LCOE Uncertainty Analysis for Hydropower using Monte Carlo Simulations

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Abstract

Levelized Cost of Energy (LCOE) is an important metric to evaluate the cost and performance of electricity production generation alternatives, and combined with other measures, can be used to assess the economics of future hydropower development. Multiple assumptions on input parameters are required to calculate the LCOE, which each contain some level of uncertainty, in turn affecting the accuracy of LCOE results. This paper explores these uncertainties, their sources, and ultimately the level of variability they introduce at the screening level of project evaluation for non-powered dams (NPDs) across the U.S.

Owing to site-specific differences in site design, the LCOE for hydropower varies significantly from project to project unlike technologies with more standardized configurations such as wind and gas. Therefore, to assess the impact of LCOE input uncertainty on the economics of U.S. hydropower resources, these uncertainties must be modeled across the population of potential opportunities. To demonstrate the impact of uncertainty, resource data from a recent nationwide non-powered dam (NPD) resource assessment (Hadjerioua et al., 2012) and screening-level predictive cost equations (O’Connor et al., 2015) are used to quantify and evaluate uncertainties in project capital and operations & maintenance costs, and generation potential at broad scale. LCOE dependence on financial assumptions is also evaluated on a sensitivity basis to explore ownership/investment implications on project economics for the U.S. hydropower fleet.

The results indicate that the LCOE for U.S. NPDs varies substantially. The LCOE estimates for the potential NPD projects of capacity greater than 1 MW range from 40 to 182 $/MWh, with average of 106 $/MWh. 4,000 MW could be developed through projects with individual LCOE values below 100 $/MWh. The results also indicate that typically 90 % of LCOE uncertainty can be attributed to uncertainties in capital costs and energy production; however, for small projects (below 10 MW) O&M uncertainty plays an important role. The potential NPDs have costs with uncertainty bands extending well above 100 $/MWh in some cases. A truly representative evaluation should complement LCOE with an assessment of potential revenues from the provision of ancillary services. Moreover, hydroelectric production is often part of multipurpose water resource projects

where other purposes (e.g., irrigation, flood control, navigation, recreation, etc.) also provide value. Neither of these considerations are accounted for LCOE.

Introduction

Recent studies indicate that up to 12 GW of untapped hydropower potential at non-powered dams (NPDs)exists in the U.S. Assessing the economic feasibility of this resource requires a clear estimate of project by project costs. In 2015, researchers from Oak Ridge National Lab have developed parametric cost tools to estimate project development and operation cost for NPD across U.S. (O'Connor et al., 2015).

The economic assessment of an energy generation project can be performed using various metrics, but levelized cost of energy (LCOE) is most often used to evaluate the cost and performance of electricity production and is a useful financial tool to compare alternative energy sources. Furthermore, LCOE can be used as a ranking tool to assess the cost competitiveness of available hydro resources, which can help to guide the policy initiatives at the national scale.

As most hydropower development is highly capital intensive, investing in such a commitment demands a greater degree of confidence than for various other energy infrastructures (Copestake and Young, 2008) and during early stage development, projects often face higher uncertainties (Zhai et al., 2012). The quantification of such uncertainties provides a clearer picture to the developer about the economic risk associated with the project while informing investors of the expected return on investment. The LCOE calculation is based on probability of uncertain future events (Tversky and Kahneman, 1974). Miscalculation of LCOE may result in an incorrect or biased decision among different technology alternatives (Branker et al., 2011). This paper quantifies uncertainty associated with hydropower LCOE calculations at the screening-level of project evaluation to explore the variation in project economics across the U.S. NPD fleet.

Levelized Cost of Energy

LCOE is calculated as the price point at which the electricity must be sold for a project to break even (i.e., lifecycle costs equal lifecycle revenues). The actual LCOE value provides a price per unit energy generated (e.g., $/MWh) by considering a project's lifecycle costs and lifetime energy production. The lifecycle cost includes a project's initial capital cost (ICC), and operation & maintenance (O&M) cost. The lifetime energy production includes total potential energy production over the lifetime of the project. In this study, LCOE is calculated using the methodology described in Electricity Utility Planning and Regulation (Kahn, 1991).

$$LCOE = \frac{Lifecycle\ cost}{Lifetime\ energy\ production}$$

A detail form of LCOE can be represented as,

$$LCOE = \frac{Present\ value\ of\ annualized\ cosntruction\ cost^{1} + Present\ value\ of annual\ O\&M\ cost^{2}}{Present\ value\ of\ annual\ energy\ proruction^{3}}$$

The above expression is used to calculate the LCOE for each of the project evaluated. To quantify the variation in LCOE, a Monte Carlo Simulation method is applied using Oracle Crystal Ball (Version 11.1.2.3.500, Oracle, 2014).

Data

A recent nationwide (lower 48 states) NPD resource assessment (Hadjerioua et al., 2012) identified the potential obtain up to 12 GW of generating potential from 54,000 dams without power. For this study, the generating potential of these sites was modified from the original site sizing method (using regional average historical capacity factors) to a more sophisticated site-sizing methodology based on flow-exceedance developed in Hadjerioua et al. (2013). The updated site-sizing methodology is intended to approximate the economically optimal design flow based on the 30% level of flow exceedance at a given site.

