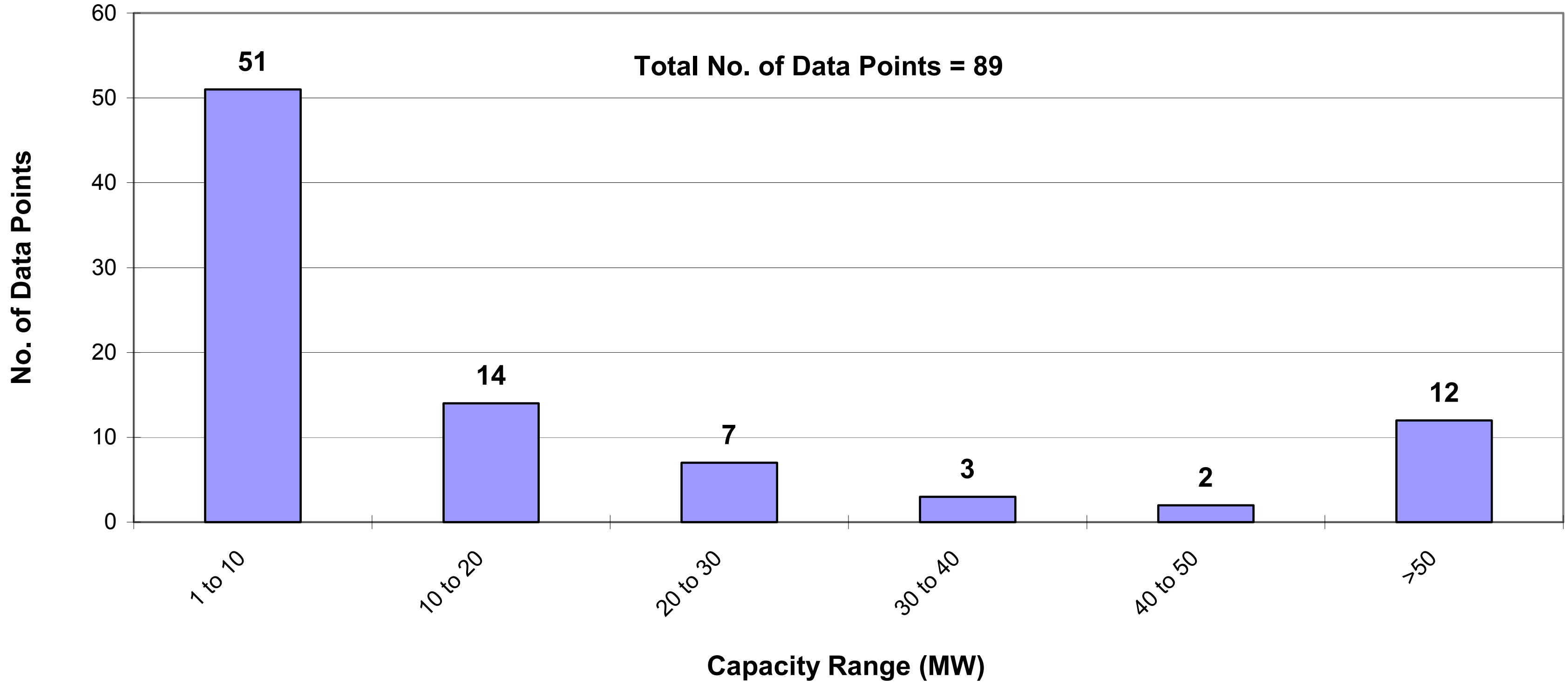


Figure A-7B. Number of water quality monitoring cost data points for various plant capacity ranges.

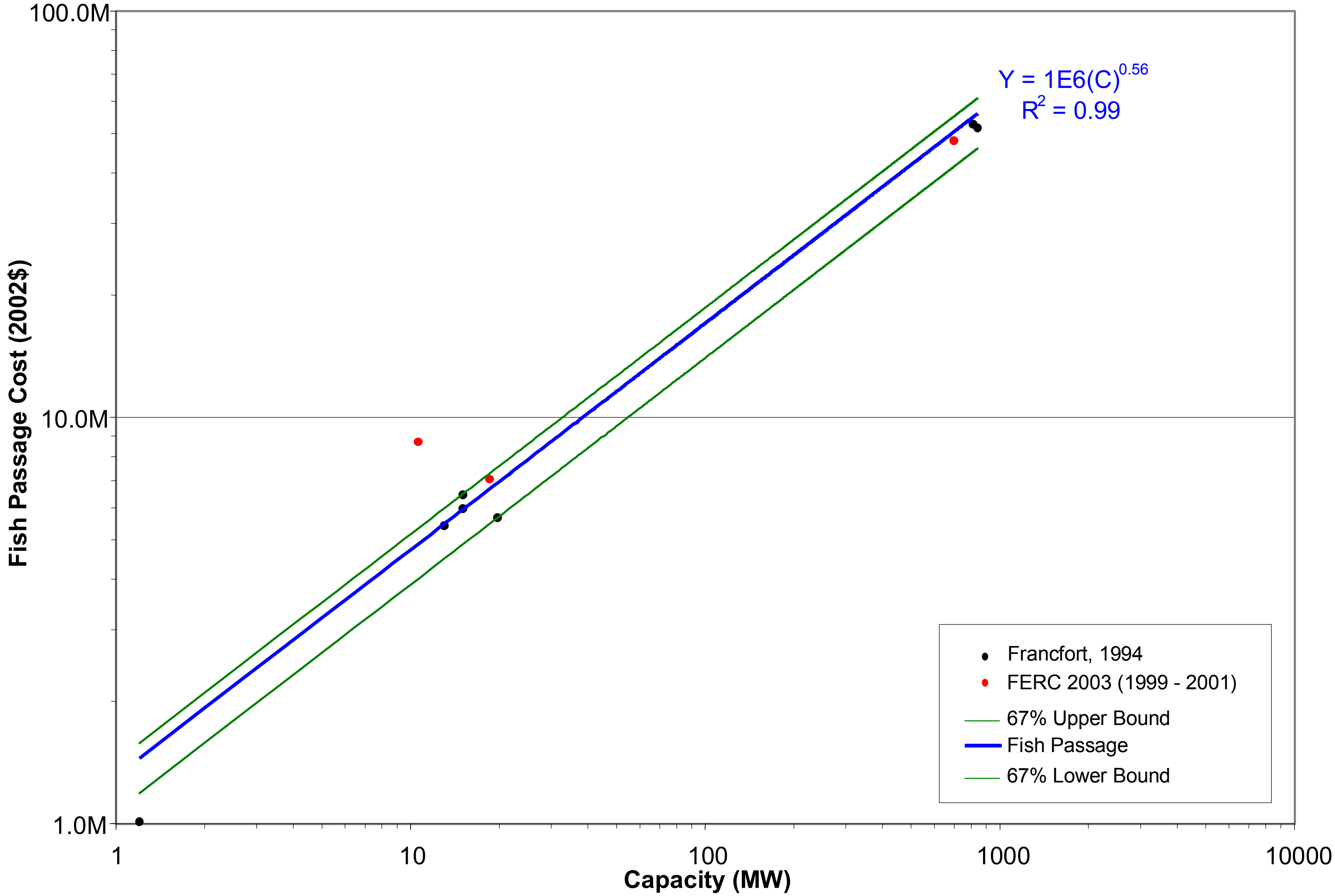


Figure A-8A. Fish passage cost as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.

