OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2012/501

Small Hydropower Cost Reference Model

October 2012

Prepared by

Qin Fen (Katherine) Zhang
Brennan Smith
Wei Zhang

UT-BATTELLE
ORNL-27 (4-00)

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via the U.S. Department of Energy (DOE) Information Bridge.

Web site http://www.osti.gov/bridge

Reports produced before January 1, 1996, may be purchased by members of the public from the following source.

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Web site http://www.ntis.gov/support/ordernowabout.htm

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange (ETDE) representatives, and International Nuclear Information System (INIS) representatives from the following source.

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Web site http://www.osti.gov/contact.html

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.

ORNL/TM-2012/501

Small Hydropower Cost Reference Model
Final Project Report

Qin Fen (Katherine) Zhang
Brennan Smith
Wei Zhang

Date Published: October 2012

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

(THIS PAGE LEFT BLANK INTENTIONALLY)

CONTENTS

Page

LIST OF FIGURES vi

LIST OF TABLES viii

ACRONYMS AND ABBREVIATIONS ix

ACKNOWLEDGMENTS x

EXECUTIVE SUMMARY xi

1.0 INTRODUCTION 1

2.0 OBJECTIVES AND METHODOLOGY 3

2.1 OBJECTIVES AND SCOPE 3

2.2 SMALL HYDRO SITE CLASSIFICATION BY EXISTING FACILITIES 3

2.3 SMALL HYDRO CLASSIFICATION BY HYDRAULIC HEAD 4

2.4 SMALL HYDRO CLASSIFICATION BY PROJECT DESIGN SCHEME 4

3.0 LITERATURE REVIEW AND COST DATA COLLECTION 6

3.1 EMPIRICAL HYDRO COST EQUATIONS 6

3.2 EFFORTS ON COST DATA COLLECTION 8

3.3 FURTHER EFFORT FOR COST DATABASE AND COST MODEL DEVELOPMENT 9

4.0 INITIAL CAPITAL COST ANALYSIS AND COST DRIVERS 11

4.1 INITIAL CAPITAL COST ESTIMATE 11

4.1.1 ICC Data Sources and Trending 11

4.1.2 ICC Estimate Equation 13

4.2 ICC COMPARISONS AND BREAKDOWNS 14

4.2.1 Capital Cost Breakdowns 16

4.2.2 Civil Works Cost Breakdowns ... 19
4.3 ELECTROMECHANICAL EQUIPMENT COST ESTIMATE ... 22
4.3.1 Equipment Data Source and Trending ... 22
4.3.2 Equipment Cost Equation ... 28
4.4 CAPITAL COST DRIVERS ... 31
5.0 LCOE ANALYSIS AND LIFE-CYCLE COST DRIVERS ... 32
5.1 LIFE-CYCLE COST COMPONENTS ... 32
5.2 ANNUAL O&M COST ESTIMATE ... 32
5.3 LCOE CALCULATION ... 34
5.4 RECOMMENDATION FOR LCOE UNCERTAINTY ANALYSIS ... 36
5.5 LCOE DATA TRENDING ... 37
5.6 LIFE-CYCLE COST DRIVERS ... 37
6.0 COST COMPARISONS FOR NEW AND TRADITIONAL TECHNOLOGIES ... 39
6.1 TURBINATOR VERSUS TRADITIONAL TURBINE TECHNOLOGIES ... 39
6.2 REMOVABLE POWERHOUSE VERSUS TRADITIONAL POWERHOUSE DESIGN ... 42
6.3 COST PERFORMANCE OF NEW TECHNOLOGIES ... 42
7.0 COST-CUTTING TECHNOLOGIES AND TRLS ... 45
7.1 TRL DEFINITIONS IN THE SMALL HYDRO DOMAIN ... 45
7.2 COST-CUTTING TECHNOLOGIES ... 46
7.2.1 Turbine Cost-Cutting Technologies and Strategies ... 46
7.2.2 Generator Cost-Cutting Technologies ... 49
7.2.3 Control and Instrument Cost-Cutting Technology ... 49
7.2.4 Powerhouse Cost-Cutting Technologies and Strategies ... 49
7.2.5 Penstock Cost-Cutting Technologies ... 50

7.2.6 Dam and Spillway Cost-Cutting Technologies 51

7.2.7 Engineering and Permitting Cost-Cutting Technologies 51

8.0 RESEARCH AND DEVELOPMENT PROPOSALS AND STRATEGIES 52

9.0 REFERENCES 55

APPENDIX A: PROSPECTUS FOR HYDROPOWER COST DATA COLLECTION 57

LIST OF FIGURES

Page

Figure 1. Project cost vs. head within different capacity ranges. *Source:* INFORSE 2012 8

Figure 2. Trend of ICC vs. head and vs. plant capacity for existing NPD and conduit sites. 12

Figure 3. ICC estimate equation for existing NPD and conduit sites. 14

Figure 4. ICC difference (new sites vs. existing sites) for small hydro in general. 15

Figure 5. Cost difference (new sites vs. existing sites) for low-head small hydro..................................... 15

Figure 6. Capital cost breakdown for low-head small hydro projects. 17

Figure 7. Capital cost breakdown for typical small hydro projects. 18

Figure 8. Capital cost breakdown averaged for six restoration plants in Afghanistan............................... 19

Figure 9. Cost breakdown for civil works and structures. 21

Figure 10. Trend of electromechanical cost vs. net head (aggregated for different turbine types). 23

Figure 11. Trend of electromechanical cost vs. capacity (aggregated for different turbine types). 23

Figure 12. Trend of electromechanical cost vs. net head (aggregated for different generator types). 24

Figure 13. Trend of electromechanical cost vs. capacity (aggregated for different generator types). 24

Figure 14. Francis turbine electromechanical cost vs. net head. 25

Figure 15. Francis turbine electromechanical cost vs. capacity. 25

Figure 16. AF/SR turbine electromechanical cost vs. net head. 26

Figure 17. AF/SR turbine electromechanical cost vs. capacity. 26

Figure 18. AF/DR turbine electromechanical cost vs. net head. 27

Figure 19. AF/DR turbine electromechanical cost vs. capacity. 27

Figure 20. Three-dimensional plot for correlation of Francis turbine electromechanical cost ($/kW) vs. (H, P) 30

Figure 21. Three-dimensional plot for correlation of AF-DR turbine electromechanical cost ($/kW) vs. (H, P)......30

Figure 22. Three-dimensional plot for correlation of AF-SR turbine electromechanical cost ($/kW) vs. (H, P)......31

Figure 23. Annual O&M cost equation......32

Figure 24. Trend of LCOE vs. head, plant capacity, and capacity factor. 38

Figure 25. Cost comparison for Turbinator vs. traditional turbine technologies (all with medium head)......41

Figure 26. LCOE components of Turbinator and other medium-head projects......41

Figure 27. Cost comparison for removable powerhouse vs. traditional powerhouse designs (all with low heads). 44

Figure 28. LCOE components of low-head projects......44

LIST OF TABLES

Page

Table 1. Spanish cost equations for electromechanical equipment 7

Table 2. ICC comparison of new sites and NPD sites 16

Table 3. Regression results for total electromechanical costs ($US) 29

Table 4. Regression results for per kilowatt electromechanical costs ($US/kW) 29

Table 5. Life-cycle costs of a hydro project 33

Table 6. Life-cycle benefits of a hydro project 34

Table 7. Comparison for Turbinator project 39

Table 8. Comparison for removable powerhouse project 42

Table 9. Definition of TRLs in the small hydro domain 45

Table 10. Potential cost-cutting technologies and technology readiness levels 47

ACRONYMS AND ABBREVIATIONS

AF	axial flow (description for one type of Kaplan propeller turbine)
AFPM	axial flux permanent magnet
CFD	computational fluid dynamics
DR	double regulated (a feature description for axial flow turbines)
EIA	US Energy Information Administration
FERC	US Federal Energy Regulatory Commission
ICC	initial capital cost
IEA	International Energy Agency
LCOE	levelized cost of energy
LAMH	Hydraulic Machine Laboratory
NID	National Inventory of Dams
NPD	non-powered dam
NHAAP	National Hydropower Asset Assessment Project (ORNL, funded by DOE)
O&M	operation and maintenance
PH	powerhouse
PMG	permanent magnet generator
PVC	polyvinyl chloride
RDD&D	research, development, demonstration, and deployment
ROR	Run-of-the-River
RPS	renewable portfolio standards
SHP	small hydro projects
SLH	Schneider Linear HydroEngine
SR	single regulated (a feature description for axial flow turbines)
TRL	technology readiness level
UK	United Kingdom

ACKNOWLEDGMENTS

This study was funded by the US Department of Energy (DOE) through the office of Energy Efficiency and Renewable Energy, Water Power Program. We thank Rocio Martinez, Shih-Chieh Kao, and Boualem Hadjerioua of the ORNL Water Power Group and Patrick O’Connor, Mike Sale, and Rajesh Dham at DOE Headquarters for supporting this activity and providing valuable input. Thanks also to Leslie Lauder for her help in editing of the final report.

EXECUTIVE SUMMARY

Small hydropower has long been developed in the United States, but still thousands of small hydro sites remain untapped. Most of them are technically and environmentally feasible but may not be cost-effective to develop at the current level of technology and carbon and fuel markets. This report aims to identify the cost drivers for small hydro generation through cost analyses, and to improve understanding of the pathways for cost reduction and the strategies for accelerating small hydro development in the United States.

Reference to the empirical cost equations in literature, an initial capital cost (ICC) equation for non-powered dam (NPD) and conduit projects has been preliminarily developed using limited project cost data collected from the Federal Energy Regulatory Commission (FERC) e-library and directly from industrial contacts. The regression analysis shows a correlation between the project ICC and plant capacity and head. The electro-mechanical equipment costs for Francis, axial flow, Kaplan, and propeller turbines are derived from the historical budget prices of a small hydro turbine manufacturer. These cost curves show the turbine-generator cost is also associated with the plant capacity and net head. In addition, the initial cost breakdowns are analyzed based on project cost data from literature and industry. It was found that the turbine-generator and the powerhouse are often the major cost components for low-head projects, whereas water conveyance is likely to be the key cost driver for high-head projects. The ICC variations for different site features, such as new greenfield sites vs. non-powered dams, are also discussed.

The life-cycle economics of small hydro generation are briefly reviewed to determine the major cost contributors to the levelized cost of hydro energy (LCOE), as well as the factors and assumptions that could greatly affect the LCOE calculations. Using the 29 sets of annual operation and maintenance (O&M) cost data collected from FERC license applications, a cost equation is regressed which shows that the annual O&M cost is highly related to the plant power capacity. In addition, the 28 sets of LCOE data from FERC's Order Issuing Licenses are aggregated and trended for the NPD and conduit projects. These data show the project LCOE is somewhat associated with the head, plant capacity, or capacity factor; but no acceptable regression equation could be arrived at because of the limited sample size or inherent weak correlations.

Two sets of projects, including those with new hydro technologies, are selected from the collected database. Both ICCs and LCOEs are analyzed and compared for the Turbinator project vs. traditional turbine projects within the medium-head range, and for the removable powerhouse project vs. traditional powerhouse projects within the low-head range. The analyses and comparisons show that the ICC is the major driver of LCOE for projects with either new or traditional technologies. However, the ICC ($/kW) alone cannot fully represent the cost-effectiveness or cost performance of a project or a technology. The LCOE, taking into account the lifetime costs and benefits, would be a more important indicator to evaluate the cost-effectiveness of a new technology. Thus a statistical model for LCOE analysis needs to be developed to quantitatively account for the uncertainties and contingencies in hydro LCOE calculation.

Potential cost-cutting technologies and their readiness levels, focusing on the identified cost drivers (e.g., turbine-generator, powerhouse, water conveyance, and dam), are reviewed and evaluated in Section 7. In the final section, research and development proposals and strategies are summarized for suggested follow-on efforts having significant impacts on small hydro development and cost reduction.

1.0 INTRODUCTION

The definition of a small hydro project (SHP) varies significantly from one country to another, but the consensus is to use the total installed generating capacity of a plant as the criterion. The following is a collection of international definitions of SHP:

- Germany ≤1 MW
- Italy ≤3 MW
- UK (NFFO[1]) ≤5 MW
- France ≤8 MW
- Colombia ≤20 MW
- Australia ≤20 MW
- India ≤25 MW
- China ≤50 MW
- Brazil ≤30 MW
- Philippines ≤50 MW
- New Zealand ≤50 MW
- Canada <50 MW

According to the European Small Hydro Association (ESHA), the European Commission, the International Union of Producers and Distributors of Electricity, and the United Nations Industrial Development Organization, a generating capacity of up to 10 MW is now generally accepted as the upper limit of small hydro. The US Department of Energy (DOE) defines SHPs as facilities that have a capacity less than 30 megawatts, but proposed legislation (S.629 Hydropower Improvement Act of 2011) defines SHPs as having a capacity of less than 5 MW. Additional definitions used for varying degrees of SHPs within the hydropower industry include

- pico-hydro: <10 kW
- micro-hydro: 10–100 kW (and/or design flow < 15 cfs)
- mini-hydro: 100–1000 kW (and/or design flow between 15-450 cfs)
- small hydro: >1000 kW (and/or design flow > 450 cfs)

Because of increasing concern regarding greenhouse gas emissions and global warming phenomena in recent years, there is worldwide renewed interest in hydropower generation, especially in small hydro development. Small hydro offers significant benefits in terms of faster deployment, distributed generation, small business opportunities, and significantly reduced concerns about regional environmental/ecological system disturbances, although the levelized cost of energy (LCOE) from small hydro generation is usually higher than from large hydro. In many US states, renewable portfolio standards and green incentives may be able to accelerate small hydro development and deployment. Very recently (June 2012), the US House Energy and Commerce Subcommittee on Energy and Power approved the advancement of H.R. 5892, "Hydropower Regulatory Efficiency Act," which contains measures that could ease domestic development of hydropower and conduit projects. The House also

---

[1] **Non-Fossil Fuel Obligation**

recently voted on the “Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act of 2011,” which seeks to remove certain requirements from conduit projects built on Bureau of Reclamation properties.

Small hydro opportunities and development are not new; 92% of existing hydro turbines in the United States (accounting for 20% of existing hydropower generation) are classified as small or low-power scale (NHA 2010). However, a large amount of small hydro resources is still untapped. A DOE assessment (2004) revealed that a total of around 165 GW of hydro resources was undeveloped, 47 GW of which is on the mini-hydro scale of less than 1 MW. A later study verified that more than 125,000 small hydro sites with a total 30 GW of potential were technically and environmentally feasible (DOE 2006, Kosnik 2010). Previous assessments have been limited to river and stream potential, but additional small hydro resources can be exploited in manmade channels such as irrigation canals and municipal water and wastewater conduits. In California alone, 255 MW of hydropower potential was identified in manmade waterways (Navigant Report 2006).

However, relatively higher installation costs (in $/kW) are a barrier to the development of many low-head and/or low-power sites. Among the 30 GW of technically and environmentally feasible capacity in the United States, only 13 GW is cost-effective for development based on currently available technologies and carbon and fuel market values (Kosnik 2010). The situation is similar in Canada: a complete inventory identified more than 5,500 small hydro sites with a technically feasible potential of about 11 GW, but only 15% of that (1.65 GW) was economically feasible to exploit at the current technology level; a further 2 GW would be economically exploitable if the capital cost could be reduced by 10–15% (International Small Hydro Atlas—Canada Country Brief[2]).