To reduce computation time, NPDs with revised capacities below 1 MW were removed, resulting in a total of 448 NPDs used for analysis. The project capacities range from 1 to 203 MW with an average value of 11.23 MW, while the hydraulic heads range from 4 to 350 ft with an average value of 51 ft. In this study, historical streamflow data from 1990 to 2008 were used to estimate monthly generation, following a method described in Hadjerioua et al. (2013).

LCOE Assumptions

The most important parameters when evaluating LCOE are energy and cost. As such, the level of accuracy in LCOE estimation is greatly influenced by the underlying assumptions made when assigning values to these parameters. For energy generation, the primary parameters of influence include installed capacity and capacity factor[4]. In assessing lifecycle costs, the various categories of costs can be separated into three primary cost categories: ICC, O&M, and financial.

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[1] $Present\ value\ of\ annualized\ construction = ICC\ \times FCR,$ Where ICC = initial capital cost, FCR= fixed charge rate $FCR = \frac{\mathrm{WACC}\ (1+\mathrm{WACC})^{n}}{(1+\mathrm{WACC})^{n}-1} + \left(\frac{\mathrm{WACC}\ (1+\mathrm{WACC})^{n}}{(1+\mathrm{WACC})^{n}-1} - \frac{1}{n}\right)\left(1 - \frac{d\,i}{\mathrm{WACC}}\right)\left(\frac{t}{1-t}\right)$, Where WACC = weighted average cost of capital, n = project life time, d = debt fraction on capital, i = interest on debt, t = income tax rate (state +federal), r = rate of return

[2] $Present\ value\ of\ annual\ O\&M = \sum_{i=1}^{n} \frac{\mathrm{annual\ O\&}M}{(1+r)^{i}}$

[3] $Present\ value\ of\ annual\ energy\ production = \sum_{i=1}^{n} \frac{\mathrm{annual\ energy\ production}}{(1+r)^{i}}$

[4] The capacity factor is the ratio of project’s actual generation to its maximum potential generation over a period of time.

Assumptions Associated with Lifetime Energy Production

Hydropower projects can be designed with different considerations in order to meet power supply or other needs. A low capacity project may be designed for a high capacity factor to meet peak demand while a high capacity project may be designed for a low capacity factor to meet base demand. The installed capacity of hydropower is estimated using the design flow and hydraulic head, and the actual project generation value is generally equal or lower than the installed capacity. Although the amount of electricity generated from a project usually varies, LCOE calculation is typically performed by deterministic analysis using fixed values for installed capacity and capacity factor, which introduces uncertainties and risks in the calculated LCOE.

An accurate prediction of energy generation over the project’s life cycle is extremely challenging. Annual generation was estimated by aggregating the projected monthly generation data. Finally, probability functions are considered to define annual generation curve, which is further modified by restricting minimum and maximum annual generation. The minimum annual generation for any project should be non-negative (≥ 0) and maximum annual generation should be constrained by the project’s installed capacity. Sample generation distributions used in the estimation of LCOE are shown in Figure 1. As seen in the figure, the generation data distribution differs significantly from project to project. This also suggests that, a simple average function would not sufficiently represent the variation inherent in hydropower generation.