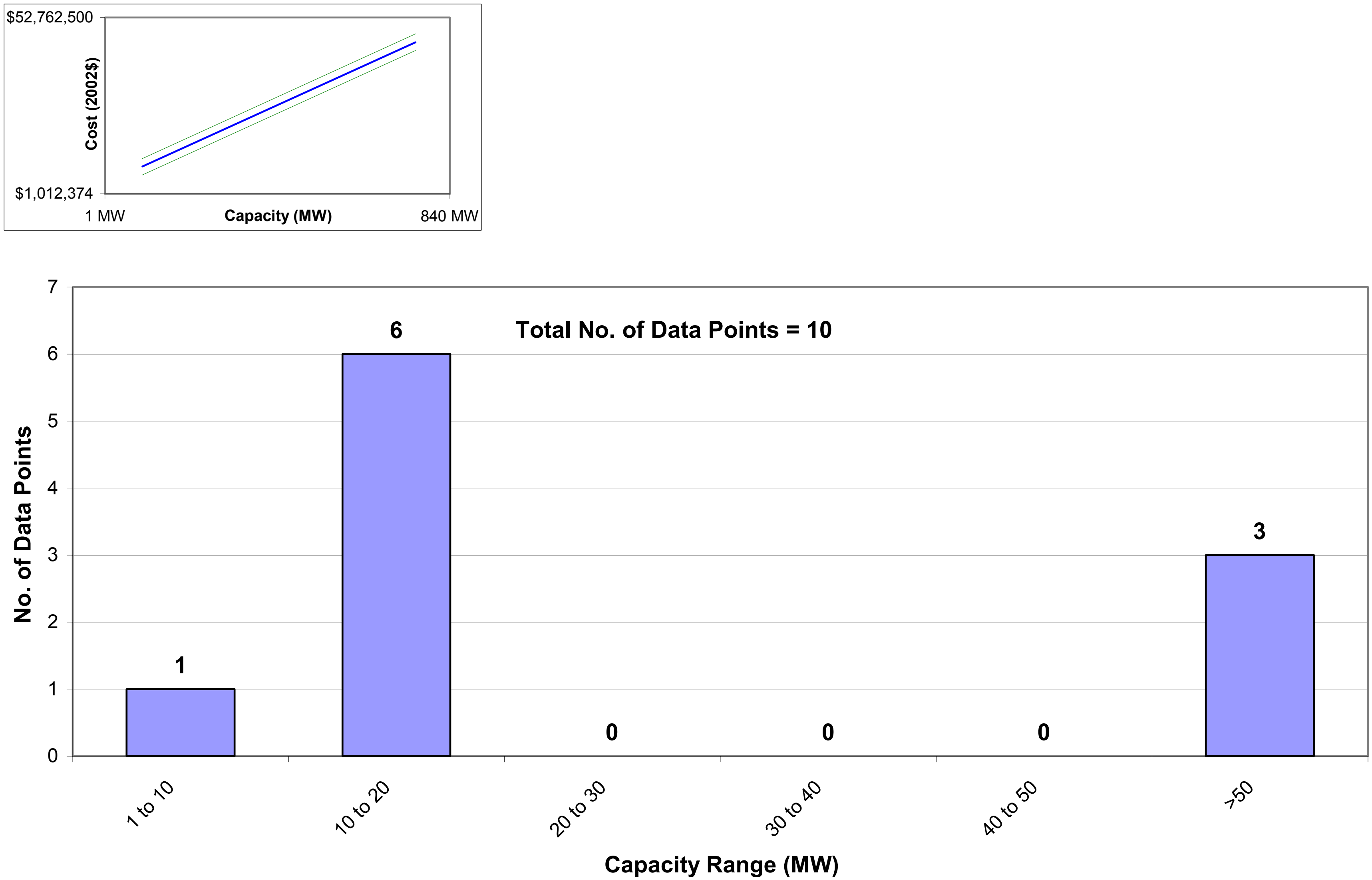


Figure A-8B. Number of fish passage cost data points for various plant capacity ranges.