It is clear that reducing initial capital costs will lead to additional deployment of small hydro projects. For many other emerging energy technologies, the cost typically must be reduced to a critical value before significant market acceptance can take place. Small hydro, on the other hand, enjoys the advantage that even a small cost reduction can open up a large number of previously unfeasible sites for commercial development. Therefore, in addition to regulatory reformation and enhanced green incentives, SHP RDD&D[3] focusing on cost reduction are critical to make small hydro economically competitive with other power generation options and promote significant future growth of clean, renewable small hydro.

---

[2] http://www.small-hydro.com/index.cfm?Fuseaction=countries.country&Country_ID=13&ok=TokenPass, accessed May 1, 2011.

[3] Research, development, demonstration, and deployment

2.0 OBJECTIVES AND METHODOLOGY

This section defines the objectives and scope of this project report and outlines the research methodology based on classification of SHPs.

2.1 OBJECTIVES AND SCOPE

One objective for this report is to define/develop the small hydro taxonomy to clarify the nomenclature used in the small hydro area and improve communication among industry, academia, research institutes, and government agencies. More important, this report aims to identify key cost drivers for small hydro generation through cost analyses, review and evaluate cost-cutting technologies, and eventually aid prioritization of RDD&D efforts and strategies that can lower the LCOE of small hydro generation and accelerate SHP development.

As the initial investment cost for development, construction, and installation of a SHP is more intensive and uncertain compared with the annual operation and maintenance (O&M) cost, the initial capital cost (ICC) curves/equations are studied first in this report (Section 4). Via literature review and limited data collection, the capital cost breakdowns for civil works/structures, equipment, and other components are reviewed and analyzed, from which the capital cost drivers are identified.

It is noted that regulatory costs, including permitting, licensing, post-licensing, relicensing, and environmental and Section 401 mandates (Clean Water Act water quality certification), have increased from 5 to 25% of the total project costs over the past 30 years (NHA 2010). These regulatory costs, in addition to the costs associated with increasingly complex grid interconnection requirements, add significantly to small hydro LCOE. Such costs are primarily a result of policy decisions that are not the focus of this report.

The rationale to include life-cycle cost analysis in the scope of this report is based upon a certain inherent relationship between initial investment and annual costs. For example, a remote control system may increase ICC but would save annual operating costs. Cost-cutting technologies must be evaluated from the viewpoint of life-cycle cost/benefit and LCOE reduction. Moreover, annual O&M cost for a small hydro plant can vary from 1 to 6% (or even more) of ICC (IRENA 2012), and the lifetime accumulated effect on LCOE may not be small. Thus technologies that can reduce annual expenses should also be considered within the small hydro RDD&D program. In addition, for aging small hydro plants, replacement and refurbishment costs are intensive and high, and how they affect the LCOE for the remaining lifespan of the energy generation is worth exploring. Thus the components of life-cycle cost and benefit (Tables 5 and 6) and a simple LCOE analysis model are developed in Section 5. The LCOE model is applied for LCOE calculations to compare the performance of two new small hydro technologies vs. traditional small hydro technologies, using the cost data for the projects within the same head ranges (Section 6).

Finally, focused on the identified cost drivers of small hydro generation, state-of-the-art and emerging technologies are reviewed. Cost-cutting technologies and their technology readiness levels (TRLs) and future research and development (R&D) efforts and priorities (including the proposed follow-on projects) in small hydro area are recommended.

2.2 SMALL HYDRO SITE CLASSIFICATION BY EXISTING FACILITIES

One strategy used in this research is to develop representative cost reference models based on different site types, design schemes, and head ranges of SHPs, reflecting real-world site features and cost variations. This is because construction costs are highly site-dependent, especially considering non-powered dam (NPD) sites where only minimal new civil work or modification is required, and energy recovery projects in municipal water conduits where the pipelines already exist and valve houses can be easily converted to powerhouses. Therefore, SHPs are first classified based on existing facilities that can be used, such as

- **New sites** (i.e., greenfield sites), where small dams and/or water diversion structures must be built for water power generation.
- **Existing sites,** where some water facilities already exist, such as NPDs; manmade waterway facilities for flooding regulation, irrigation, and navigation; water supply pipelines; and water treatment outlets. The existing water drops, otherwise dissipated and wasted, can be leveraged for power generation.

  Statistics for NPDs in the United States: There are 84,131dams with total storage of 1.46 billion acre-feet (1800 km^3), but only 2,411 dams are used for hydropower generation. A total of around 12.1 GW of power could potentially be developed at NPD sites. Among all the dams, 83,651 are higher than 1.83 m (6 ft) and 6,795 are higher than 15 m (50 ft, so-called large dams). Many large dams are constructed for multiple purposes, although the greatest use is for flood control. Based on the primary usage of the dams, among total 6,795 large dams, 1,529 are principally for flood control, 1,060 for water supply, 754 for irrigation, 709 for recreation, 578 for hydropower, 98 for navigation, and the rest for other purposes (National Inventory of Dams and NHAAP databases).
- **Restoration/expansion sites,** which are abandoned or underused aging hydro facilities. Many small hydro plants are now at an age at which maintenance and refurbishment are critical, so they may be underused or even desolated. With state-of-the-art turbine design technology aided by computational fluid dynamics (CFD), it is possible not only to restore the original capacity but also to increase the capacity with improved efficiency. Moreover, compared with the ICC per kilowatt for many mini- and micro-scale sites, restoration or rehabilitation of historical plants might be more cost-effective, thus attracting increased interest from original owners or new investors.

2.3 SMALL HYDRO CLASSIFICATION BY HYDRAULIC HEAD

Hydraulic head is a key site-specific factor affecting the turbine type selection, equipment, and construction costs of an SHP. Hence a set of representative reference models should be developed for different head ranges and corresponding turbine types:

- **Low head** (2–25 m): axial flow (AF) Kaplan/propeller, cross-flow, Francis
- **Medium head** (25–70 m): conventional Kaplan/propeller, Francis
- **High head** (>70 m): Francis, Turgo, Pelton

It is noted that the suggested water head ranges are not rigid but are merely a means of categorizing sites, and the turbine selection also depends on flow ranges and other factors at the individual sites.

2.4 SMALL HYDRO CLASSIFICATION BY PROJECT DESIGN SCHEME

SHPs can also be classified based on the configuration and general arrangement of powerhouses (ESHA 2004):

- **Water diversion scheme**. In this scheme, a long penstock or channel diverts the water flow and accumulates the hydraulic head from river intake to downstream powerhouse. The dam or barrage is usually just a weir used only to regulate the water level at the intake and to store the water, so the dam has very low environmental impact. This scheme is usually designed for medium to high head, where the flow is not huge but the natural elevation difference is sufficient within a reasonable distance of a stream/river section.

- **Dam-toe scheme**. In this scheme, the powerhouse is located immediately downstream of a dam, and the penstock is short and penetrates through the dam to convey water from intake to turbine.
- **Siphon intake scheme**. At low-height dams, siphon intakes can be installed. This scheme is generally for heads of up to 10 m and capacities of up to 1000 kW, although there are examples of siphon intakes with installed power up to 11 MW (in Sweden) and heads of up to 30.5 m (in the United States). The turbine can be located either on the top or on the downstream side of the dam. This scheme is a good solution to avoid major modifications to existing NPDs.
- **River-based or canal-based scheme** (including open flume scheme for smaller-scale projects). In this scheme, the powerhouse is integrated into the dam/barrage and intake structure as one part of the powerhouse construction.
- **Pipeline integrated scheme**. In this scheme, the powerhouse is integrated into the existing water pipelines; in most cases, the turbine units replace the pressure dissipation valves to recover the otherwise wasted water energy.

These five schemes cover almost all small hydro sites that are under development.

In addition, hydropower projects are also simply classified by water impoundment. Run-of-the-river (ROR) is a type of hydroelectric generation whereby limited or no water storage is provided, while storage hydro is another type of hydroelectric generation where dams store enormous quantities of water in reservoirs, necessitating the flooding of large tracts of land. Some ROR projects may have low impact dams or weirs for raising intake water elevation or for daily flow storage and adjustment. However, the distinct feature of ROR projects is that there is neither significant water storage nor significant downstream hydrograph changes. ROR projects could have “water diversion” design scheme or “river-based or canal-based” design scheme.

3.0 LITERATURE REVIEW AND COST DATA COLLECTION

A thorough search and review has been carried out for relevant journal papers and published reports. Some existing cost equations and associated work are summarized in Section 3.1. To update the existing cost equations and apply them in current US small hydro development, cost data must be collected for recent SHPs in the United States. Section 3.2 documents the challenges encountered, efforts made, and lessons learned during cost data collection. In Section 3.3, further efforts are recommended for cost database and cost equation development.

3.1 EMPIRICAL HYDRO COST EQUATIONS

J. L. Gordon is the pioneer who made remarkable contributions to cost estimating techniques for hydro projects. Early in 1979, correlations of electromechanical equipment cost and overall project cost to the net head and capacity were developed for projects below 5 MW at existing dams (Gordon and Penman 1979):

$$C_{EM} = 9000 \times P^{0.7} / H^{0.35} \qquad \text{(US\$, 1978)} \qquad (1)$$

$$C_P = 9000 \times S \times P^{0.7} / H^{0.35} \qquad \text{(US\$, 1978)} \qquad (2)$$

Here, C_{EM} = cost of electromechanical equipment, C_P = cost of overall project, S = site factor depending on the project size and penstock requirement, P = installed capacity in kW, H = hydraulic head in meters. In subsequent studies (1981, 1983, 1986), Gordon further developed the mathematical formulae to estimate the cost of hydro projects, including civil site costs, equipment costs, and engineering and administration costs, for different ranges of P and H:

$$C_P = k \times L \times (P / H^{0.3})^{0.82} \qquad \text{(US\$, 1982)} \qquad (3)$$

Here, the coefficient k is introduced to reflect system load factor, etc., and coefficient L represents the location/country of the project.

Limitations are recognized for using Gordon’s empirical equations today, because (1) the project data were consolidated from different countries, assuming no cost variations for equipment among countries, (2) the data are out of date (1956–1986), and (3) the effects of project schemes and turbine types on the overall plant cost were not considered.

Based on Austrian data, Matthias, Doujak and Angerer (2001) developed an estimate of investment costs for projects with $P < 2$ MW and $H < 15$ m. The cost included direct and indirect investment costs. The interest rates on investment, O&M costs, and influence of ecological and environmental measures on energy costs were also studied.

Papantonis (2001), based on the Europe data, developed cost estimate formulae for different components and project cost equations differentiated for different turbine types. The cost of electromechanical equipment confirmed Gordon’s equation with an inflation rate adjustment:

$$C_{EM} = 20570 \times P^{0.7} / H^{0.35} \quad (4)$$

Where P (in kilowatts) and H (in meters) are the same as defined earlier, and C_{EM} is in 2000 British pounds (£)

Recently, Aggidis et al. (2010) pointed out that caution is needed when using Papantonis (2001) equations as they are based on inconsistent European data, much of which is out of date. Meanwhile, based on project data for hydro sites in the northwestern region of the UK, Aggidis et al. (2010) developed cost estimate equations for overall plant and electromechanical equipment:

$$C_P = 25000\left(P / H^{0.35}\right)^{0.65} \quad \text{for heads between 2 - 30 m} \tag{5}$$

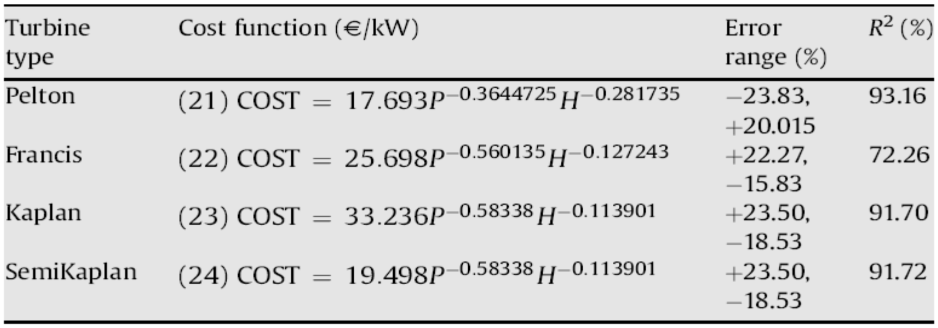
$$C_P = 45500\left(P / H^{0.3}\right)^{0.6} \quad \text{for heads between 30 - 200 m} \tag{6}$$

$$C_{EM} = 12000\left(P / H^{0.2}\right)^{0.56} \tag{7}$$

where *P* is in the range of 25–990 kW, and C_P and C_{EM} are in 2008 British pounds (£).

Another recent study using empirical equations to estimate the cost of electromechanical equipment (<2 MW) was carried out based on Spanish data (Ogayar and Vidal 2009a); the results are shown in Table 1, in which *P* (in kW) and *H* (in meter) are the same as defined earlier and COST is given in euro. Note that Ogayar's cost is provided on a per-kilowatt basis. To obtain the total cost, the cost per kilowatt is multiplied by the capacity *P*. The same authors also discussed restoration costs of abandoned SHPs in another article (Ogayar, Vidal, and Hernandez 2009b): by applying a refurbishment percentage based on the condition of each component, the cost for recovering a component can be estimated using the same equations as for new site construction.

Table 1. Spanish cost equations for electromechanical equipment



Turbine type	Cost function (€/kW)	Error range (%)	R^2 (%)
Pelton	(21) $\text{COST} = 17.693P^{-0.3644725}H^{-0.281735}$	−23.83, +20.015	93.16
Francis	(22) $\text{COST} = 25.698P^{-0.560135}H^{-0.127243}$	+22.27, −15.83	72.26
Kaplan	(23) $\text{COST} = 33.236P^{-0.58338}H^{-0.113901}$	+23.50, −18.53	91.70
SemiKaplan	(24) $\text{COST} = 19.498P^{-0.58338}H^{-0.113901}$	+23.50, −18.53	91.72

Source: (Ogayar and Vidal 2009a)

A series of research efforts by Singal et al. (2008a, 2008b, 2010), based on project data in India, developed correlations of component costs to *P* (kW) and *H* (m) for canal-based, low-head dam-toe, and low-head run-of-river SHP schemes, respectively. Each type of design scheme contains different civil work components. For canal-based schemes, civil work is classified as diversion channel, spillway, and powerhouse. For dam-toe schemes, civil work components are intake, penstock, powerhouse, and tailrace. For run-of-river schemes, the diversion weir and intake, desilting chamber, power channel, forebay and spillway, penstock, powerhouse building, and tailrace are included in the civil work cost analysis. The electromechanical components are the same for all three schemes. They include (1) turbine with governing system; (2) generator with excitation system, switch gear, control and protection equipment; (3) mechanical and electrical auxiliaries; and (4) main transformer and switchyard equipment.

According to a World Bank report, total initial project costs are between US $1800 and $8000 per kilowatt for a head range of 2.3–13.5 m, and $ 1000–3000 per kilowatt for a head range of 27–350 m (INFORSE 2012). Figure 1 shows the per kilowatt project cost (in ECU/kW) varying with the head within three different ranges of plant capacity. For projects with smaller capacities (<250 kW) or with lower heads (<20 m), the initial project cost is more sensitive to the available head on the site.