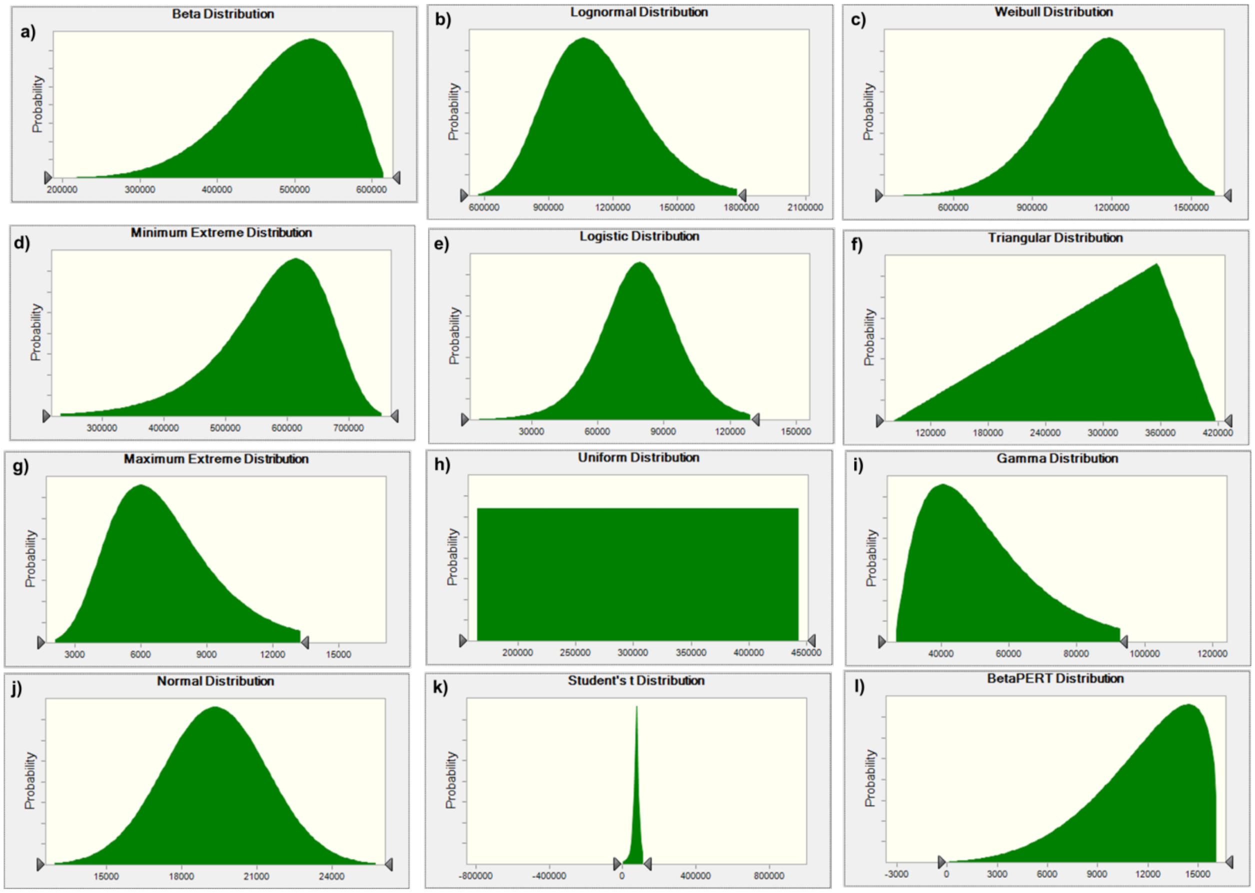

Figure 1 probability distribution of annual generation (in MWh)

A summary of different generation distribution used for this study is shown in Table 1.

Table 1 Project statistics for annual generation distribution

Distribution Type	Project Count
a) Beta	101
b) Lognormal	97
c) Weibull	73
d) Min Extreme	59
e) Logistic	40
f) Triangular	36
g) Max Extreme	18
h) Uniform	11
i) Gamma	4
j) Normal	4
k) Student's t	4
l) BetaPERT	1

ICC Assumption

The initial capital cost of hydropower includes the costs associated with access roads, land, dams, waterways, powerhouse, turbines & generators, transmission facilities, etc. The initial investment cost for hydropower is high relative to other energy producing technologies (Kumar et al., 2011). Uncertainties in hydropower cost estimation are also relatively high due to the complex geological, hydrological characteristics and topographic relief (high head, medium head, and low head) which can greatly influence development cost.

A hydropower project's development can generally classified into 3 stages; planning stage, engineering stage, or construction stage. Cost estimation generally improves as the maturity level of the project increases. An accuracy of cost estimation for different project development stage typically ranges from -50 to +100% for planning stage, and -20 to +30% for engineering stage, and -10 to 15% for construction stage (AACE, 2013).

In this study, the ICC was estimated using a recently developed parametric cost equation (O'Connor et al., 2015) appropriate for the screening or planning stages of development. The ICC model equation is shown below:

$$ICC\ (in\ 2014\$) = 11{,}489{,}245\ P^{0.976}\ H^{-0.240}$$

Where P = installed capacity (MW), H = hydraulic head (ft)

The uncertainty in the ICC equation follows a lognormal distribution with standard error 37% (Figure 2).

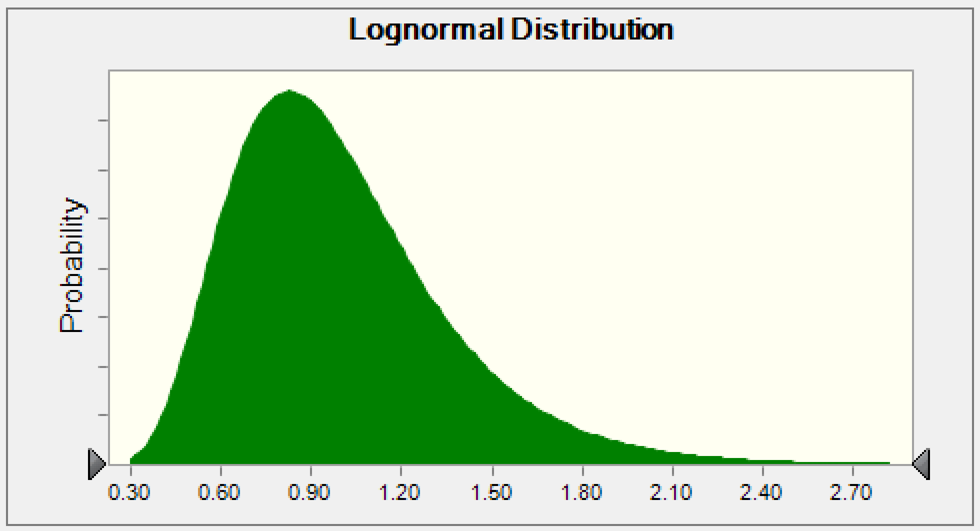

Figure 2 probability distribution of initial capital cost

O&M Cost Assumption

One major advantage of hydropower is the lack of fuel cost necessary for operation, which greatly reduces the overall cost of the project. While hydropower O&M cost is highly site-specific, typical projects experience an annual O&M cost of 1 to 4 % of ICC, which can greatly influence LCOE over the life of the project (IRENA, 2015). Generally, larger hydropower projects have relatively low per-kW O&M cost compared to smaller projects. Thus, while O&M plays an important role in evaluating the lifecycle feasibility for any hydropower projects, it is especially critical to the cost of small hydropower.