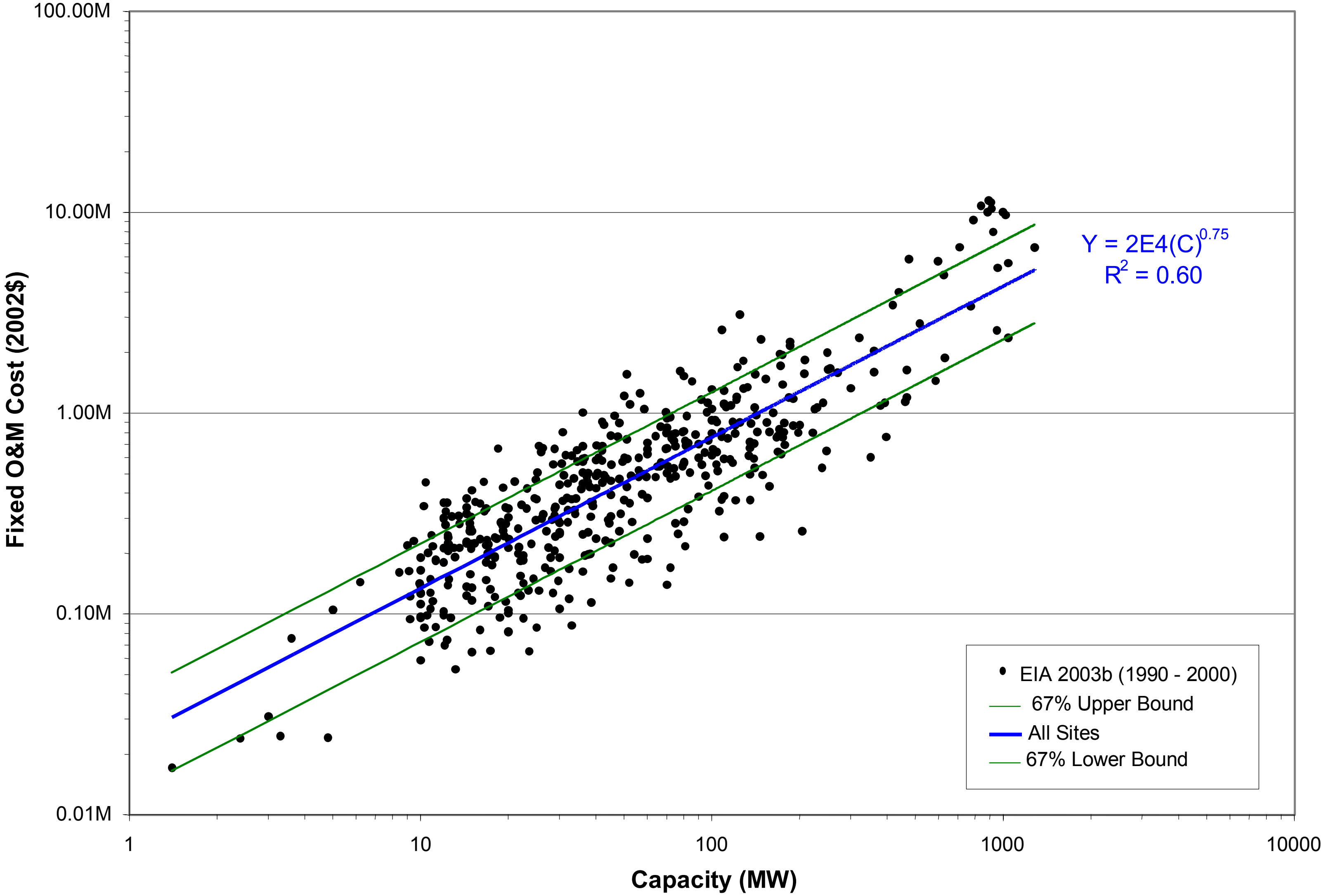


Figure A-9A. Fixed operating and maintenance costs as a function of plant capacity for undeveloped sites and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.

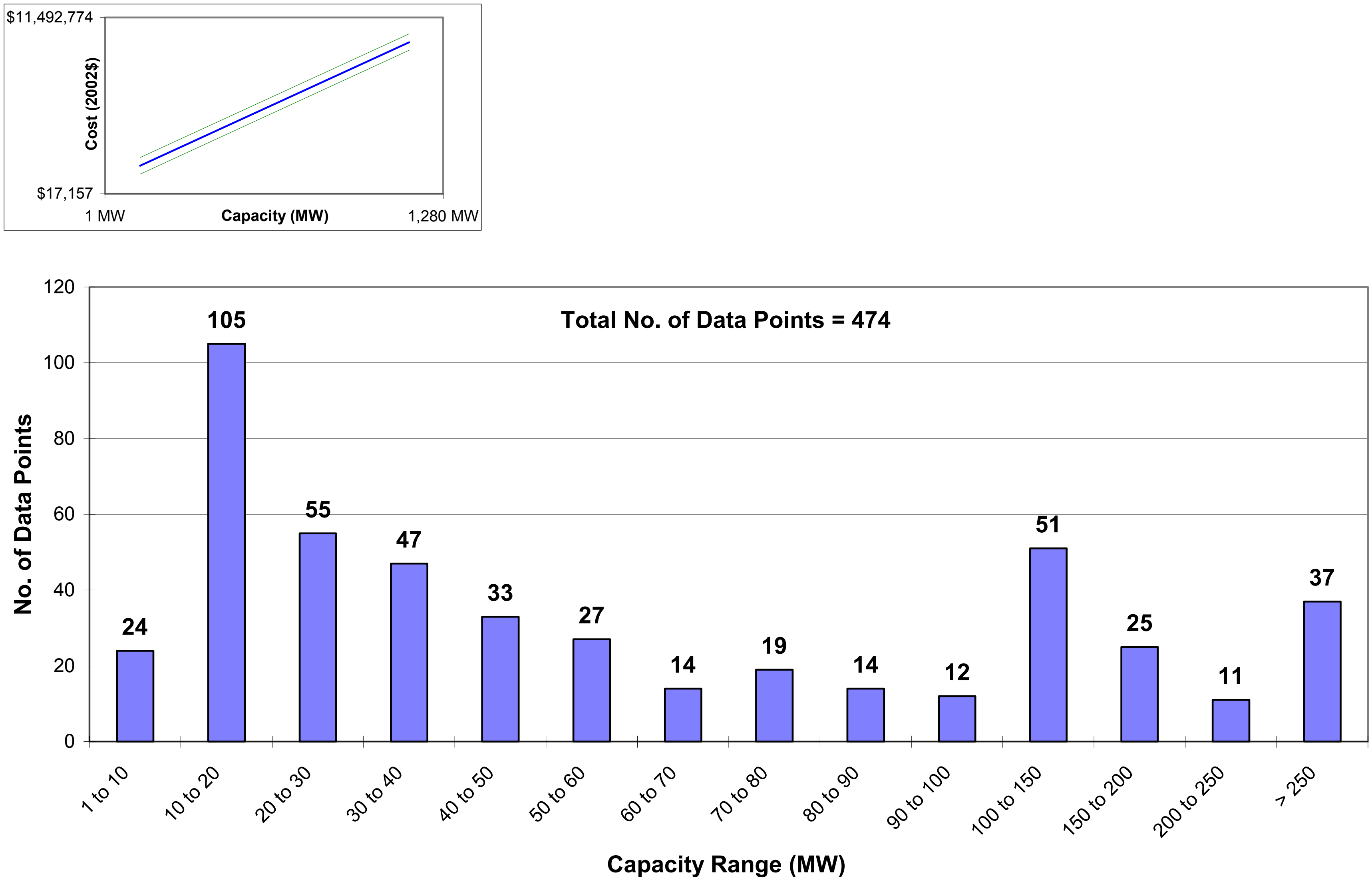


Figure A-9B. Number of fixed operation and maintenance cost data points for various plant capacity ranges.