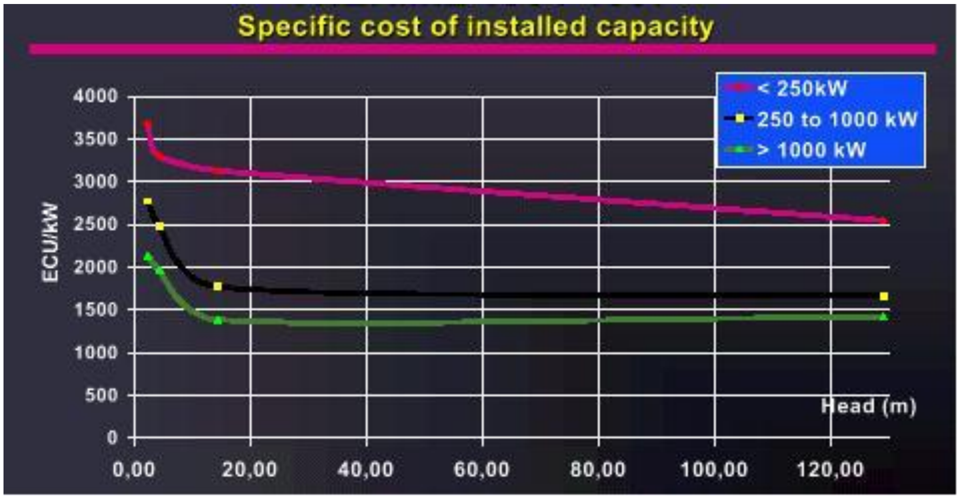


Figure 1. Project cost vs. head within different capacity ranges. ***Source:*** **INFORSE 2012**

The DOE/Idaho National Laboratory report *DOE and INL Estimation of Economic Parameters of U.S. Hydropower Resources* (2003) is the most recent study of US hydro cost estimates for hydropower projects with capacities from 1 to 1300 MW. The cost data were mainly sourced from an Energy Information Administration database (originally from Federal Energy Regulatory Commission [FERC] Form 1) and FERC licensing documents during 1980–2000. Some limitations are recognized for applying the cost estimate tools to current site or project assessments: (1) the cost database was not specifically for small hydro; (2) the project data were at least one decade old; (3) the mitigation costs that were used to develop the INL's cost estimating tool were the total costs that would occur over 30 years. In other words, the initial cost and O&M cost were not differentiated during the cost equation development; and (4) all the costs were related to plant capacities only, whereas other studies showed the relationship between costs and the available heads at the sites (this may be because the historical projects used for regression analysis usually had high dams, which significantly raised site available heads). The report itself also pointed that additional data and research were needed to refine the cost estimating tools.

3.2 EFFORTS ON COST DATA COLLECTION

Unsurprisingly, collecting cost data directly from the hydro industry is a challenging task, as the costs of recent projects are usually regarded as proprietary/business sensitive. A preliminary effort was made to collect project cost data from SHP developers and consultants using the "Prospectus for Hydropower Cost Data Collection" (Appendix A of this report) and a prepared data template, but only a few responses and valid data sets were received (Note: the term "data set" in this report refers to all the cost data, relevant design parameters, and other information for one specific hydropower project). However, a thorough search for publicly accessible license documents was performed in the FERC e-library. The current cost data collection includes 35 projects from the FERC e-library, developers, and consultants, and 15 in-canal projects located in the western United States collected from other sources, but some of them are missing hydraulic head numbers or detailed breakdown costs. This section summarizes the experience of the FERC e-library search, as well as some interesting findings from licenses; the data and analyses for ICC and LCOE will be discussed in Sections 4 and 5.

In the submitted FERC license applications, proposed projects with capacities of 5 MW or more usually supply “Exhibit D—Cost and Financing”; projects with capacities of 5 MW or less (minor license applications) may provide only the cost information in “Exhibit A—Project Description.” In the submitted exemption applications and license applications for projects with capacities below 1 MW, often no cost data are provided. For most licenses issued before 2007, only unreadable microfilm documents can be found, as the applications were submitted in earlier years. For this reason, only licenses and exemptions issued since 2007 have undergone a thorough search in the FERC e-library.

From the FERC license documents, the current trend and status of hydro development, including adoption of cost-cutting technologies, is provided as follows.

- Since 2007, 31 new or original licenses (with a total 285 MW of proposed new capacity) have been issued for conventional hydro development, of which only 2 projects have a plant capacity greater than 30 MW (large hydro) and the other 29 projects all fall within the range of small hydro scales. In addition, 27 projects are developed on existing dams or conduits and only 4 projects are using new dams or impoundments.
- A total of 42 exemptions have been issued since 2007 with a total proposed capacity of 31 MW, of which 32 exemptions are conduit projects and only 10 are non-conduit projects. Exemption is authorized for SHPs with installed capacities of 5 MW or less that (1) are located at the site of any existing dam (i.e., one in existence on or before July 22, 2005) or (2) use a “natural water feature” to generate electricity, without the need for any dam or impoundment. (Note: The recently approved “Hydropower Regulatory Efficiency Act” gives FERC the option to exempt hydro projects with a capacity of less than 10 MW and conduit projects with capacities between 5 and 40 MW from the permitting process.)
- Polyvinylchloride (PVC) polymer penstocks are used for micro/mini projects (at least 3 examples found among the 31 licensed projects);
- Infallible rubber dams are used for small projects (at least 2 examples in the 31 licensed projects).
- Modular removable powerhouses are proposed for installation at eight existing dam and locks (8–15 ft of head) for generating during navigation seasons. The powerhouse is removed and stored in the winter. The preliminary permit was issued, which indicates an emerging technology of powerhouse design and operation has been considered and studied by developers.

3.3 FURTHER EFFORT FOR COST DATABASE AND COST MODEL DEVELOPMENT

The literature review showed that a number of empirical equations have been developed worldwide to estimate overall project cost, civil works and electromechanical costs. However, each of these studies has certain limitations with regard to applying them to predict costs for new hydro projects in the United States (e.g., data out of date, small sample size, specific regions of projects, and certain types of projects). Especially, the cost of a hydro project is nonlinearly correlated to the installed capacity and head, and it is very site-dependent and sensitive to the evolving economy and technologies. Therefore, extrapolating the empirical curves developed for large projects for use with SHPs, or using existing cost equations developed for projects in other countries or decades ago, would likely result in an unreasonably inaccurate cost prediction. To validate the empirical cost equations, adjust their coefficients, or develop new cost correlations, it is necessary to collect the cost data from historical and recent US projects that may have adopted the most advanced hydro technologies.

During the performance of this research, informal interviews and surveys were conducted with major hydro consultants and equipment vendors in North America, but formal procedures (through contracting) were not pursued for acquiring cost data because of funding constraints. Although multiple efforts have been made to collect needed data from the FERC website, literature, and industry, the collected cost data are still insufficient to develop a set of new cost equations for the following reasons:

- Most of the collected cost data are for projects connecting to NPDs and for in-canal projects, which cannot be used for costing new site projects.
- The total number of data sets (i.e., the sample size) is not large enough to conduct a meaningful statistical (regression) analysis when the data sets are categorized for various site types or different power scale or head ranges.
- The costs collected from FERC license documents are rough estimates only; actual project costs may vary significantly when detailed design and construction are carried out.

Further effort is recommended for a hydro project cost database and modeling. A few reputable hydro consulting companies located in different regions will be selected and awarded contracts to provide cost data anonymously using a pre-designed Excel spreadsheet (data collection template) for the projects that the consulting companies have studied or designed during the past few decades. ORNL will then categorize, archive, and maintain the collected cost data for different site types and various design schemes. For each set of project data, the cost base year, data source (FERC or consulting companies), and cost status (e.g., budget in license application, feasibility study, or detailed design stages) will be recorded. Using this updated cost database, ORNL will validate/modify the existing cost equations or develop new correlations between the costs and major project parameters for various site categories or design schemes.

The refined cost estimate tool resulting from this proposal can be made publicly available for developers, consultants, and other project stakeholders for economic assessment during the site selection and financing stages, thus reducing early-stage development costs and risks. The robust cost equations could also help for regional and national hydro development planning, promoting commercial development of small hydro sites—relevant to the DOE Water Power Program mission. The pressing need for a robust cost modeling tool has been recognized by the ongoing DOE-sponsored projects (e.g., DOE Water Power Vision and Basin Scale Opportunity Assessment). In addition, the cost equations and trends for different site features and design parameters will help to identify key cost drivers for the development of different types of sites (e.g., for low-head site development, the turbine-generator equipment may be the cost driver, whereas for high-head site development, the penstock could be the cost driver). The cost equations and trends for project components (e.g., turbine-generator equipment, environmental mitigation measures) may help to identify cost-cutting technologies (e.g., how the advanced technology and design for fish passage helps reduce the total project cost). This proposal may not be limited to small hydro only, although the reality is that the most recently developed and developing projects are in the range of small hydro, i.e., below 30 MW.

4.0 INITIAL CAPITAL COST ANALYSIS AND COST DRIVERS

In the context of this report, ICC is defined as the total ICC of a project including all the direct construction costs and indirect costs (see Table 5 in Section 5). The capital costs used for discussions in this section may have slightly different scopes of cost items owing to different sources of raw data. For instance, for some sets of cost data extracted from reference reports, the direct construction costs may not include contingencies and indirect costs may not include financing or license/permitting costs. However, the comparisons and comments are usually made based on the same or consistent data sources.

4.1 INITIAL CAPITAL COST ESTIMATE

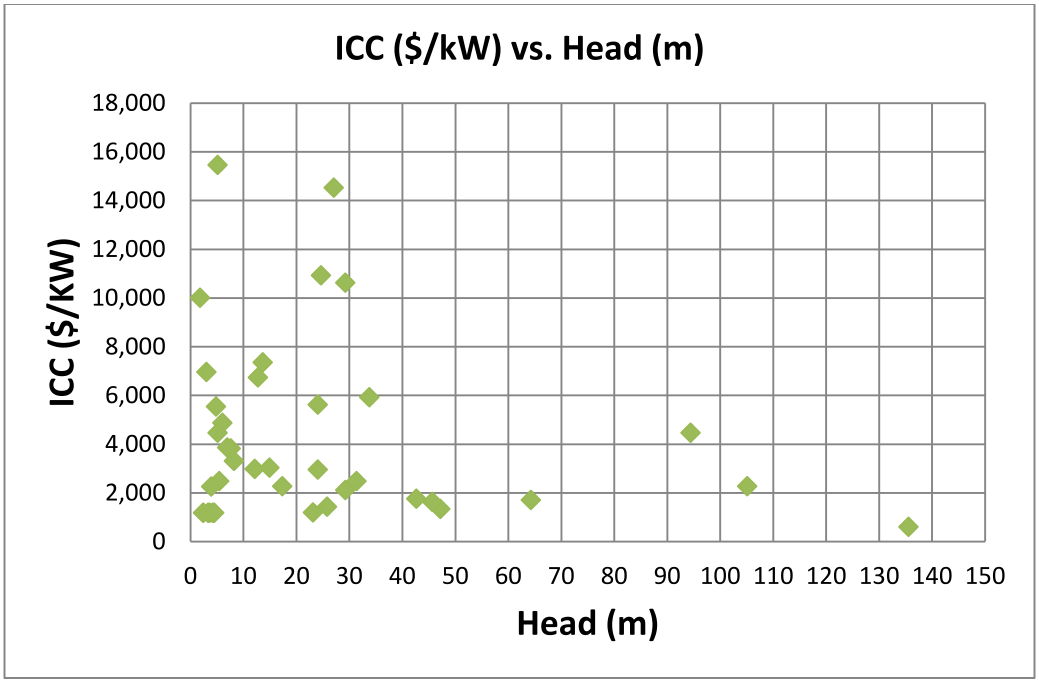
As previously discussed, most collected cost data are for projects with existing NPDs or conduits in which no new dam construction will be involved. Thus the cost regression analyses and discussions in this report will focus on NPD and conduit projects, and the results should be useful because this type of site development is indeed the current trend of small hydro development in the United States

4.1.1 ICC Data Sources and Trending

Excluding the cost data for any new site development and existing plant expansion projects, only 20 valid data sets are from FERC e-library, 7 data sets are directly from industry (developers and consultants), and 15 sets are data from other sources for in-canal projects located in the western United States. These 42 data sets are aggregated in Figure 2 (a) and (b) for trending ICC vs. head and ICC vs. plant capacity, respectively. The figure shows that the projects with lower head or smaller capacity usually require higher initial investment per kilowatt of power installed. However, a significant scatter of data points is also shown in Figure 2 because

1. The number of data sets is insufficient.
2. Different levels of existing facilities are used for each project
3. Most in-canal projects are on the mini-hydro scale, and the sites without vertical head drops usually require a long penstock to collect the hydraulic heads along the distance. This contributes significantly to higher initial costs per kilowatt installed.

To retain consistency across different projects and data sources, interest rates during the construction period have been removed from this cost data aggregation, and the costs in different project base years have been escalated to US dollars in 2011 using the annual average index from “Hydropower Construction Costs Trend” (USBR 2012).



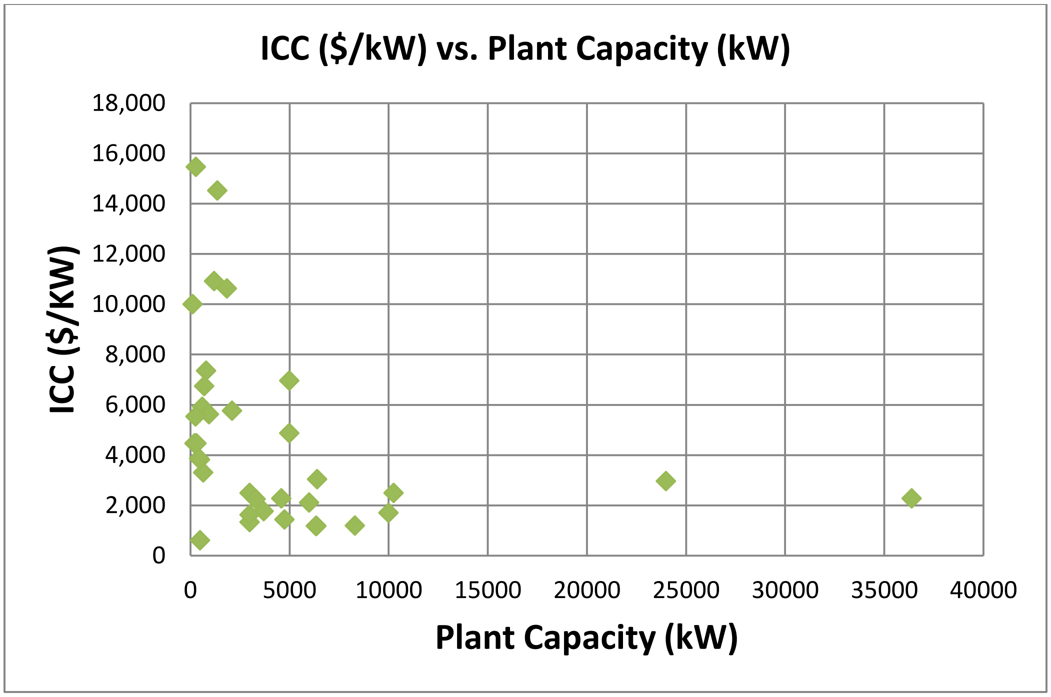


Figure 2. Trend of ICC vs. head and vs. plant capacity for existing NPD and conduit sites.

Note: Data collected from FERC license documents

4.1.2 ICC Estimate Equation

The cost equations/equations in the literature suggest that an equation of “three parameter power” should be assumed for regression of SHP ICC (or C_P), that is,

$$C_P \text{ (\$)} = aH^b P^c \qquad (8)$$

where H is the head in meter (the first independent variable), P is the plant capacity in kilowatt (the second independent variable), and a, b, and c are three parameters to be determined by regression analysis. The total project cost per kilowatt can be deduced from Eq. (8):

$$C_P \text{ (\$/kW)} = aH^b P^{c-1} \qquad (9)$$

The commercial software Datafit 9.0 is used for this nonlinear and two-variable regression problem. Based on the same aggregated data used in Figure 2, the regression analysis is performed and a correlation results for the total project cost vs. the head and plant capacity:

$$C_P \text{(\$)} = 566.9H^{0.01218}P^{1.1452} \qquad (10)$$

In Eq. (10), the coefficient of multiple determination seems high (R^2 = 0.915), but the error range of the results is huge.