The annual O&M cost was estimated using a parametric O&M cost equation developed recently as a part of DOE's hydropower cost modeling efforts (O'Connor et al., 2015).

$$O\&M\ (in\ 2014\$) = 225{,}417\ P^{0.547}$$

The uncertainty in the O&M model follows a lognormal distribution with standard error 47% (Figure 3).

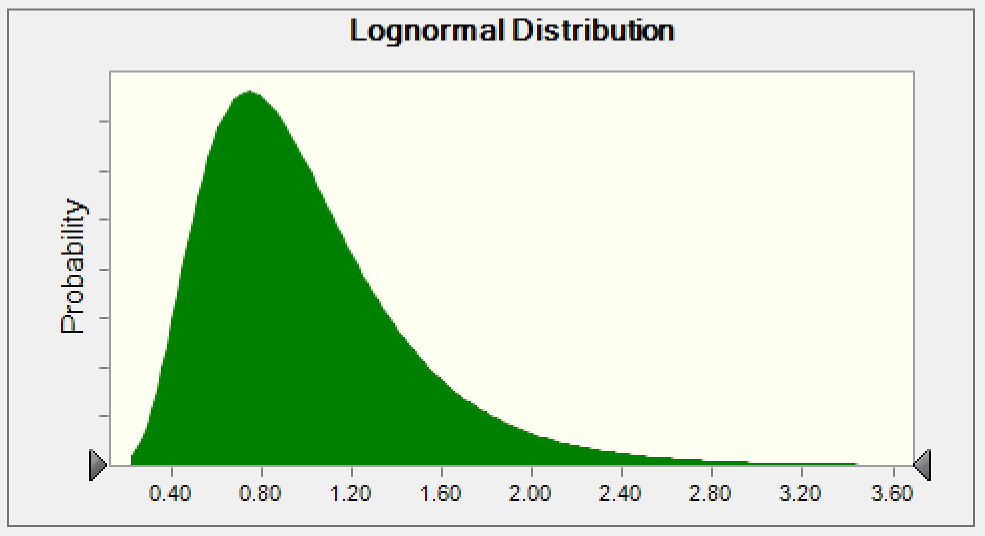

Figure 3 probability distribution of annual O&M cost

Financial Assumption

In addition to the risk associated with ICC and O&M, there is also a financial uncertainty associated with the future value of money. In this study, financial parameters such as interest rate (7%), inflation rate (2.8%), debt fraction on capital structure (60%), return on equity (15%), corporate incorporate taxes (federal: 36%, state: 5.5%) are assumed to be fixed for the analysis period. A project life of 40 years is chosen for the analysis.

Monte Carlo Simulation

With the introduction and widespread availability of computing systems, numerical modeling has become an increasingly popular method to analyze complex physical systems. Monte Carlo simulation methods can provide a range of expected LCOE values for a single project by using a probabilistic computational mathematical approach, which allows solving complex deterministic problems by a large number of random experimental trial values. These LCOE ranges are determined by taking input values, each of which are selected randomly using probability distributions. In each trial or iteration, the model selects and records unique input values determined from the defined probability distributions for each variable. This process is repeated a significant number of times in order to demonstrate a full array of what-if scenarios. This mathematical technique accounts for risk assessment in quantitative analysis and decision making and is capable of handling both large and small uncertainties for a large number of input variables.

The major advantages of Monte Carlo techniques over the deterministic analysis are that it provides probabilistic results, sensitivity analysis of model input variables, and correlation of input variables (Darling et al., 2011). For this paper, a run size of 1000 trials was selected for LCOE uncertainty analysis.

Results and Discussion

Monte Carlo, a probabilistic approach was applied for the analysis of influences on LCOE assumptions by project by project basis. Assumptions for financial parameters are assumed to be fixed during the analysis to isolate the technical uncertainties in energy generation, ICC and O&M, which are represented by probability functions.

Figure 4 shows median LCOE value across the subset of U.S. NPDs with potential above 1 MW. The lowest LCOE ($/MWh) projects are indicated by dark green coloration, while the highest LCOE projects are indicated by orange coloration. Also, both statistical and graphical results show that LCOE is generally lower for larger capacity projects, indicating that these larger NPD projects benefit from the economies of scale associated with large hydropower development. Of the 448 projects represented in the map, 33 are below 75 $/MWh. Most of these lowest LCOE projects are of relatively high capacity (ranging from 3 to 192 MW, with an average 19 MW) and benefit from relatively high head (ranging from 24 to 350 ft, with an average of 129 ft). In contrast, 27 projects are above 150 $/MWH and have relatively low head (ranging from 4 to 77 ft, with an average of 12 ft). As seen in the map, most of the lower LCOE projects are located in the semi-mountainous terrain of the Appalachians and Rocky Mountains or in other high-relief areas, further illustrating that high head can significantly benefit to project economics. This key observation is attributed to the influence of head on predicted ICC, an outcome that is expected through use of the parametric ICC model (O'Connor et al., 2015).