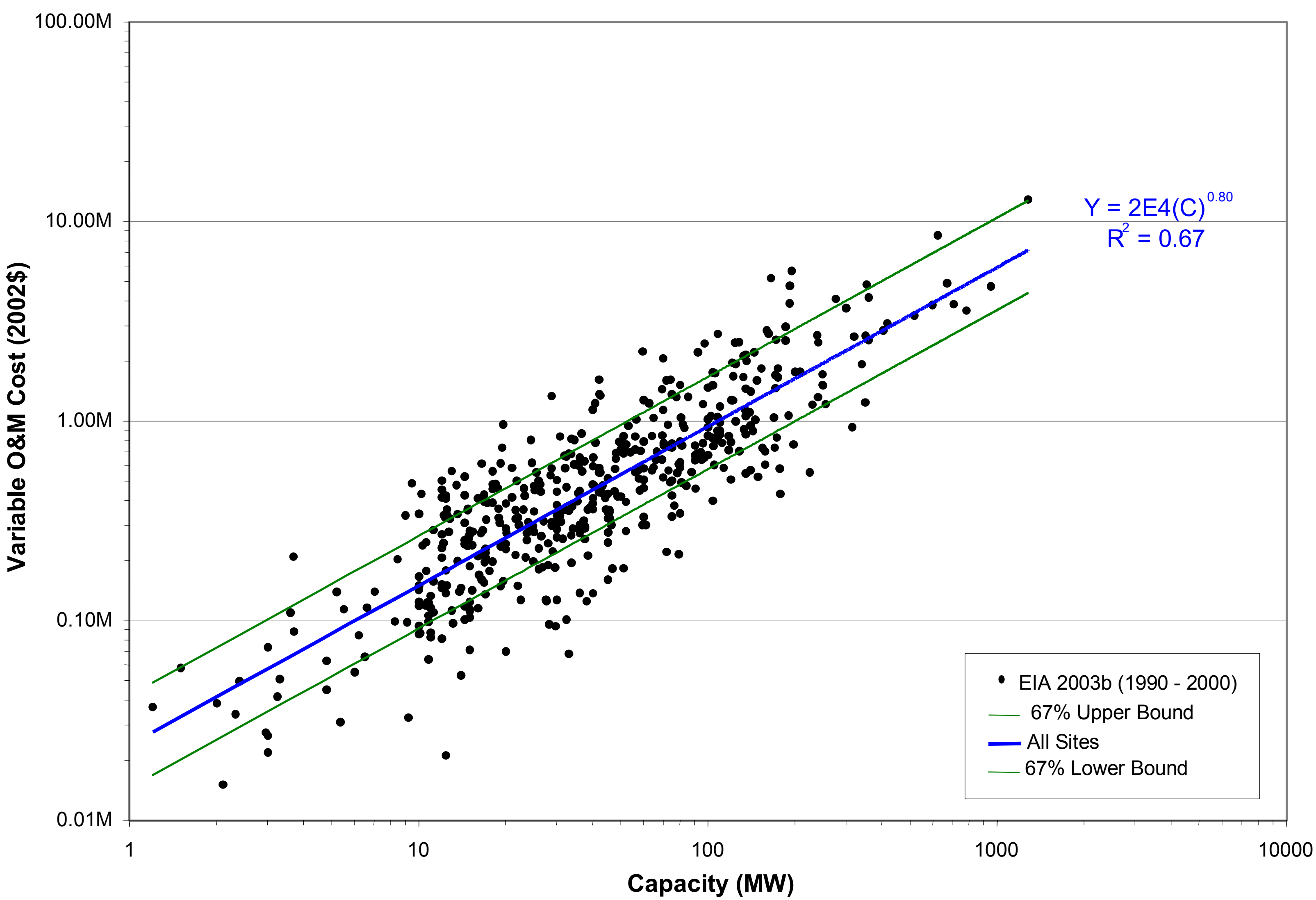
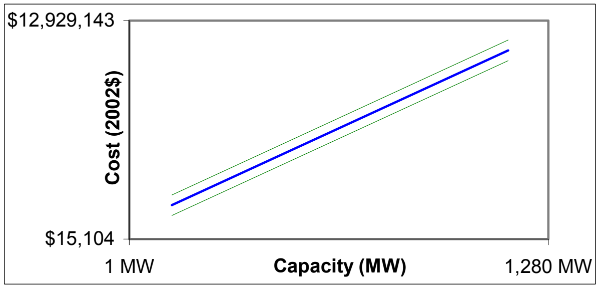


Figure A-10A. Variable operating and maintenance costs as a function of plant capacity for undeveloped and powerhouse installation at a dam without power and as a function of added capacity for a plant expansion.