Equation (10) implies that the project ICC is highly related to the plant capacity (kW) but only loosely related to the head. As deduced from Eq. (10), the ICC per kilowatt has the following correlation:

$$C_P \text{(\$/kW)} = 566.9H^{0.01218}P^{0.1452} \qquad (11)$$

Equation (11) indicates that the installation cost per kilowatt rises as the plant capacity or head increases, which is contrary to reality and engineering experience. This inaccurate correlation results largely from the limited size of the data sample; it is realized that a robust cost database is the required foundation for cost equationing. Thus intensive and extensive efforts must be made to collect project cost data to increase the sample size and improve the accuracy of regression results.

In addition, various linear and nonlinear equations have been tried in regression analysis and applied to the wide range of new NPD sites in the NHAAP database to verify the reasonableness of the cost equations. A lesson learned is that, given the limited size of sample data, the best way to establish a reasonable cost tool is to update the coefficient a while keeping the same power indices of b and c as in the classic or widely recognized cost equations. In this study, the power indices of H and P in Eq. (8) are taken from the classic empirical equations (Gordon and Penman 1979); that is, $b = -0.35$, $c = 0.7$, and then the coefficient a is determined by linear regression analysis using the collected cost data. The regression result is shown in Figure 3 and the following cost equation:

$$C_P \text{(\$/kW)} = 110{,}168H^{-0.35}P^{-0.3} \qquad (12)$$

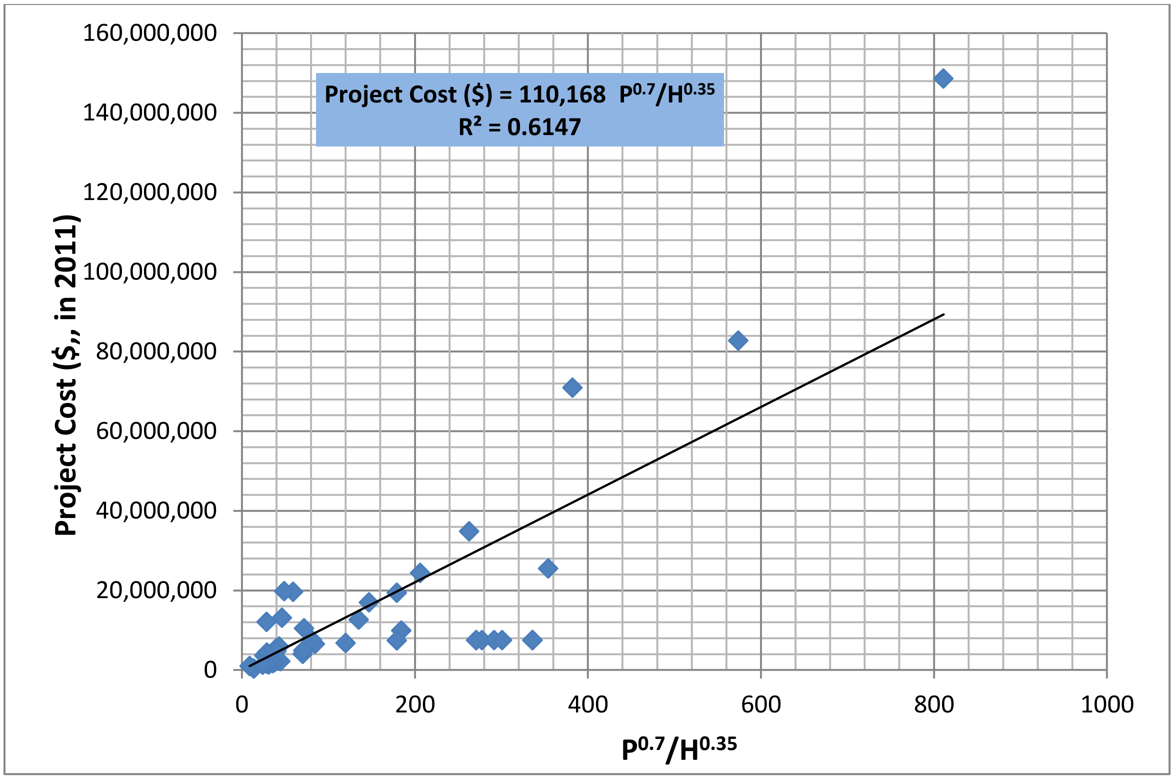


Figure 3. ICC estimate equation for existing NPD and conduit sites.

4.2 ICC COMPARISONS AND BREAKDOWNS

Based on data from the 2010 IEA report (IEA-ETSAP 2010), the ICC could range from $2000/kW to $7500/kW for small scale hydro and from $2500/kW to $10,000/kW for mini-hydro, which would result in an LCOE of $45–120/MWh (typically, $83/MWh) for small hydro and $55–185/MWh (typically, $90/MWh) for mini-hydro, assuming annual O&M cost is 1.5–2.5% of initial investment.

Based on the cost data obtained from Canadian project experience (Hatch 2008), the ICC difference is around $500/kW between new sites and existing sites for small hydro generally (Figure 4) and as high as $1500–2500/kW for low-head small hydro, resulting in a $30–50/MWh difference in LCOE (Figure 5). Thus existing site development is significantly more cost-effective, particularly for low-head cases.

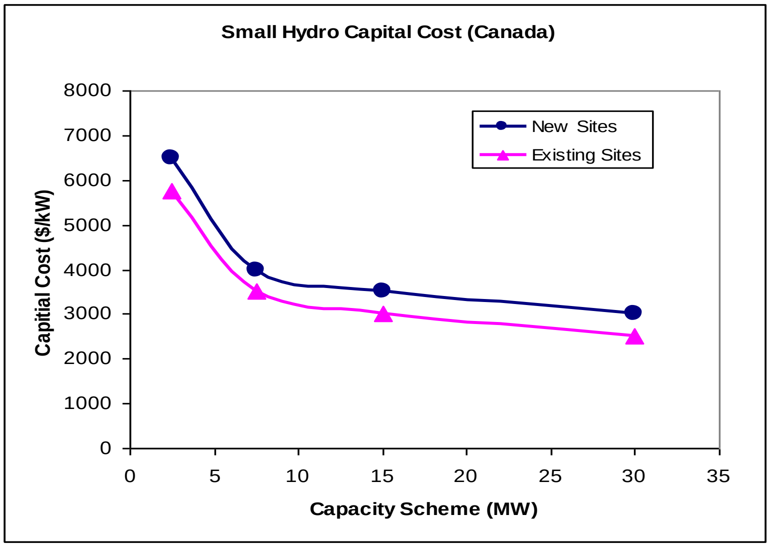


Figure 4. ICC difference (new sites vs. existing sites) for small hydro in general.

Source: Data adapted from Hatch Report; all dollar amounts adjusted to 2008 dollars.

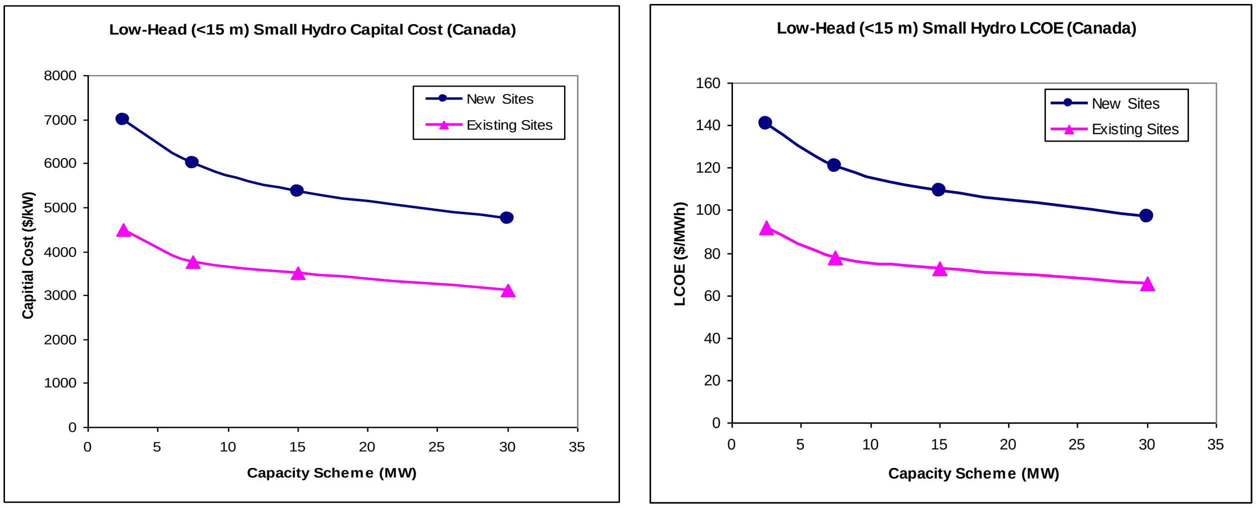


Figure 5. Cost difference (new sites vs. existing sites) for low-head small hydro.

Source: Data adapted from Hatch (2008); all dollar amounts adjusted to 2008 dollars.

A US design matrix was created for projects with low heads (10 and 20 ft) and the same capacity of 5 MW; initial costs are compared between new sites and NPD sites, as shown in Table 2. Development at NPD sites can save $1500–2000 per kilowatt of installed capacity. The lower the head, the higher the cost savings.

Table 2. ICC comparison of new sites and NPD sites

Capacity, net head	New sites cost ($/KW)	NPD site cost ($/KW)	Cost difference ($/KW)	Cost savings (%)
5 MW, 10 ft	8,948	6,959	1,989	22
5 MW, 20 ft	6,427	4,867	1,560	24

4.2.1 Capital Cost Breakdowns

The capital cost breakdowns are shown in Figures 6–8, which are created using the raw cost data, respectively, from three different project reports (Hatch 2008, IDEA 1996, and Nexant 2006). Note that the capital cost breakdown in these charts may not include the grid connection cost, regulatory cost, engineering cost, or other indirect costs. Note also that all three data sources, compiled from SHPs in Canada, Europe, and South Asian, respectively, indicate that civil works and electromechanical equipment are two major cost components, no matter the type of project site (e.g., new, existing, or restoration sites). Figure 6 also shows that for low-head small hydro, the civil works will cost 20% more at new sites than at existing sites. More detailed raw data further show that the turbine is usually the key cost driver among the electromechanical equipment for new site development, particularly for low-head cases. Based on Figure 7 (d) and more detailed raw data for components of civil works (IDEA 1996), a high-head project will spend 47% of its total 60% civil cost on penstocks, and a low-head project will spend 38% of a 47.5% total civil cost on dams and powerhouses. In other words, the penstock is the key cost driver for a high-head new site project; and the powerhouse and dam, in addition to turbines, are the key cost drivers for a low-head new site project.

Figure 8 is the cost breakdown averaged from six restoration projects in Afghanistan with medium to high heads (gross heads 27–120 m). The major cost drivers are civil works and electricity transmission and distribution, including all networks, equipment, and appliances inside and outside the powerhouse to deliver electricity to the local decentralized power service areas (Note: this cost is typical in rural regions but not typical in most regions of the United States). Although their ages vary greatly (dates of construction 1913, 1971, 1971, 1983, 1986, 2003), the assets of all six plants are in bad condition because of lack of proper maintenance and overhaul: four of them are not in operation and two are only partially in operation. The cost of restoration would range from 1000 to 3000 $US/kW.

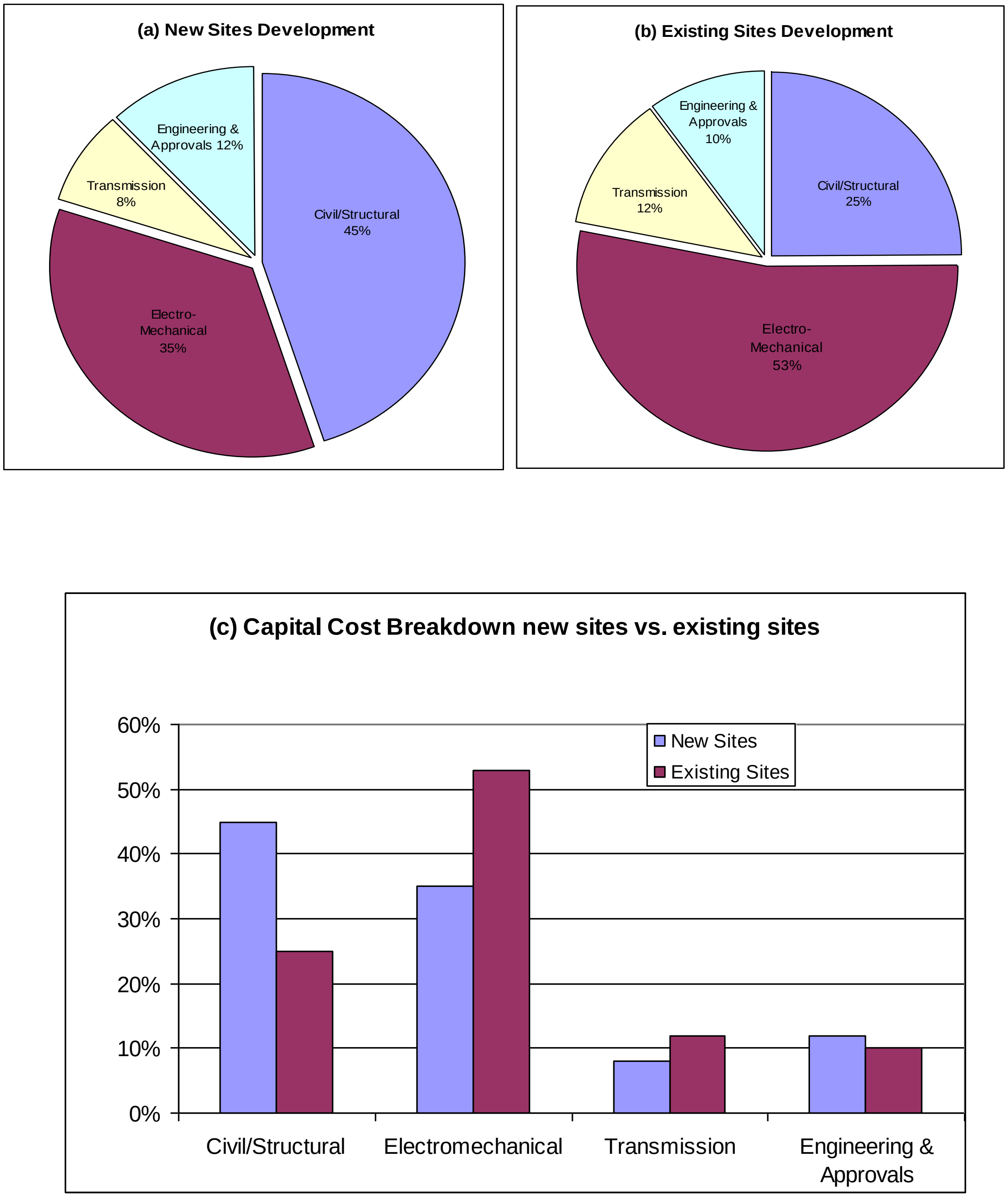


Figure 6. Capital cost breakdown for low-head small hydro projects.

Source: Data adapted from Hatch (2008).