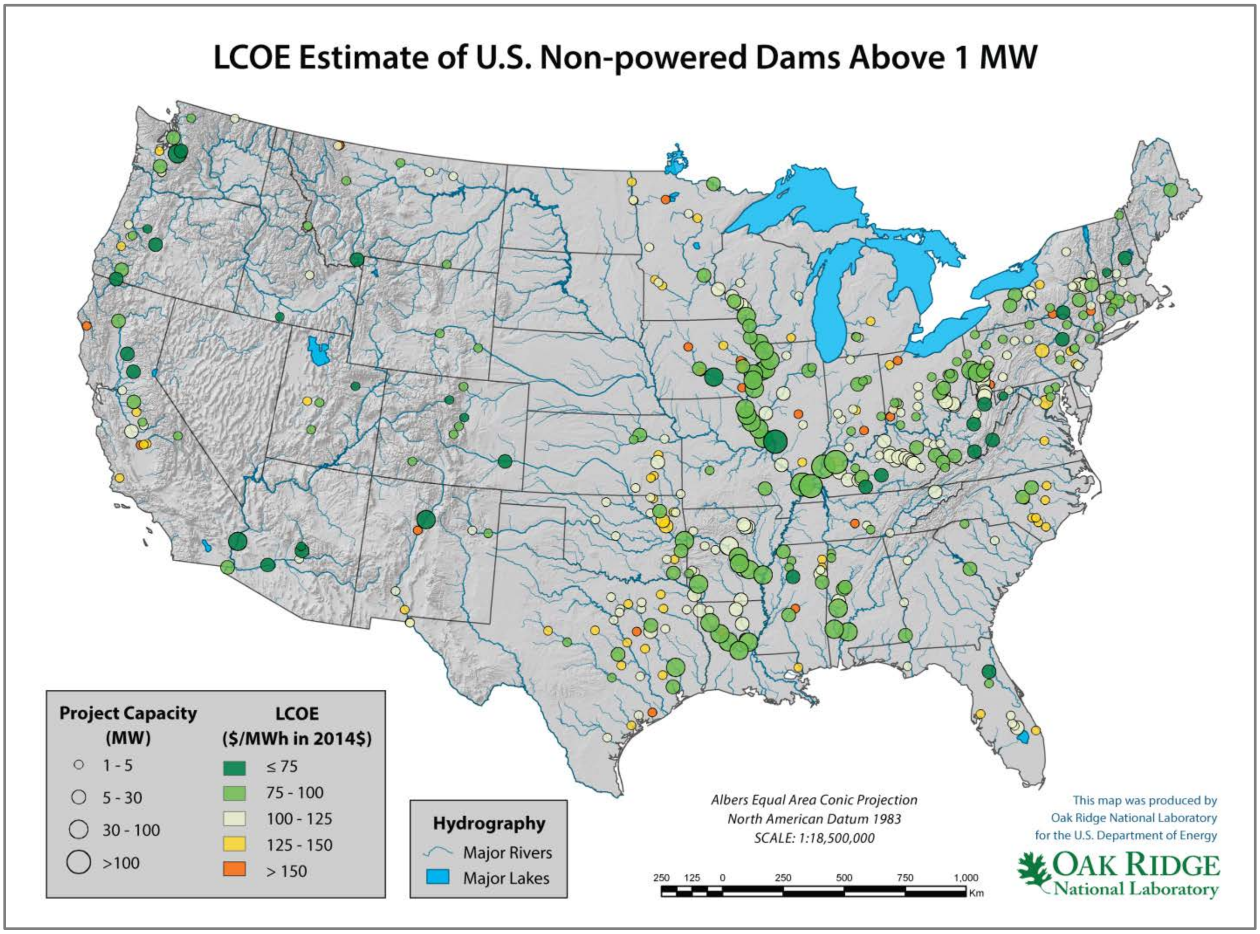

Figure 4 LCOE estimate of U.S. NPDs

Figure 5 shows the uncertainty band (95% confidence interval) for 448 NPD projects. The black line represents the median LCOE value after running the Monte Carlo simulations, while the surrounding red lines represent the upper and lower 95% confidence intervals. The median LCOE for the 448 potential NPD projects varies from 40 to 182 $/MWh, with average 106 $/MWh. Out of the 448 projects evaluated, 111 projects (25%) contained median LCOE values above 120 $/MWh, all of which are below 10 MW with a total capacity of 258 MW. Uncertainty scales proportionally with increases in the median LCOE, resulting in higher absolute uncertainties for the least competitive projects. In some cases, the potential NPDs have costs with uncertainty bands extending well above $100/MWh.