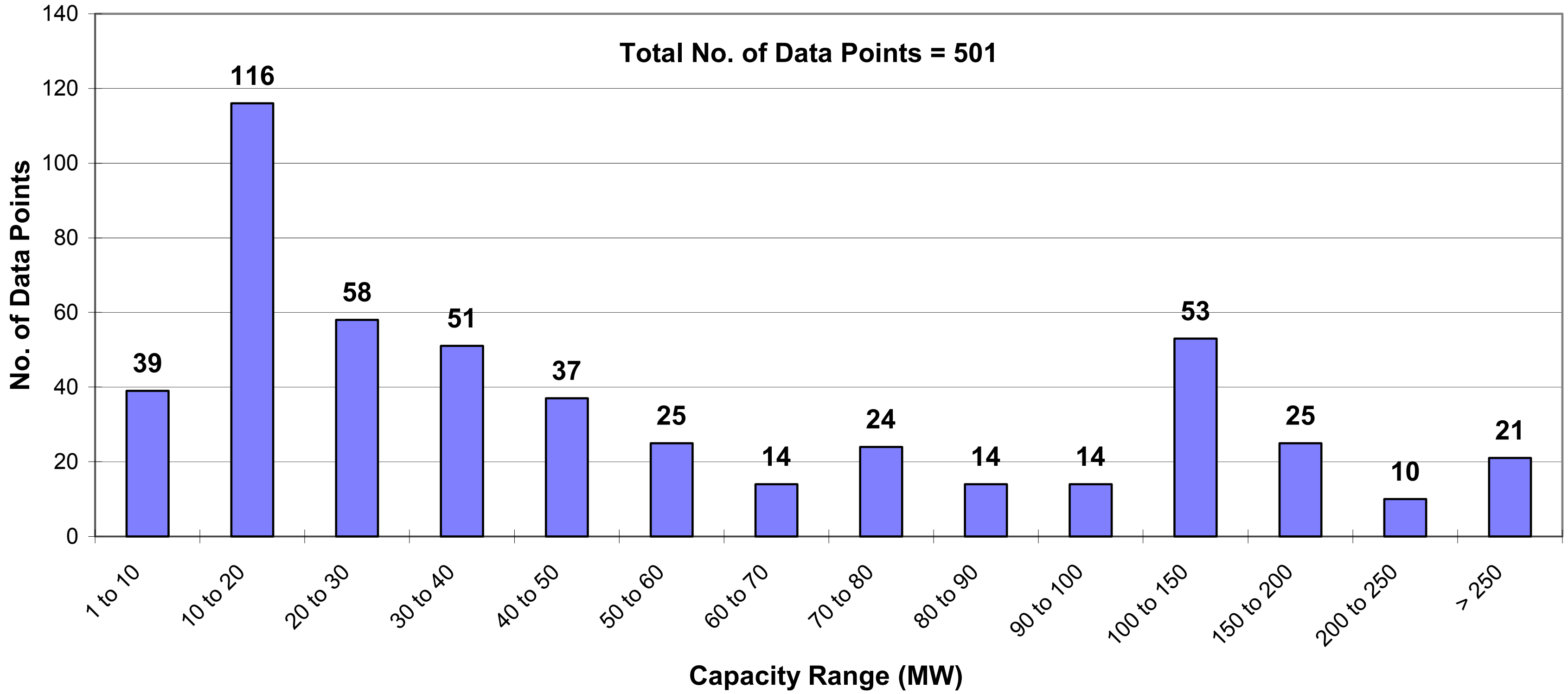


Figure A-10B. Number of variable operation and maintenance cost data points for various plant capacity ranges.

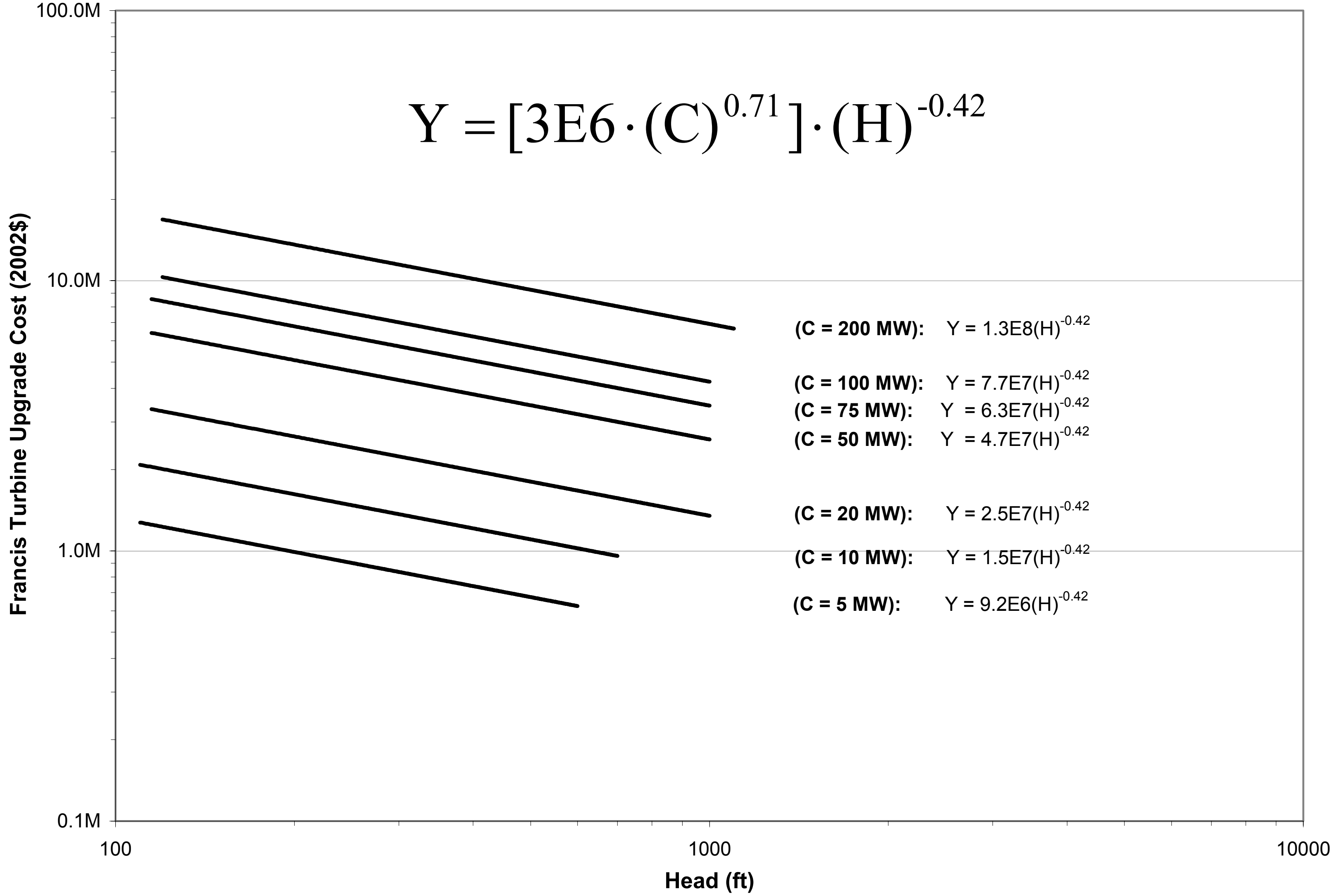


Figure A-11. Francis turbine upgrade cost as a function hydraulic head for various plant capacities.