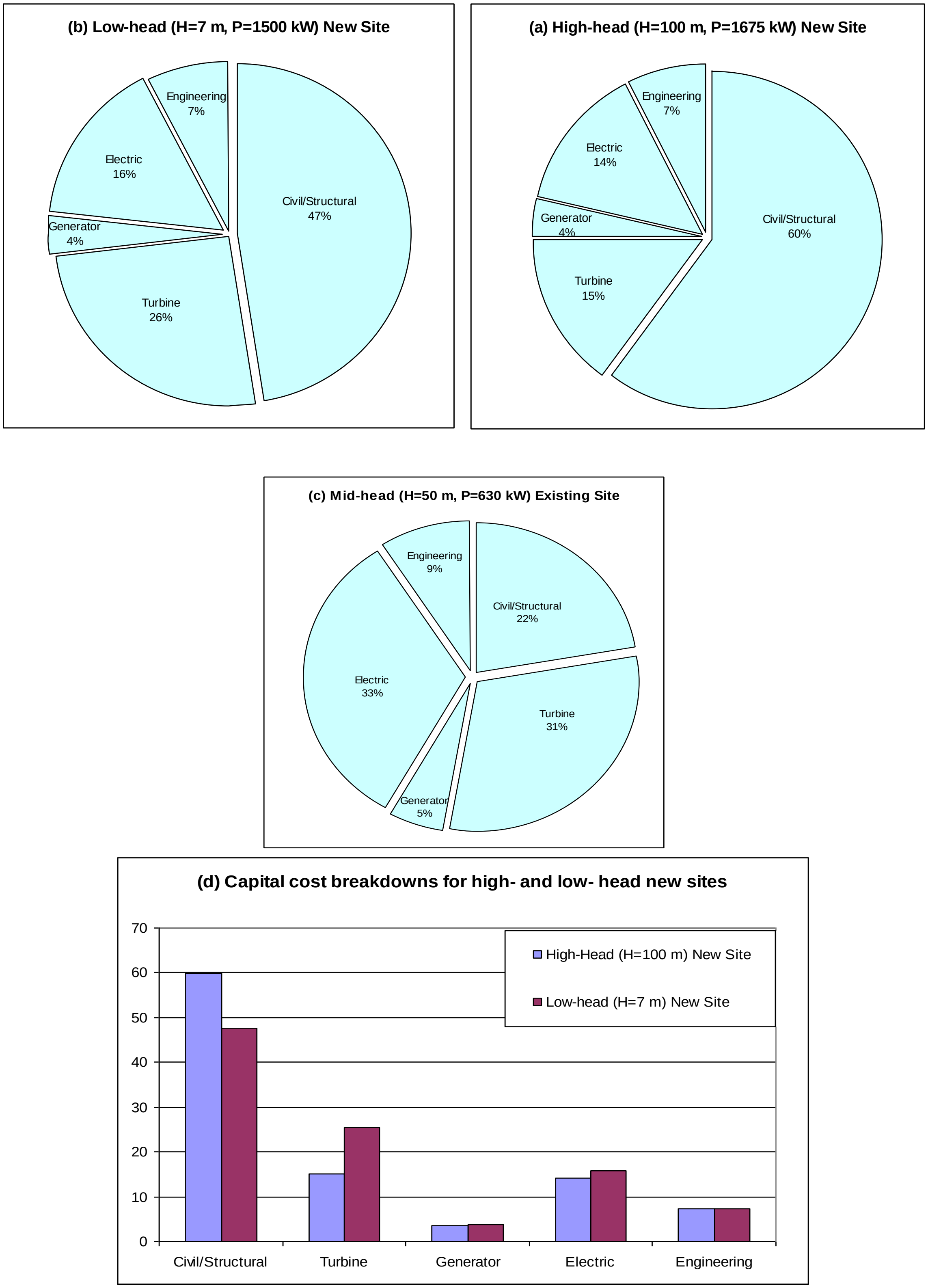


Figure 7. Capital cost breakdown for typical small hydro projects.

Source: Data adapted from IDEA (1996).

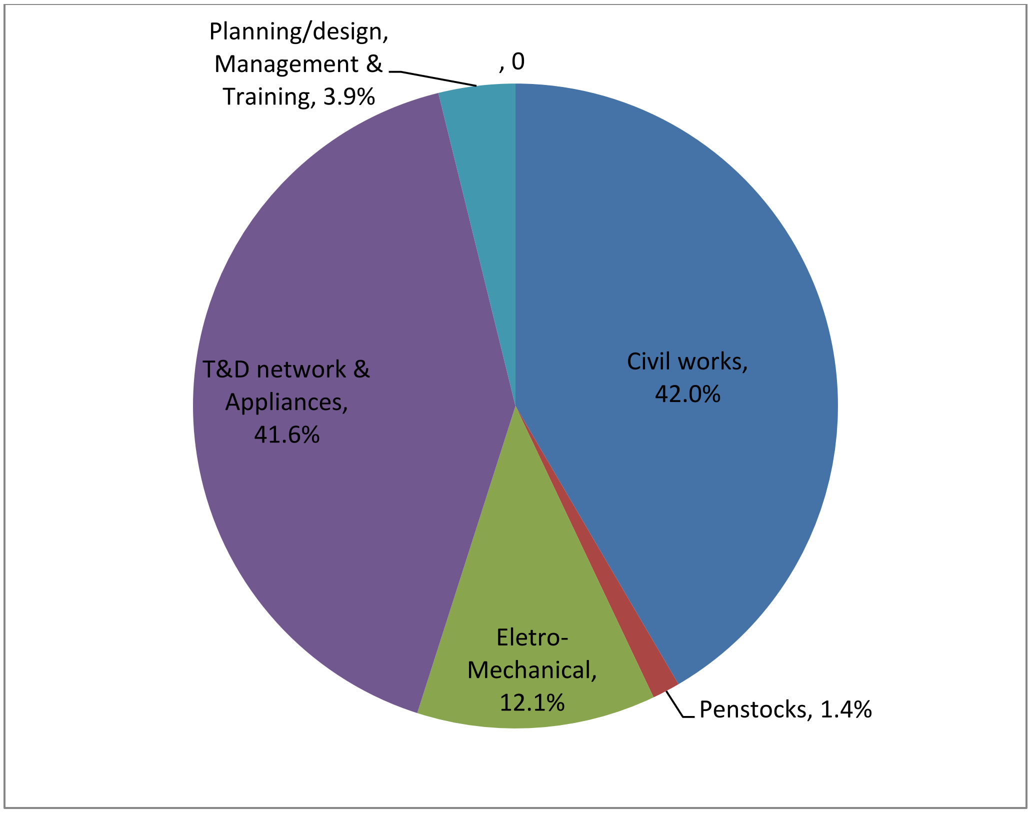


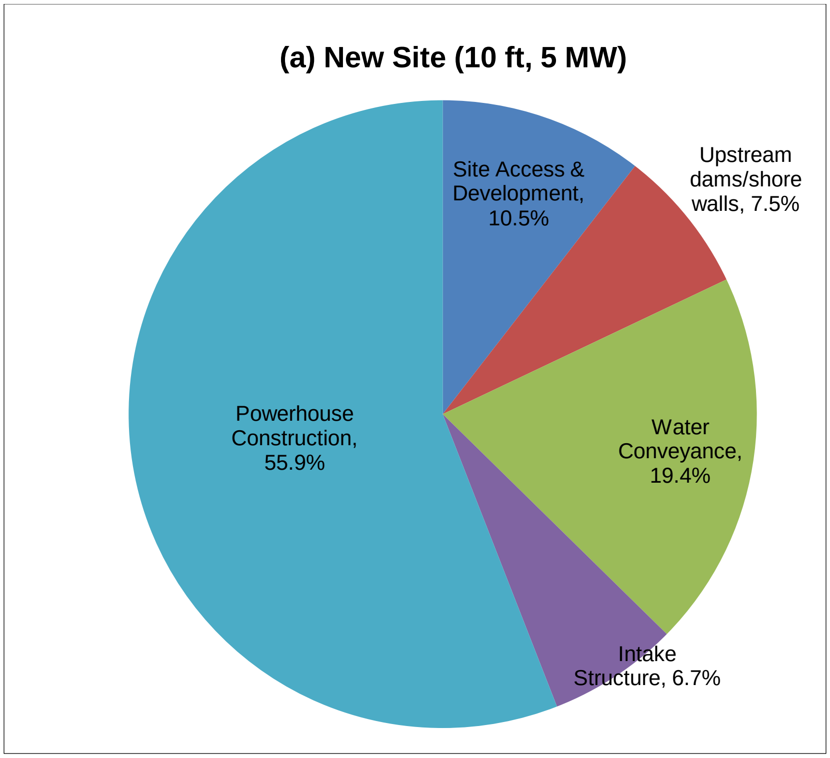
Figure 8. Capital cost breakdown averaged for six restoration plants in Afghanistan.

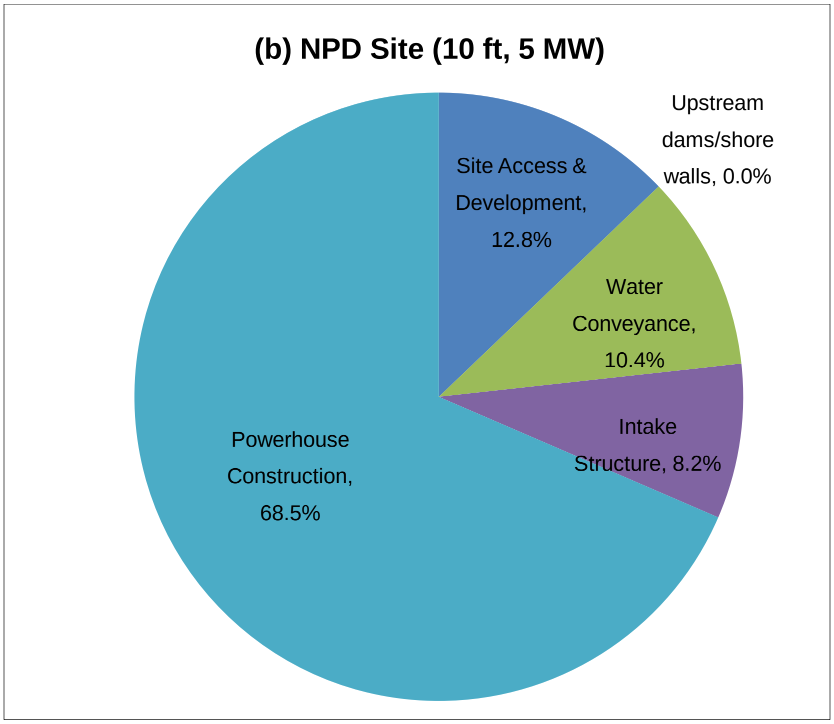
Note: (1) Cost is typical in rural regions, not typical in most regions of the United States.

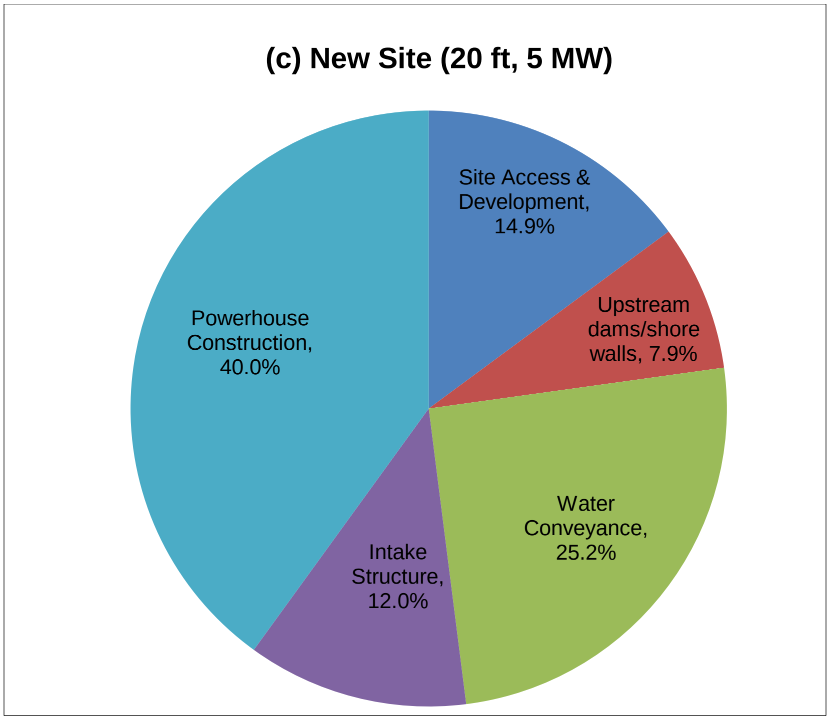
Source: Data adapted from Nexant (2006).

4.2.2 Civil Works Cost Breakdowns

Figure 9 shows the cost breakdowns for components of civil works and structures. The data are taken from the US projects listed in Table 2. For this set of low-head projects, the civil works and structures constitute 40–55% of total project cost; among the civil investments, powerhouse construction is the key cost driver, accounting for 40–56% of the cost for new sites and 54–68% for NPD sites. Therefore, eliminating or minimizing powerhouse construction should be pursued in innovative low-head generating systems to reduce the total capital cost, particularly for power capacity installation at NPDs and existing conduit sites.


(a) New Site (10 ft, 5 MW)
Site Access & Development, 10.5%
Upstream dams/shore walls, 7.5%
Water Conveyance, 19.4%
Intake Structure, 6.7%
Powerhouse Construction, 55.9%


(b) NPD Site (10 ft, 5 MW)
Upstream dams/shore walls, 0.0%
Site Access & Development, 12.8%
Water Conveyance, 10.4%
Intake Structure, 8.2%
Powerhouse Construction, 68.5%



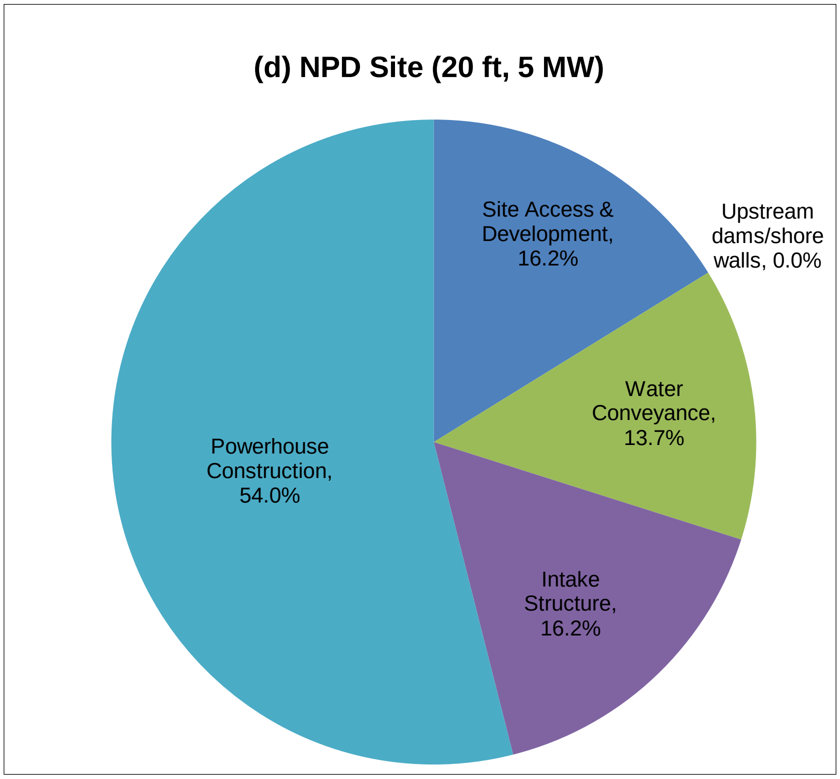


Figure 9. Cost breakdown for civil works and structures.