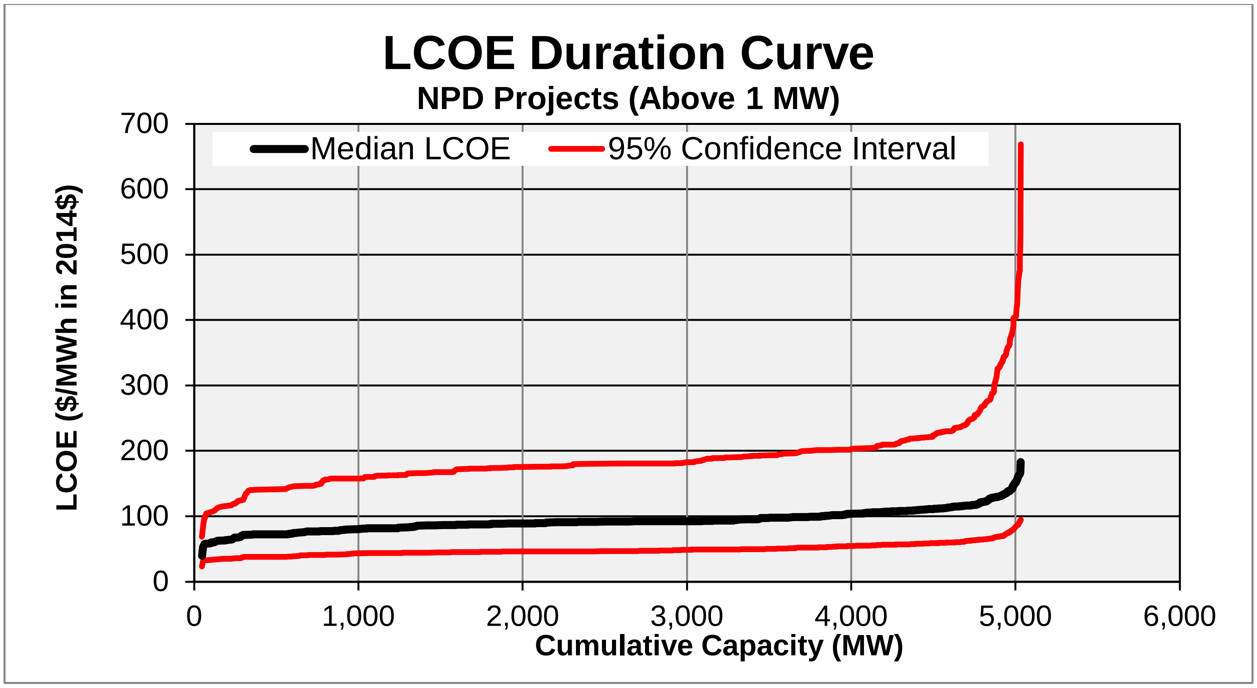

Figure 5 LCOE duration curve for NPD projects

As seen in Figure 6a, a negative correlation exists between capacity and LCOE, demonstrating that larger NPD projects benefit from economies of scale associated with large hydropower development. In addition, Figure 6b reveals that a strong negative correlation exists between capacity and O&M LCOE. Figure 6c shows strong negative correlation with capacity and O&M cost. Typically annual O&M cost ranged from 0.4 to 6% of ICC[5], which is similar to the reported range in IRENA (2015). As the results stem from using the ICC and O&M parametric models developed in O'Connor et al. (2015), these overall trends are expected.

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[5] $Percent\ ICC = \frac{Annual\ O\&M\ Cost}{ICC} \times 100$

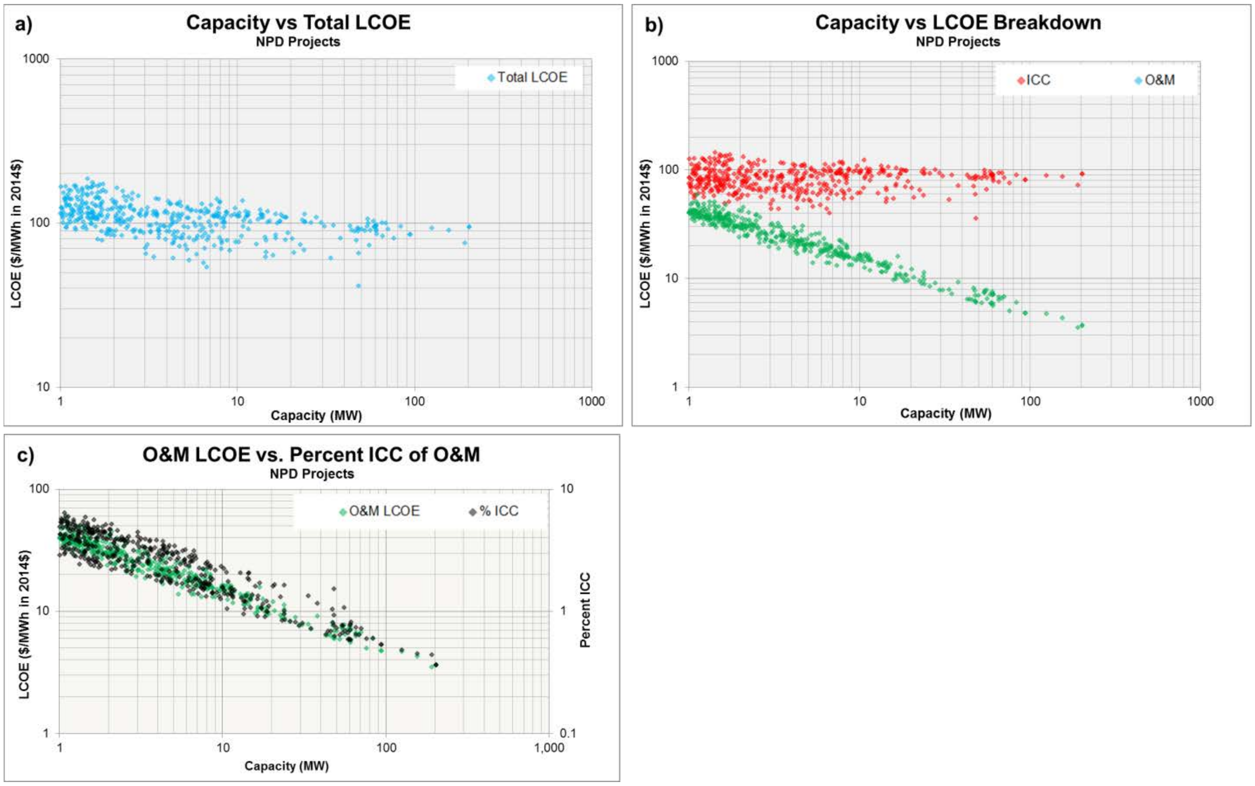

Figure 6 LCOE and Capacity relationship in NPD projects[6]