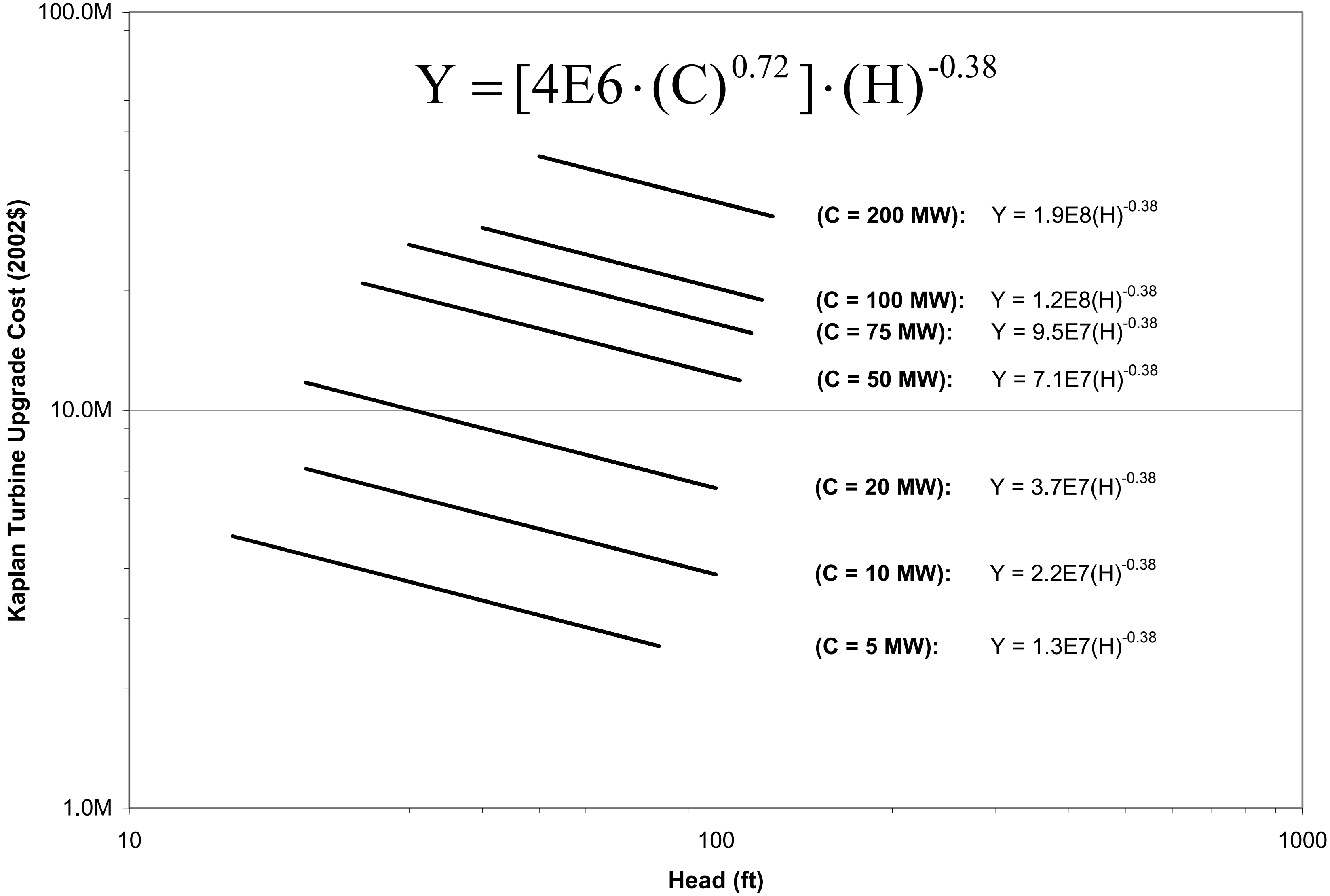


Figure A-12. Kaplan turbine upgrade cost as a function hydraulic head for various plant capacities.

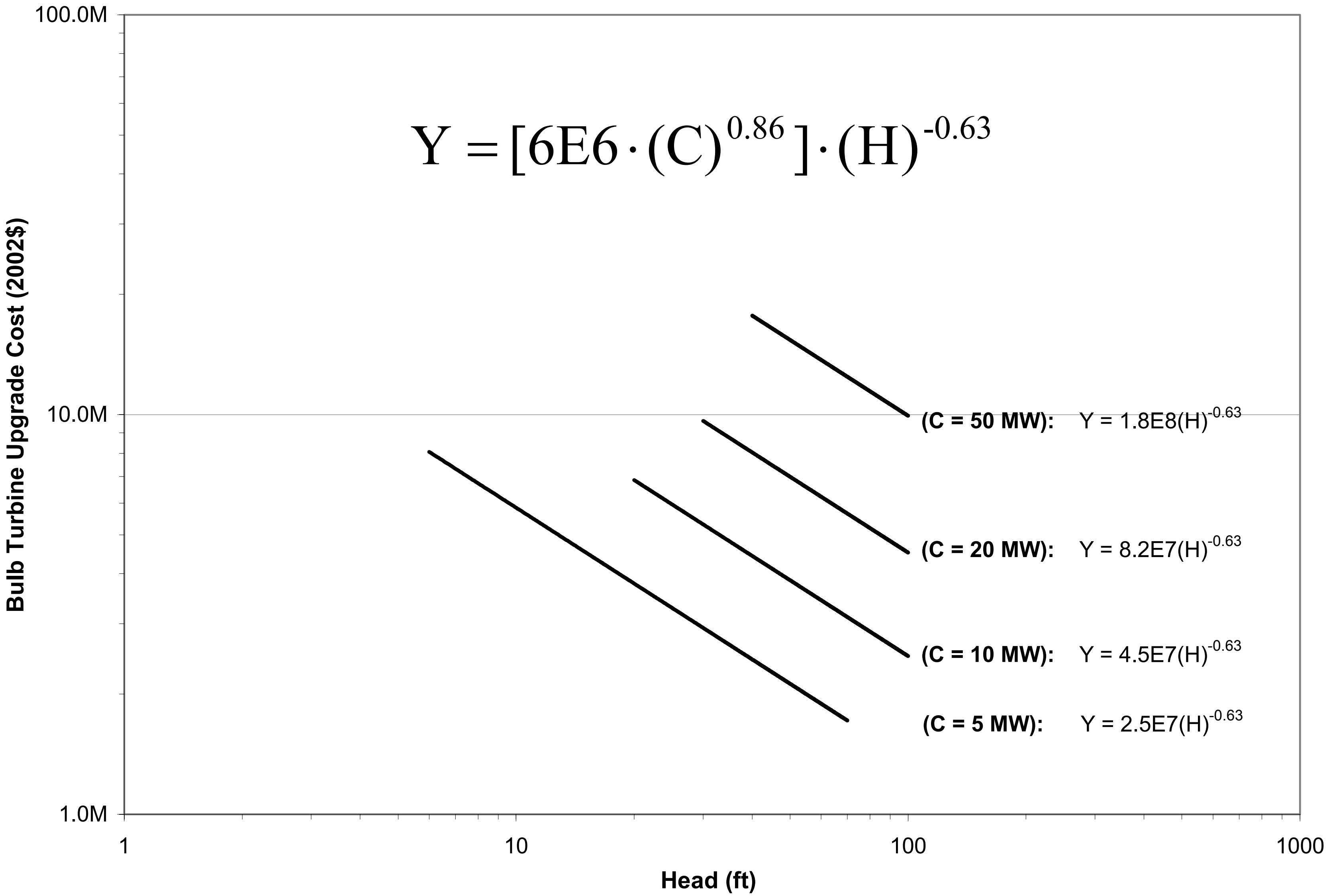


Figure A-13. Bulb turbine upgrade cost as a function hydraulic head for various plant capacities.