Source: Data adapted from a recent US SHP design matrix.

4.3 ELECTROMECHANICAL EQUIPMENT COST ESTIMATE

As mentioned earlier, electromechanical equipment is a key ICC driver, especially for low-head sites. The cost estimating equation for electromechanical equipment would have a great effect on the accuracy of ICC and LCOE predictions for SHPs.

4.3.1 Equipment Data Source and Trending

The budget prices of electromechanical equipment for a total of 731 projects during 2003–2009 are collected from a small hydro turbine manufacturer in North America (mostly for projects in the United States). All of the prices are for a package of electromechanical equipment, including runner/distributor assembly, draft tube liner, generator, hydraulic power unit, and switchgear/control/protection system. In this report, the cost for the package of electro-mechanical equipment is also referred as "Turbine-Generator Cost" in the figures. All the prices used in this report have been converted to US dollars in the year of 2010, using the historic exchange rates and consumer price indices.

The cost data collected and studied are associated with three turbine types: (1) Francis, (2) double-regulated AF (AF/DR)—AF Kaplan, and (3) single-regulated AF (AF/SR)—AF propeller. An AF Kaplan turbine is a bulb type used at low-head small hydro sites; it is characterized as having a high, flat efficiency curve for a wide range of heads. The generators included in the budget prices are synchronous and induction types; the latter is less expensive and usually applied at sites with lower power capacities.

The collected budget prices were used to trend the relationship between the equipment costs vs. head and capacity (or flow). Except for a few projects with missing information (e.g., the head) and a few with extremely high or low costs, almost all raw data are plotted in cost trending charts.

In Figures 10 and 11, different turbine types are aggregated and marked differently— red squares representing the costs of Francis turbines; blue dots, AF/SR turbines; and pink triangles, AF/DR turbines. Figure 10 shows that the turbine-generator cost tends to decrease as net head increases. Francis turbines are in the higher head range, and so the kilowatt cost is lower; whereas AF turbines are in the lower head range, and the kilowatt cost is higher. Figure 11 shows that the turbine-generator cost tends to decrease as capacity increases, and there is not a clear capacity range for using a small Francis turbine or AF turbine. In Figures 12 and 13, both generator types are aggregated and differentiated by pink triangles (synchronous) and blue squares (induction). Figure 12 shows that turbine-generator cost tends to decrease as net head increases, and there seem to be no clear ranges for different types of generators. Figure 13 shows that turbine-generator cost tends to decrease with increasing of capacity, and induction generators are concentrated at the low-capacity end.

Figures 14–19 show electromechanical cost trends for individual turbine types.

All of the plots in Figures 10–19 show a common trend that costs raise rapidly at the low-head and low-capacity ends. That is, the equipment for low-head and low-power sites would cost more in terms of dollars per kilowatt; this is often the barrier to developing low-head SHPs, and thus advancements are needed for low-head turbine-generator technologies to make them economically viable.

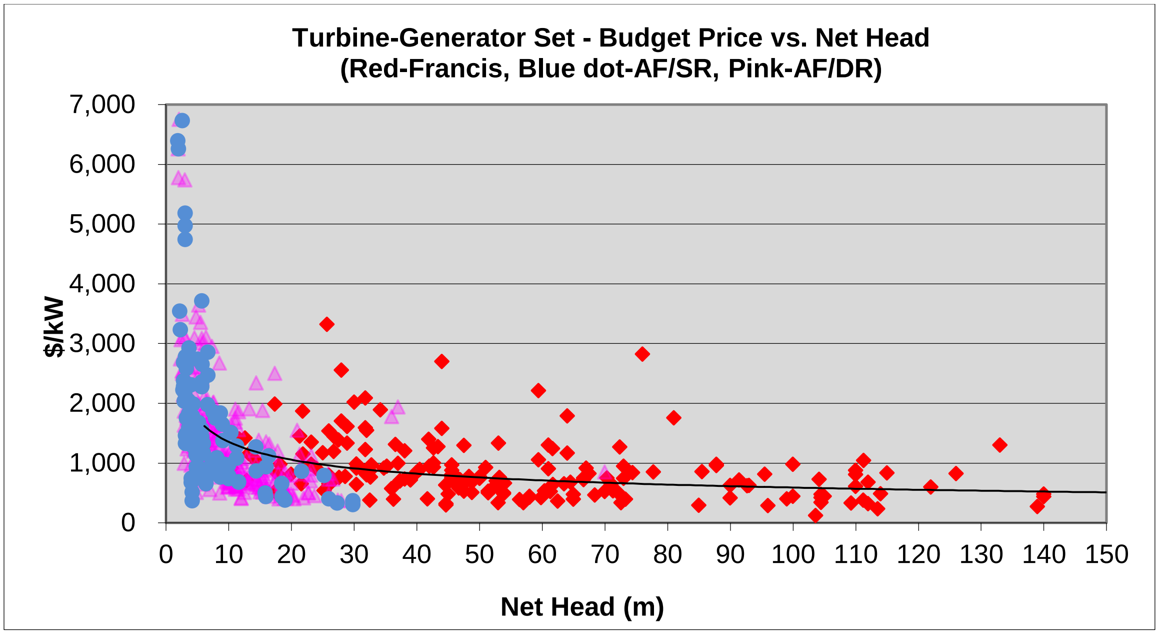


Figure 10. Trend of electromechanical cost vs. net head (aggregated for different turbine types).

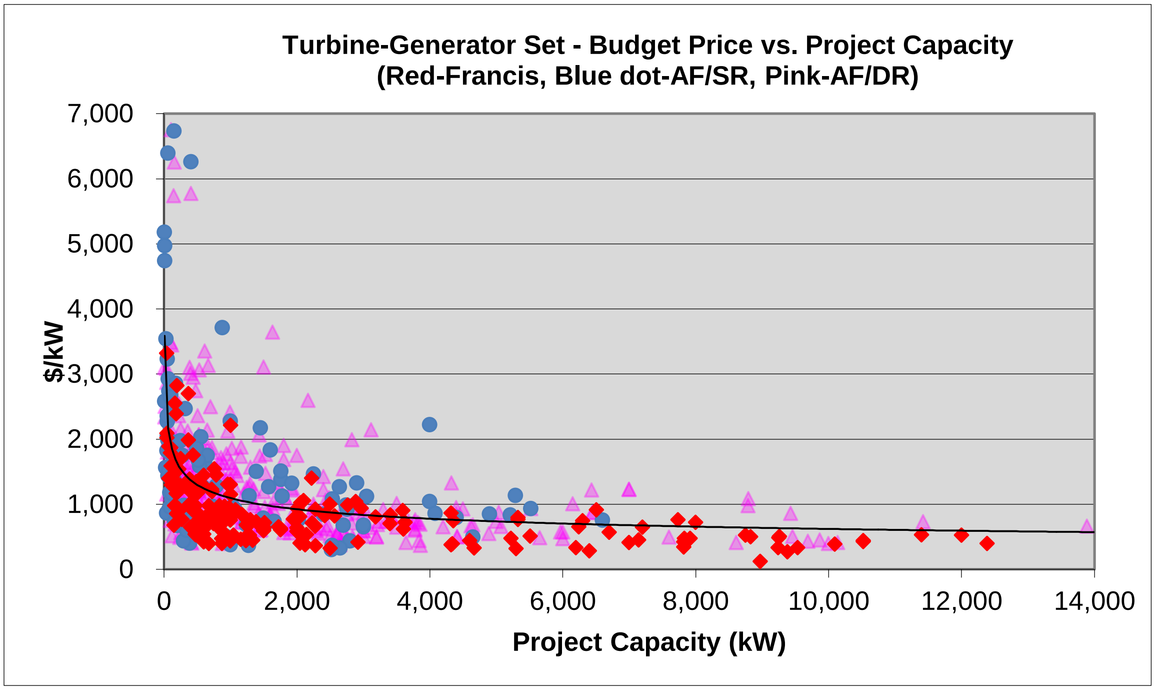


Figure 11. Trend of electromechanical cost vs. capacity (aggregated for different turbine types).

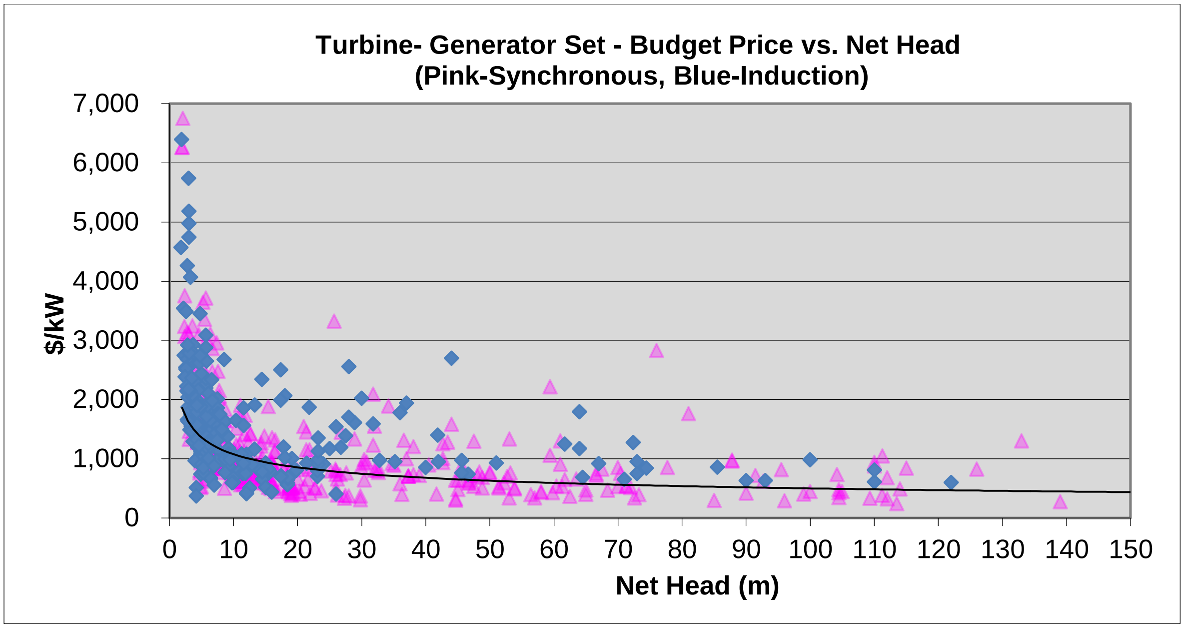


Figure 12. Trend of electromechanical cost vs. net head (aggregated for different generator types).

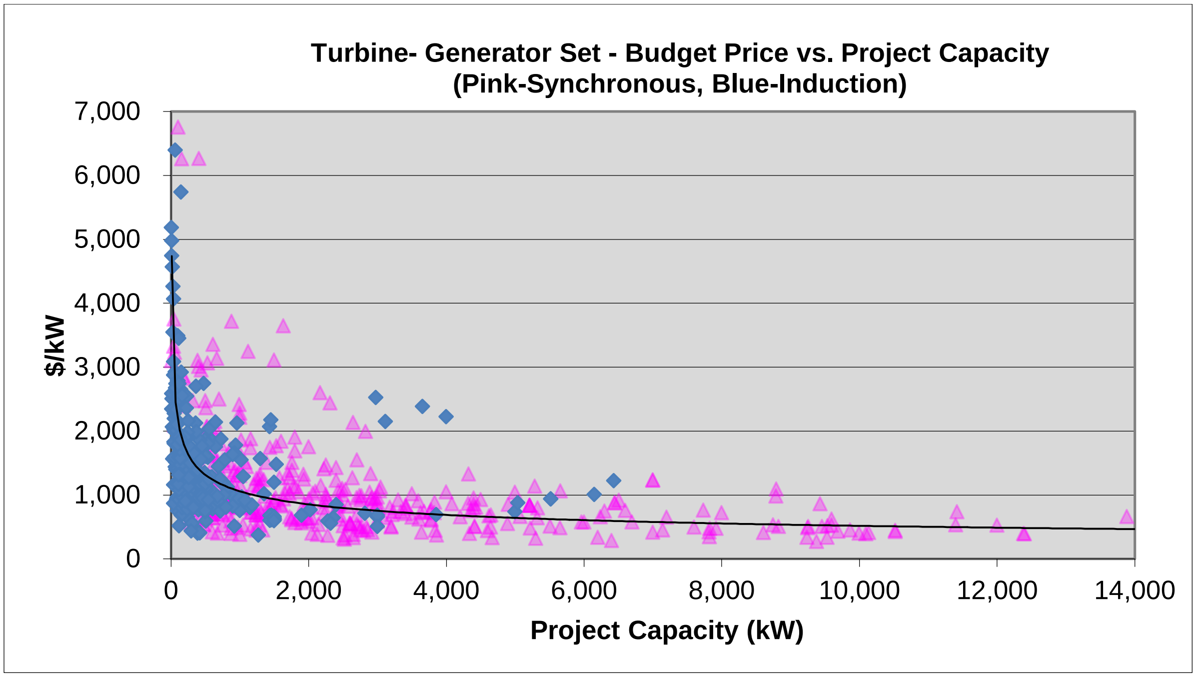


Figure 13. Trend of electromechanical cost vs. capacity (aggregated for different generator types).

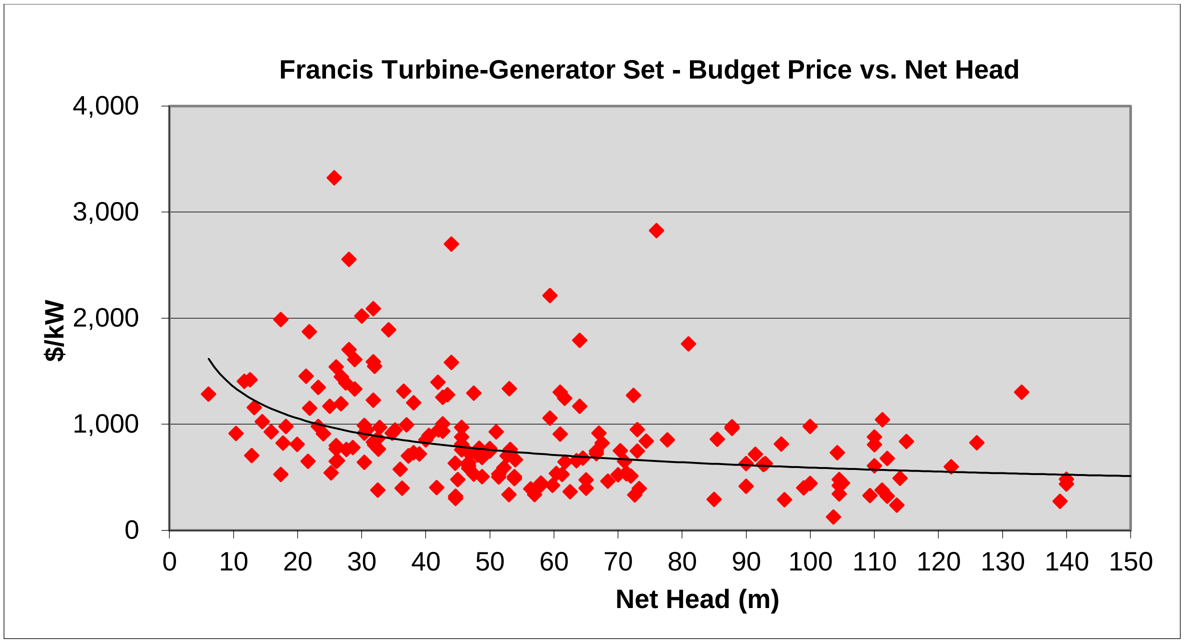


Figure 14. Francis turbine electromechanical cost vs. net head.