Effect of Interest Rate on LCOE Supply Curve

As one of the variables that ultimately affects LCOE calculation, the interest rate can potentially be a major cost driver for capital intensive projects like hydropower (KEMA, 2012). As interest rates and inflation vary month-to-month and year-to-year, the fixed interest rate assumed when capital is borrowed can greatly influence lifecycle costs and LCOE sensitivity. Additionally, different types of project developers have access to capital at varying rates. Independent power producers funding projects on a non-recourse debt basis may pay very high interest rates. Alternatively, highly creditworthy public power entities (such as municipalities or public utility districts) will pay substantially lower rates on project bonds. Interest rate sensitivities were run to illustrate the sensitivity of the LCOE Monte Carlo simulation to the financing assumptions.

Figure 7 shows LCOE supply curve for different interest rate scenarios. As seen in the figure, LCOE can fall by 7 to 9% if the interest rate is reduced from 7 to 5%. On the other side, the LCOE can rise from 8 to 10% if the interest rate is increased from 7 to 9%. This illustrates that financial parameters, such as interest rate, can greatly influence LCOE sensitivity, which highlights the importance of ownership/investment structure. In this study, LCOE is calculated using a fixed 7% interest rate.

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[6] Total LCOE = ICC LCOE + O&M LCOE

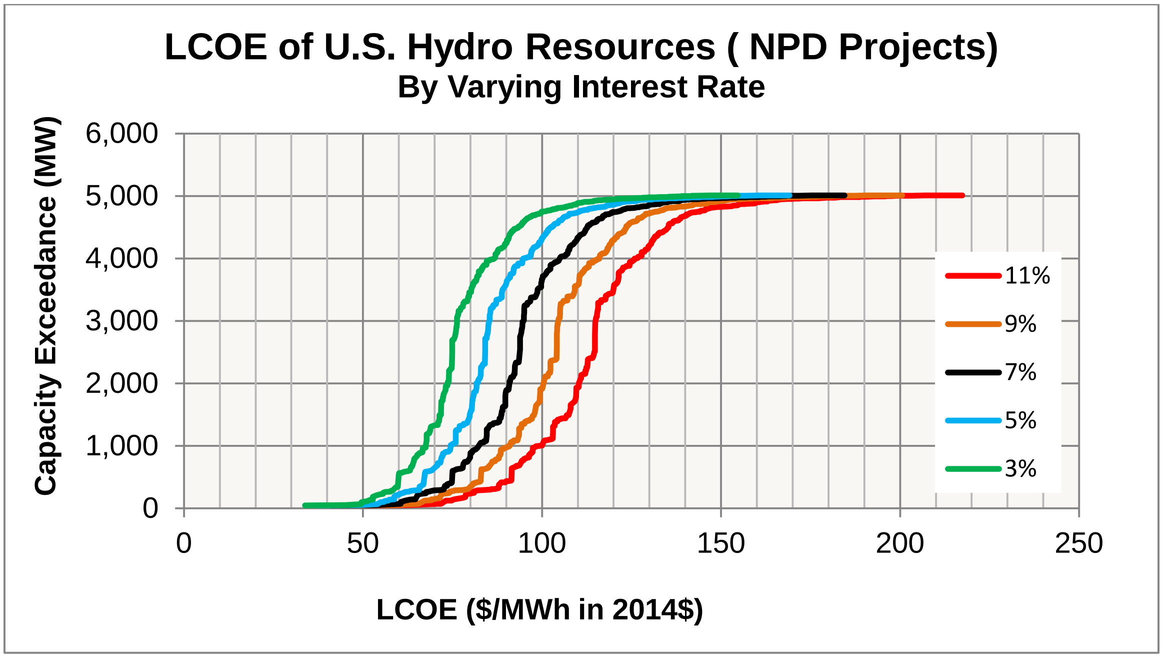

Figure 7 Sensitivity of financial parameter on LCOE supply curve

Sensitivity Analysis on LCOE

Sensitivity analysis was performed to identify the most important model parameters and their influence on LCOE calculation. Figure 8 shows a relative percent contribution of three LCOE model parameters (ICC, O&M, annual generation) for all 448 projects sorted from lowest to highest capacity. ICC uncertainty typically explains more than 50% of the LCOE variation. In addition, annual generation is identified as second important variable affecting the LCOE uncertainty, although in select projects with highly variable hydrology, it can be the predominant source of uncertainty. In general, ICC and annual generation uncertainty explain more than 90% of LCOE variation. While not a major factor for larger projects, O&M uncertainty plays important role in smaller projects below 10 MW.