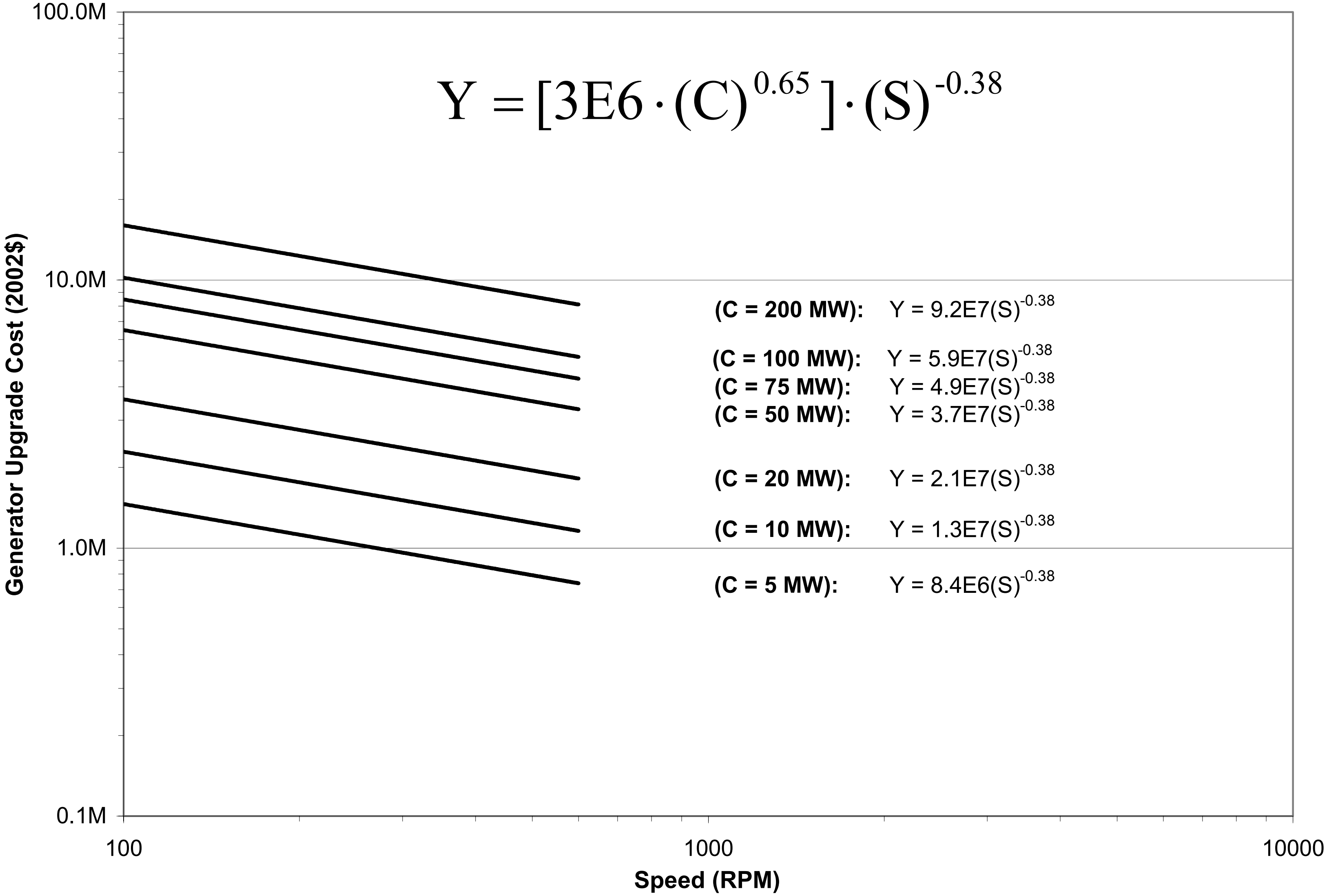


Figure A-14. Generator upgrade cost as a function of RPM for various plant capacities.

Appendix B

INEEL Hydropower Resource Economics Database

(see document back cover for IHRED compact disk)

Appendix B

INEEL Hydropower Resource Economics Database

B.1 IHRED Data Dictionary

The data dictionary for the INEEL Hydropower Resource Economics Database (IHRED) is given in Table B-1. This table lists the field number, parameter name, field type (number or text), field description, and units for the 78 fields in the database.

B.2 IHRED

The IHRED in Excel format is provided on the compact disk, which is in a pocket on the back cover of this document. The database contains resource characteristic data, estimated development and O&M costs, and estimated annual and monthly generation for 2,155 U.S. hydropower resources.

Table B-1. INEEL Hydropower Resource Economics Database Data Dictionary.*

Field Number	Field Name	Type	Description	Units
1	ProjectNumber	Text	Project Number (FERC number or pseudo FERC number)	—
2	PlantName	Text	Name of the project	—
3	StreamName	Text	Name of the stream where the project is located	—
4	StateAbbr	Text	Two letter abbreviation for the state where the project is located	—
5	NERCSubregion	Text	NERC Subregion (1 = East Central Area Reliability Coordination Agreement (ECAR), 2 = Electric Reliability Council of Texas (ERCOT), 3 = Mid-Atlantic Area Council (MAAC), 4 = Mid-America Interconnected Network (MAIN), 5 = Mid-Continent Area Power Pool (MAPP), 6 = Northeast Power Coordinating Council/New York (NY), 7 = Northeast Power Coordinating Council/New England (NE), 8 = Southeastern Electric Reliability Council/Florida (FL), 9 = Southeastern Electric Reliability Council/Excl. Florida (STV), 10 = Southwest Power Pool (SPP), 11 = Western Systems Coordinating Council/NWP (NWP), 12 = Western Systems Coordinating Council/RA (RA), 13 = Western Systems Coordinating Council/CNV (CNV))	—
6	Latitude	Number	Latitude (first digits refer to degrees north, last 2 digits refer to minutes)	ddmm
7	Longitude	Number	Longitude (First digits refer to degrees west, last 2 digits refer to minutes)	ddmm
8	ClassCode	Text	Owner class code (C = Cooperative, F = Federal, I = Industrial, M = Municipal and other non-federal, P = Private utility, R = Private nonutility)	—
9	OwnerName	Text	Name of project owner	—
10	Capacity	Number	Potential capacity at undeveloped sites or sites without power, or potential additional capacity at sites with power	MW
11	UnitType	Text	Type of unit (C = Conventional, R = Reversible, Z = Missing)	—
12	PlantType	Text	Type of Plant (CMB = Combined conventional and reversible units, DIV = Gravity diversion (powerhouse on different stream), PDV = Pumped diversion (one-way pumped storage), PMP = Pure (recycled) pump storage, RES = Reservoir only, ROR = Run-of-river (dam <= 10 ft high and minimal storage), RRG = Reregulating, STG = Storage, conventional hydro (dam > 10 ft high with significant storage), TID = Tidal conventional hydro)	—

Table B-1. (continued).