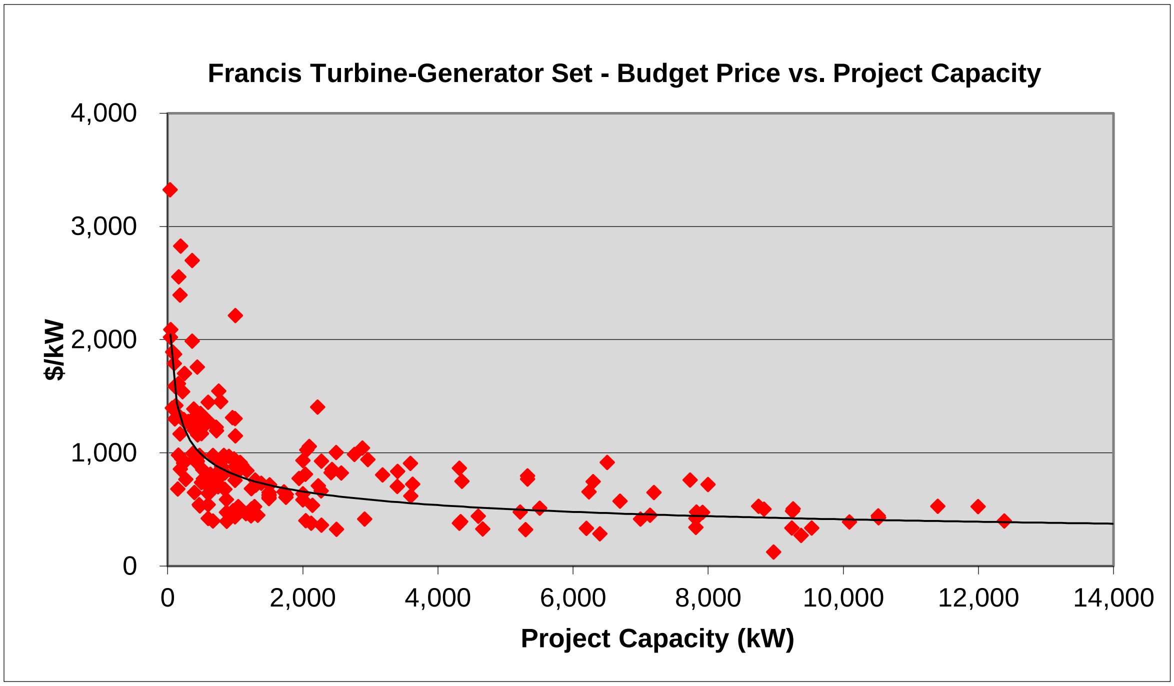


Figure 15. Francis turbine electromechanical cost vs. capacity.

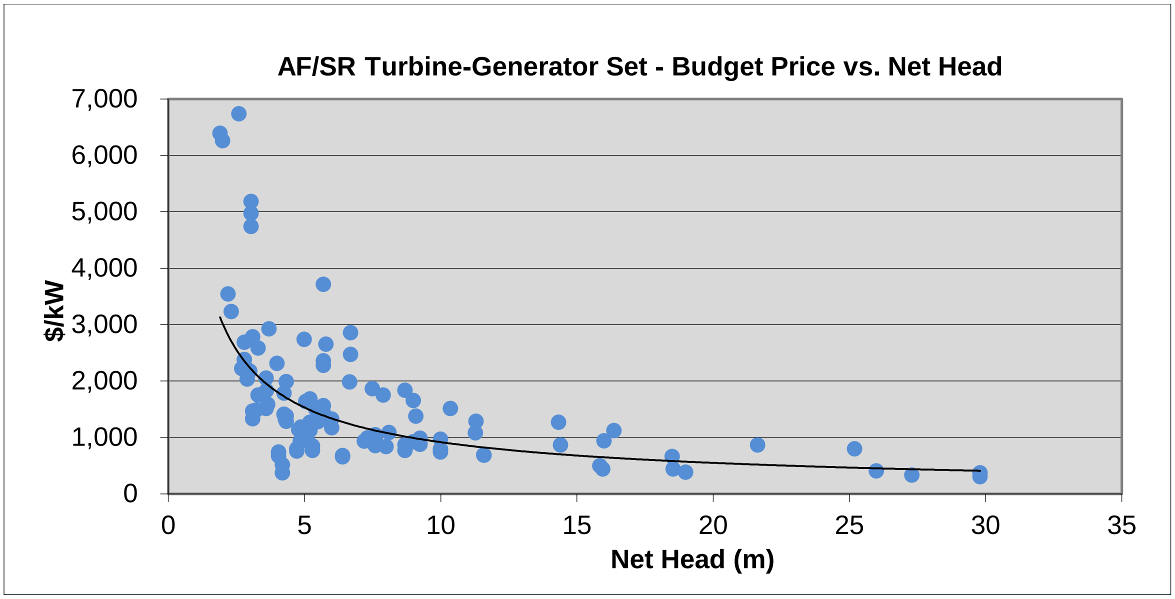


Figure 16. AF/SR turbine electromechanical cost vs. net head.

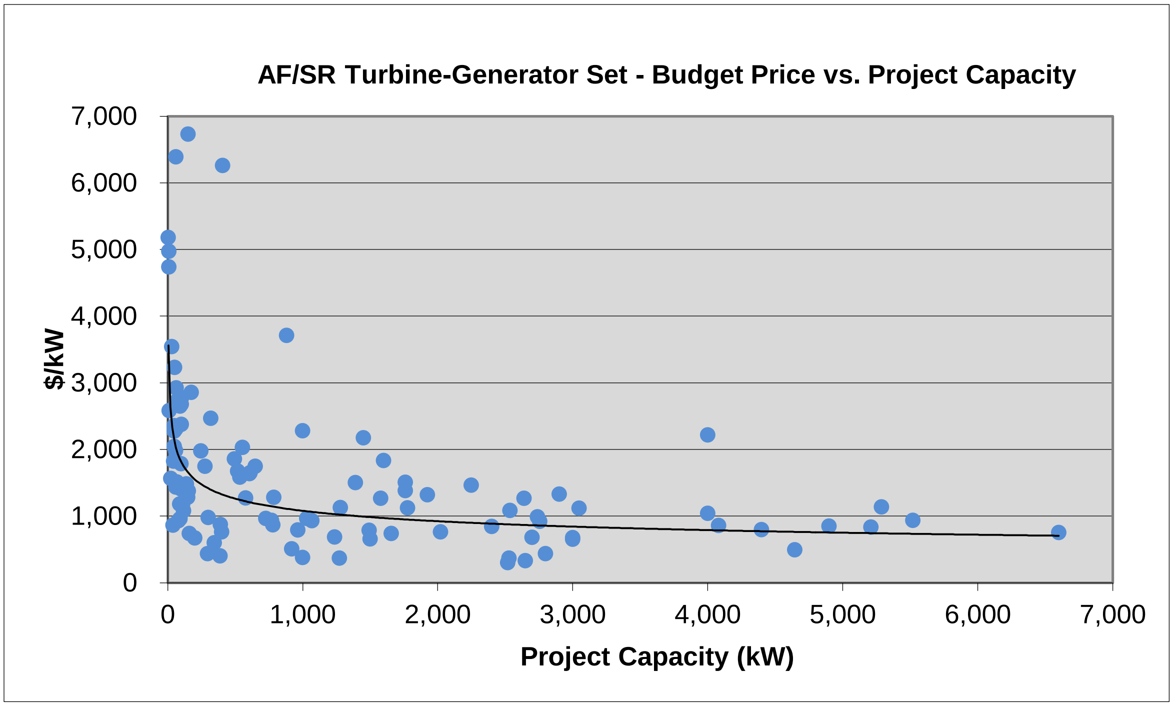


Figure 17. AF/SR turbine electromechanical cost vs. capacity.

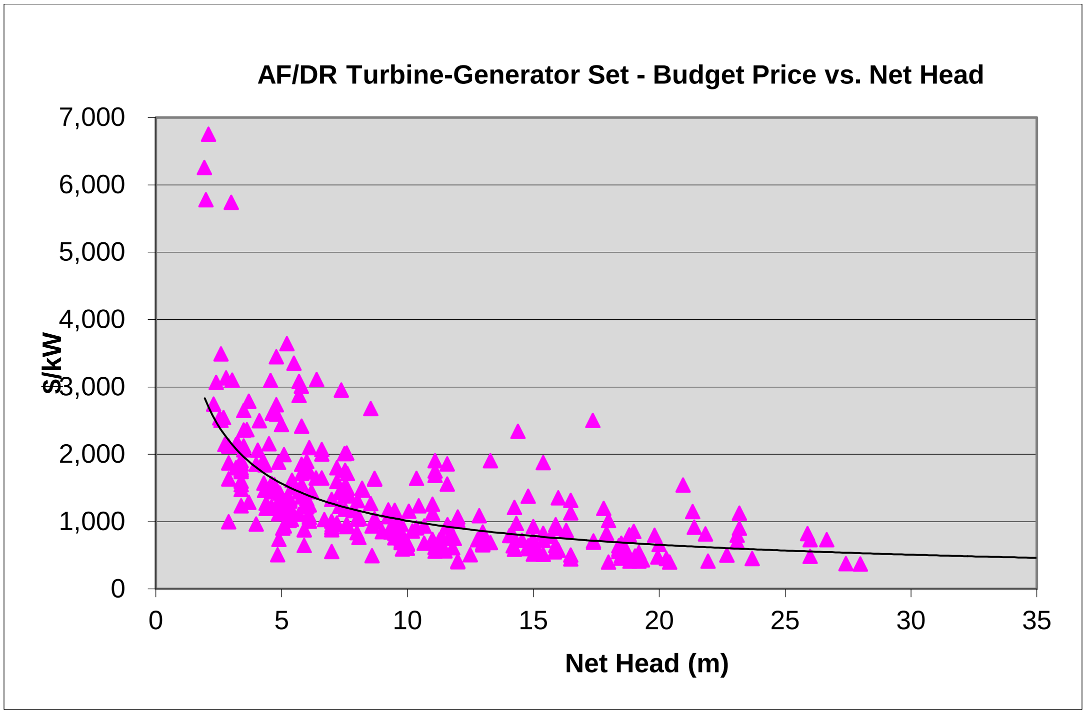


Figure 18. AF/DR turbine electromechanical cost vs. net head.

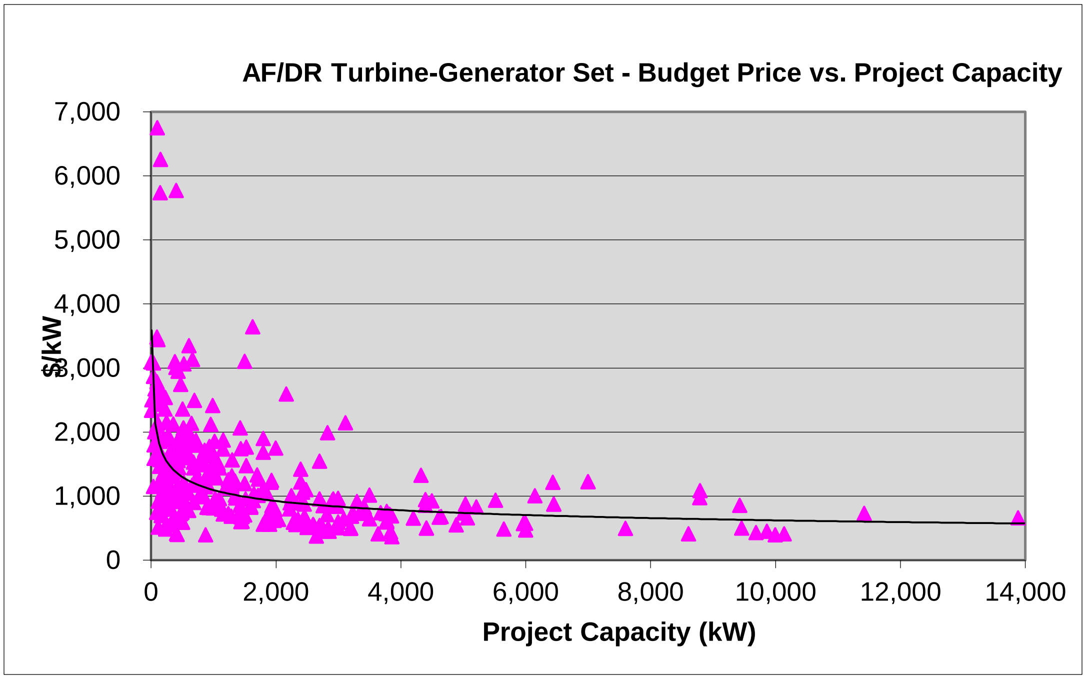


Figure 19. AF/DR turbine electromechanical cost vs. capacity.

4.3.2 Equipment Cost Equation

Based on the empirical cost equations found in the literature, a predefined equation for electromechanical cost is used for regression analysis:

$$C_{EM}(\$) = aH^{b}P^{c} \quad (13)$$

where H is the turbine net head in meter, P is the plant capacity in kilowatt, and a, b and c are the parameters to be determined through regression analysis.

The electromechanical per kilowatt cost would be

$$C_{EM}(\$/\mathrm{kW}) = aH^{b}P^{c-1} \quad (14)$$

Datafit 9.0 is used for regression analysis. The results are summarized in Tables 3 and 4, respectively, for regression analysis using total equipment costs and using per kilowatt equipment costs.

Tables 3 and 4 show that the regression results, using total equipment costs and per kilowatt equipment costs, do not follow the theoretical relationship between equations (13) and (14). The total equipment cost is certainly more dependent on the plant capacity (Table 3), while per kilowatt cost is more dependent on the net head (Table 4). Overall, the consistency of regression results is greater among the three turbine types using per kilowatt cost data than using total equipment cost data, although the coefficients' R^2 are lower.

Table 3. Regression results for total electromechanical costs ($US)

Turbine type	**Cost equations (2010 $US)**	R^2
Francis	$C_{EM}(\$) = 29379H^{-0.274}P^{0.660}$	0.86
Axial flow—DR	$C_{EM}(\$) = 1536H^{-0.193}P^{0.982}$	0.78
Axial flow—SR	$C_{EM}(\$) = 18872H^{-0.546}P^{0.761}$	0.84

Table 4. Regression results for per kilowatt electromechanical costs ($US/kW)

Turbine type	**Cost equations (2010 $US/kW)**	R^2
Francis	$C_{EM}(\$/\text{kW}) = 10513H^{-0.134}P^{-0.287}$	0.55
Axial flow—DR	$C_{EM}(\$/\text{kW}) = 11839H^{-0.646}P^{-0.137}$	0.58
Axial flow—SR	$C_{EM}(\$/\text{kW}) = 15311H^{-0.950}P^{-0.125}$	0.62

From Table 4 and Figures 20–22, it is clear that the cost of the AF-SR turbine and generator package is the most sensitive to the head, especially at the low-capacity end; while cost of Francis turbine-generator is the least sensitive to the head but more sensitive to the capacity. This is because AF-SR turbines are used in very low head and low power sites, while Francis turbines are used at the sites with relatively higher head. A slight increase in the hydraulic head would greatly reduce the per kW cost on the equipment; R&DD for cost reduction is pressing for low-head and low-power turbine-generator applications.

As discussed earlier, among the collected raw data, only a few projects with missing information (e.g., missing head figures) and a few with extremely high or low costs are excluded. More detailed data screening should be done to ensure the quality of the raw data and robustness of the regression results.