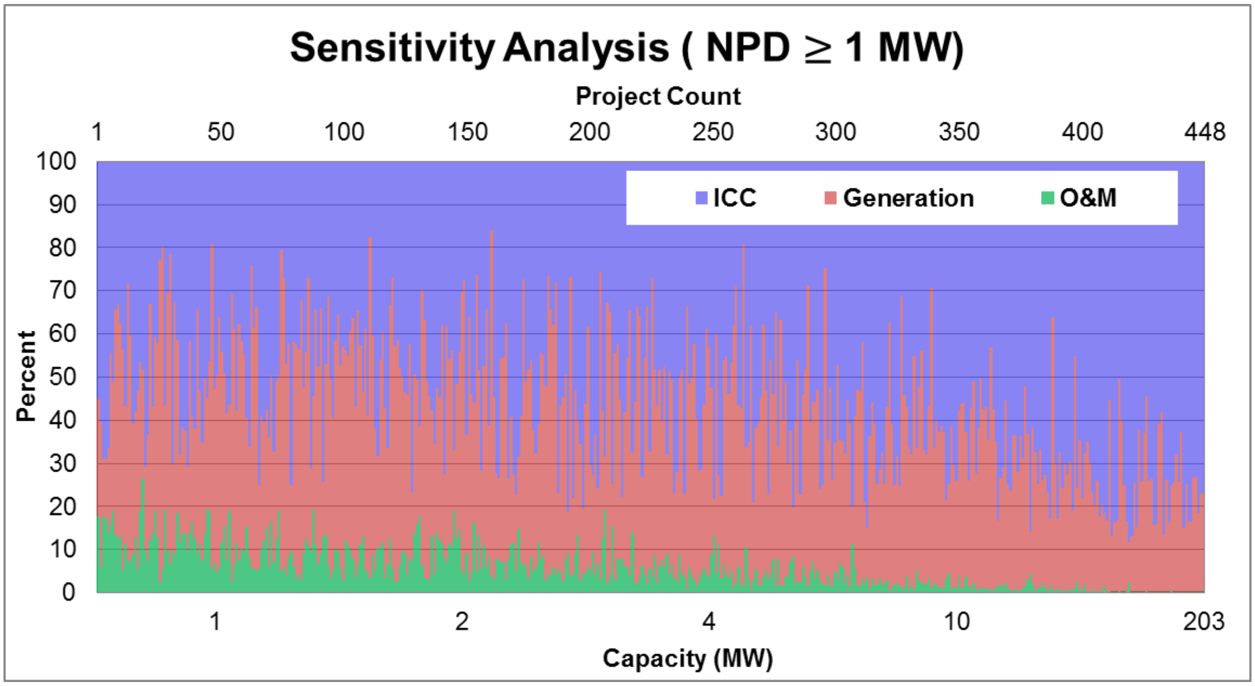

Figure 8 Sensitivity analysis for U.S. NPD projects

Study Limitation

As a high-level evaluation illustration of the effects of uncertainty on the national scale distribution of NPD LCOE considered three major factors (ICC, O&M, and generation) that can affect the LCOE calculation. The study overlooks some other factors which also influence LCOE. For example, both hydraulic head and capacity in the NPD projects depends on hydrology and the water level available at the dam. Similarly, the lifespan of a project can also greatly influence the LCOE, as costs and generation change over the life of a project, and the lifespan duration can vary project-to-project.

A truly representative evaluation should complement LCOE with an assessment of potential revenues from the provision of ancillary services. Moreover, hydroelectric production is often part of multipurpose water resource projects where other purposes (e.g., irrigation, flood control, navigation, recreation, etc.) also provide value. Neither of these considerations are accounted for LCOE.

Conclusion

As renewable energy technologies continue to expand their influence in the world energy market, hydropower will continue to represent a large share of this sector. Hydropower has a distinct benefit over other renewable resources, as it can operate in near-real-time and represents the most diverse energy storage media available today. As a mature technology, the unit cost of hydropower has remained fairly constant over a long period of time, while newer renewable energy resources (e.g., solar and wind power) continue to reduce costs every year. Although recent studies indicate that significant opportunities exist to expand U.S. hydropower development, a key question remains: Is hydropower development still economically justifiable and competitive as compare to other available renewable resources?

In this study, LCOE was used as a metric to estimate the unit cost of 448 non-powered dams of capacity greater than 1 MW. A probabilistic Monte Carlo simulation approach was selected to conduct the study and used probability distributions of major input parameters (ICC, O&M, and generation) to estimate LCOE. Simulating 1000 trials, the results provide a range of possible LCOE values for each project, which demonstrates the risk associated with project development and, especially at a national scale, can be invaluable in identifying projects with the highest probability of success. The resulting cost competitive NPDs can be further compared with generation alternatives, which can help to guide U.S. policy and deployment initiatives. The LCOE estimates for the potential NPD projects range from 40 to 182 $/MWh, with average of 106 $/MWh.

A sensitivity analysis was performed to evaluate the influence of major input parameters on LCOE. The results indicate that ICC and generation can drive up to 90% of LCOE variation; however, O&M plays an increasingly important role in the cost of small projects. While financial parameters were assumed to be fixed when computing LCOE, sensitivity of interest rate was explored. The results indicate that LCOE can be greatly influenced by financial parameter, illustrating the importance of ownership/investment structure.

Acknowledgment

The authors would like to acknowledge and express their appreciation to Ms. Nicole Samu from Oak Ridge National Laboratory for her technical support for this publication. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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