Field Number	Field Name	Type	Description	Units
13	ProjectStatus	Text	Status of Project (DJ = Disclaimer of FERC jurisdiction, EA = Exemption applied for, FA = Federally authorized, FR = Federally recommended, LE = License exemption, LJ = Lack of FERC jurisdiction, MA = FERC major license application, MO = FERC license outstanding, NA = FERC minor license application (<1.5 kW), NO = FERC minor license outstanding (<1.5 kW), PA = FERC preliminary permit application, PO = FERC preliminary permit outstanding, XX = No status, YO = FERC minor part license outstanding, ZZ = Missing)	—
14	BasinName	Text	River basin name	—
15	CountyName	Text	County where the project is located	—
16	DamStatus	Text	Status of Dam (W = With Power, W/O = Without Power, U = Undeveloped)	—
17	WSProtection	Text	Wild/Scenic Protection	—
18	WSTributary	Text	Wild/Scenic Tributary or Upstream/Downstream, Wild/Scenic Location (Y,N,<blank>)	—
19	Cultural	Text	Cultural Value (Y,N,<blank>)	—
20	Fish	Text	Fish Value (Y,N,<blank>)	—
21	Geological	Text	Geological Value (Y,N,<blank>)	—
22	Historical	Text	Historical Value (Y,N,<blank>)	—
23	Other	Text	Other criteria, such as rare wetland communities and wilderness designation.	—
24	Recreation	Text	Recreation Value (Y,N,<blank>)	—
25	Scenic	Text	Scenic Value (Y,N,<blank>)	—
26	Wildlife	Text	Wildlife Value (Y,N,<blank>)	—
27	TEW	Text	Threatened/Endangered Wildlife (Y,N,<blank>)	—
28	TEF	Text	Threatened/Endangered Fish (Y,N,<blank>)	—
29	FLC103	Text	Federal Land Code 103 (National Park, Monument, Lakeshore, Parkway, Battlefield, or Recreation Area) (Y,N,<blank>)	—
30	FLC104	Text	Federal Land Code 104 (National Forest or Grassland) (Y,N,<blank>)	—
31	FLC105	Text	Federal Land Code 105 (National Wildlife Refuge, Game Preserve, or Fish Hatchery) (Y,N,<blank>)	—
32	FLC106	Text	Federal Land Code 106 (National Scenic Waterway or Wilderness Area) (Y,N,<blank>)	—
33	FLC107	Text	Federal Land Code 107(Indian Reservation) (Y,N,<blank>)	—
34	FLC108	Text	Federal Land Code 108 (Military Reservation) (Y,N,<blank>)	—
35	FLC198	Text	Federal Land Code 198 (Not On Federal Land) (Y,N,<blank>)	—
36	SiteProb	Number	Project Environmental Suitability Factor (0.10 = Development prohibited or highly unlikely, 0.25 = Major reduction in likelihood of development, 0.50 = Likelihood of development reduced by half, 0.75 = Minor reduction in likelihood of development, 0.90 = Little effect on likelihood of development)	—
37	LicensingCost	Number	Total Licensing Cost	$K
38	ConstructionCost	Number	Total Construction Cost	$K
39	OvrNiteDevCost	Number	Overnight Development Cost (LicensingCost + ConstructionCost)	$K
40	MitHist_Arch	Number	30 year Archaeological and Historical mitigation cost (applicable if either Cultural or Historical fields are "Y")	$K
41	MitFish_Wildlife	Number	30 year fish and wildlife mitigation cost (applicable if any of the Fish, Wildlife, or TEW fields are "Y")	$K
42	MitScenic_Rec	Number	30 year scenic and recreation mitigation cost (applicable if either Recreation or Scenic fields are "Y")	$K

Table B-1. (continued).

Field Number	Field Name	Type	Description	Units
43	MitWaterMonitor	Number	30 year water quality monitoring cost	$K
44	MitFishPassage	Number	30 year fish passage cost (applicable if TEF field is "Y")	$K
45	MitTotal	Number	Total Mitigation Cost (Sum of MitHist_Arch, MitFish_Wildlife, MitScenic_Rec, MitWaterMonitor, and MitFishPassage)	$K
46	TotalDevCost	Number	Total Development Cost (OvrNiteDevCost + MitTotal)	$K
47	UnitTotalDevCost	Number	Total Development Unit Cost	$/kW
48	FixedOM	Number	Average Annual Fixed O&M	$K
49	UnitFixedOM	Number	Average Annual Fixed O&M Unit Cost	$/kW
50	VariableOM	Number	Average Annual Variable O&M	$K
51	UnitVariableOM	Number	Average Annual Variable O&M Unit Cost	Mills/kWh
52	FERCAnnChrg	Number	FERC Annual Charge (applicable if Capacity >= 1.5 MW)	$K
53	PFAnnual	Number	Average Annual Plant Factor	-
54	PFJan	Number	Average January Plant Factor	-
55	PFFeb	Number	Average February Plant Factor	-
56	PFMar	Number	Average March Plant Factor	-
57	PFApr	Number	Average April Plant Factor	-
58	PFMay	Number	Average May Plant Factor	-
59	PFJun	Number	Average June Plant Factor	-
60	PFJul	Number	Average July Plant Factor	-
61	PFAug	Number	Average August Plant Factor	-
62	PFSept	Number	Average September Plant Factor	-
63	PFOct	Number	Average October Plant Factor	-
64	PFNov	Number	Average November Plant Factor	-
65	PFDec	Number	Average December Plant Factor	-
66	GenAnnual	Number	Average Annual Generation	MWh
67	GenJan	Number	Average January Generation	MWh
68	GenFeb	Number	Average February Generation	MWh
69	GenMar	Number	Average March Generation	MWh
70	GenApr	Number	Average April Generation	MWh
71	GenMay	Number	Average May Generation	MWh
72	GenJun	Number	Average June Generation	MWh
73	GenJul	Number	Average July Generation	MWh
74	GenAug	Number	Average August Generation	MWh
75	GenSept	Number	Average September Generation	MWh
76	GenOct	Number	Average October Generation	MWh
77	GenNov	Number	Average November Generation	MWh
78	GenDec	Number	Average December Generation	MWh

*** Special field values**

N/A Value not available in source data.

Value removed due to homeland security concerns.