Since all these equipment cost data were sourced from a single manufacturer, the use of additional, diverse data sources is recommended to build equipment cost equations for more general application. In addition, Pelton turbine-generator cost data are not collected in this report.

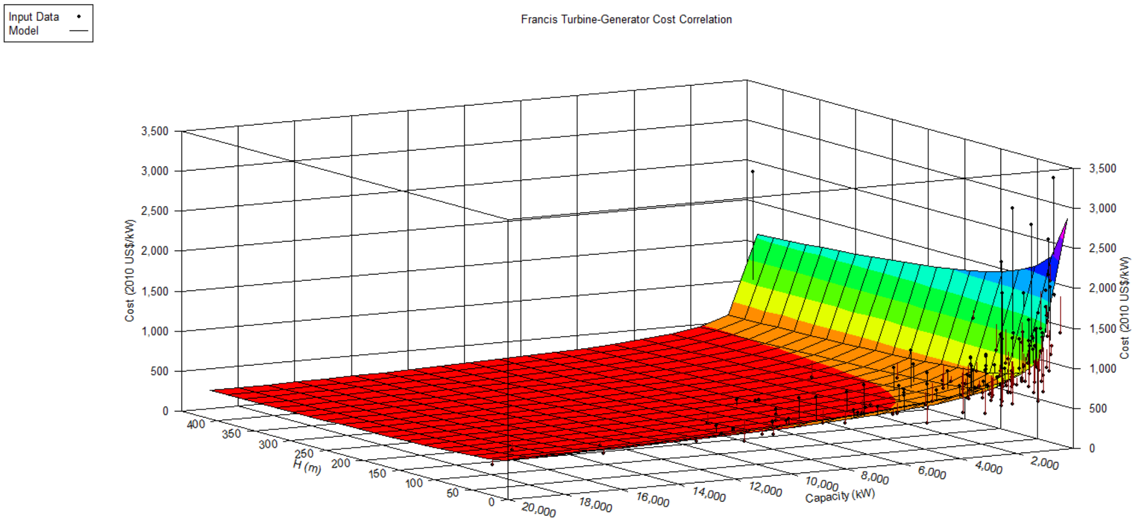


Figure 20. Three-dimensional plot for correlation of Francis turbine electromechanical cost ($/kW) vs. (H, P)

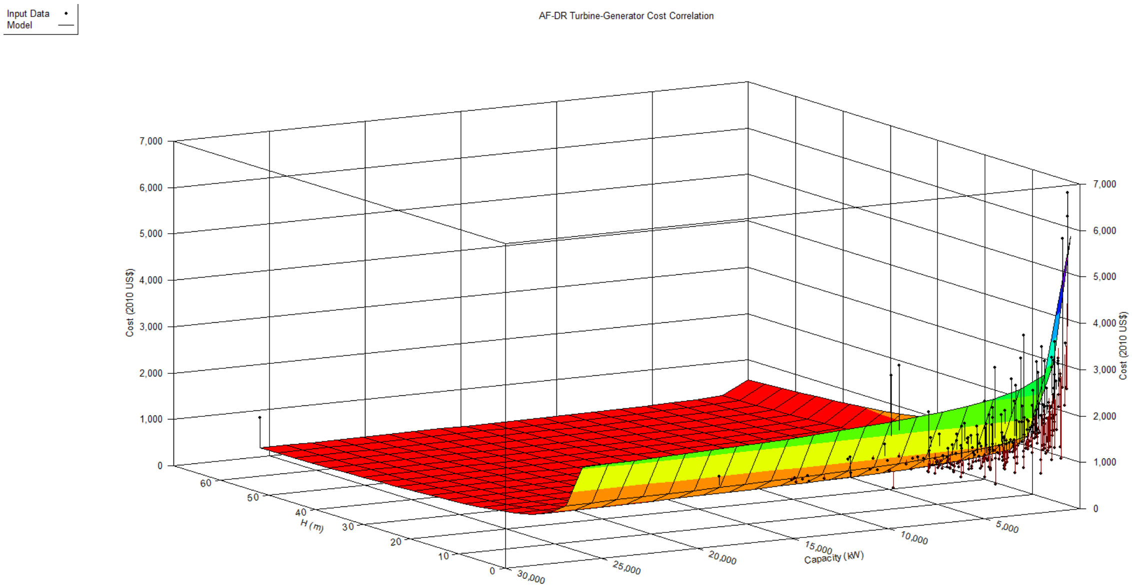


Figure 21. Three-dimensional plot for correlation of AF-DR turbine electromechanical cost ($/kW) vs. (H, P).

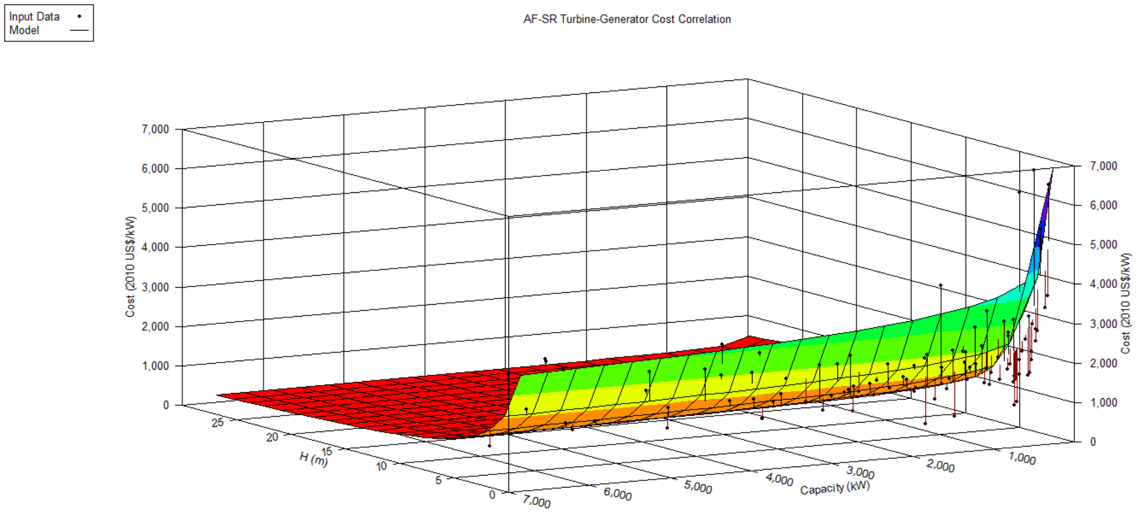


Figure 22. Three-dimensional plot for correlation of AF-SR turbine electromechanical cost ($/kW) vs. (H, P).

4.4 CAPITAL COST DRIVERS

Through capital cost breakdown analysis and regression analysis, the capital cost drivers are identified and summarized as follows:

- Electromechanical equipment is a major component of the total initial investment; its cost is sensitive to the head and capacity at a site, especially at low-head sites (at which the equipment cost may be greater than 50% of total project cost). The turbine is the key cost driver among the items of electromechanical equipment.
- For low-head and existing sites, turbine selection must be balanced between cost, efficiency, and reliability. Traditional turbine technologies can already achieve very high 85–93% efficiency. Pure improvements in turbine design for higher efficiency are not likely to have a significant impact on LCOE reduction. Hence, innovative technologies for low-head mini/micro turbines are demanded.
- For high-head projects, the turbine represents about 15% of total cost. There still exist opportunities to reduce LCOE through turbine efficiency improvement.
- Civil works cost is another major component of total project investment, especially for new sites, at which the dam might be one significant cost component and powerhouse construction another cost driver, especially for low-head projects.
- Among civil costs, the water conveyance system is the major cost component for high-head sites. On the other hand, the powerhouse is the major cost component for low-head site development.

This capital cost trending and regression analysis provides a preliminary but quantitative understanding of high-level cost items. Detailed cost breakdown analysis for a cost component (such as turbine cost) can be readily pursued in future R&D funding projects at DOE’s discretion. Such a detailed cost breakdown might be useful in quantifying the cost reduction impact of individual technology development efforts (such as the use of alternative low-cost materials for low-head turbine parts).

5.0 LCOE ANALYSIS AND LIFE-CYCLE COST DRIVERS

5.1 LIFE-CYCLE COST COMPONENTS

A life-cycle of a hydropower project can be divided into (1) development and construction stage, (2) O&M stage, and (3) end-of-life stage. Table 5 lists almost all the cost items during the life-cycle of a typical SHP. The end-of-life costs refer to those expenses incurred when a facility is demolished and removed, which is not common for hydro facilities; thus they are excluded from the total life-cycle cost and LCOE analyses in this report.

Table 6 lists actual and potential benefits during the life-cycle of an SHP. All realized benefits should be considered in life-cycle economic analysis and LCOE calculation, but they may not be explicitly expressed in a simplified LCOE calculation model, such as the model discussed in Section 5.2. For instance, governmental subsidies/grants during the development stage may be subtracted from the actual ICC amount; capacity and ancillary service values may be blended in an energy equivalent rate; and tax credits should be reflected in the tax rate used in LOCE calculation. The carbon market value may not be currently available; the residual value of the project is not taken into account in most hydro LCOE models, although the project is assumed to continually function at the end of the project life with major renovations and replacements.

5.2 ANNUAL O&M COST ESTIMATE

As shown in Table 5, the annual O&M cost for a hydropower project includes maintenance and interim replacement insurance, personnel and labor, taxes and duties, general operation and administration, and FERC and other annual charges (e.g., the annual payment for using a federal NPD facility).

Using the 29 sets of annual O&M cost data collected from FERC documents, a cost equation is regressed as shown in Figure 23. The annual O&M cost is closely related to the plant power capacity.

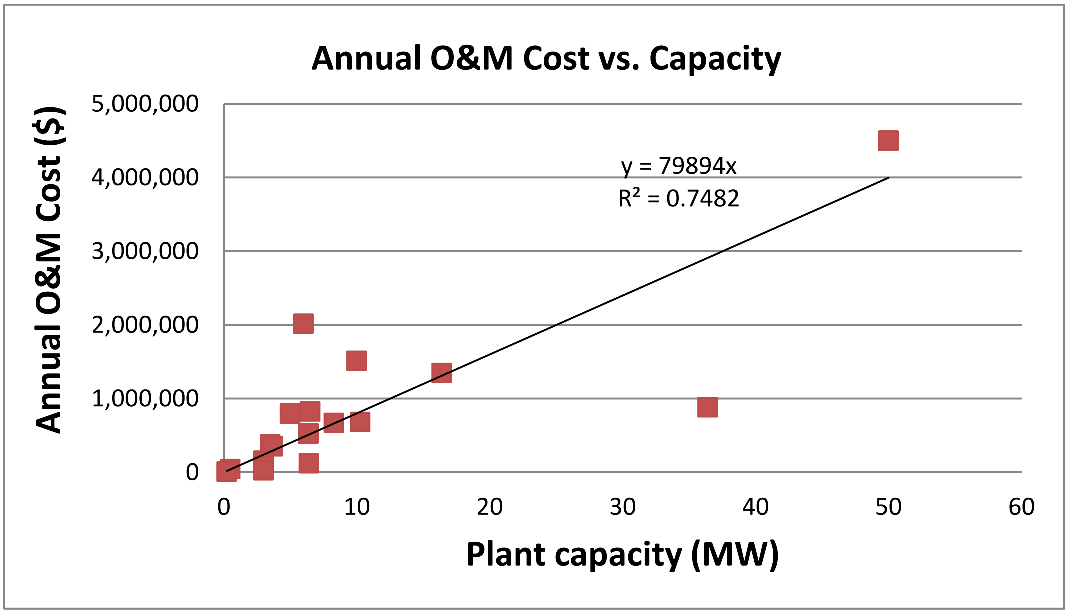


Figure 23. Annual O&M cost equation.

Table 5. Life-cycle costs of a hydro project

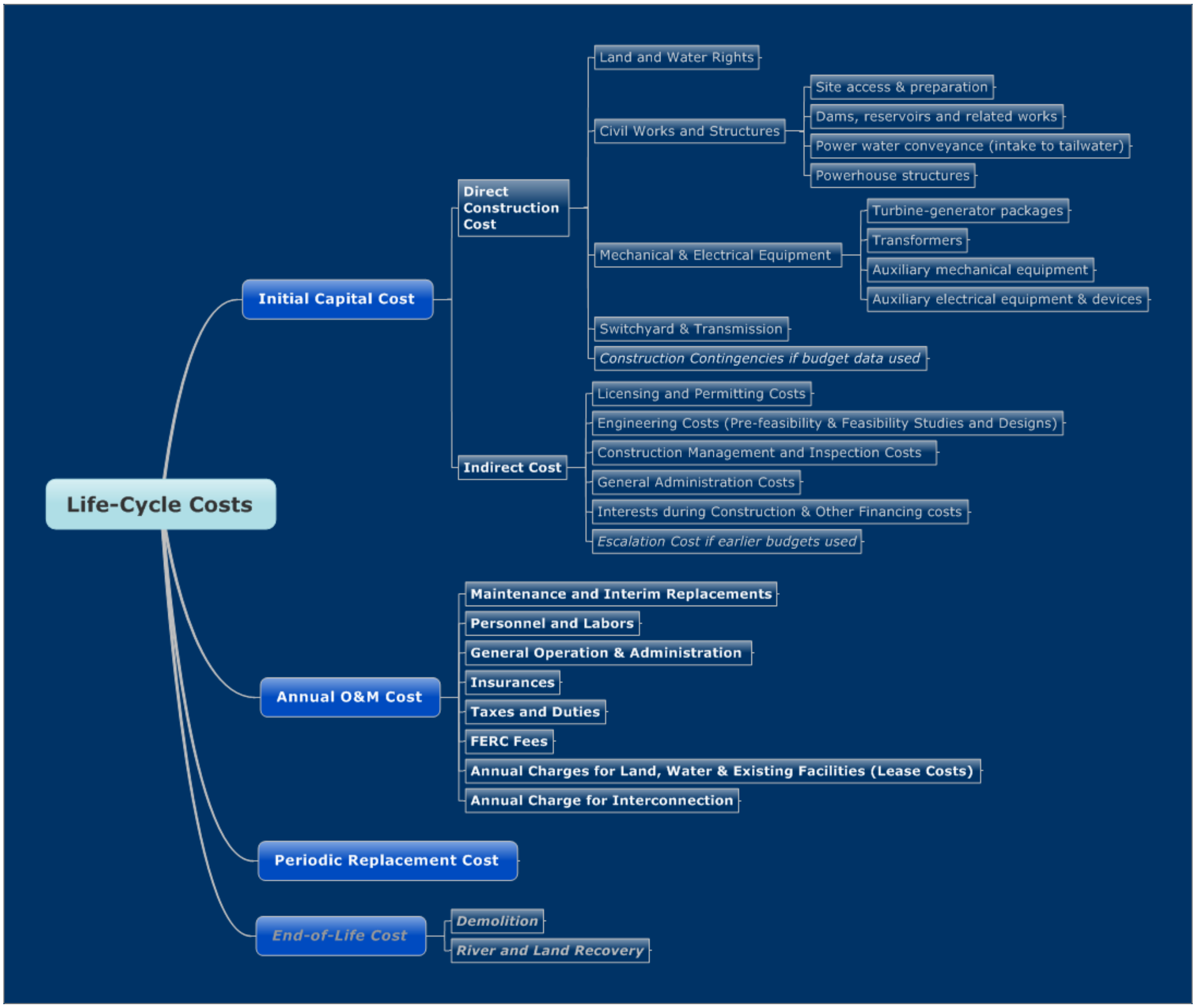
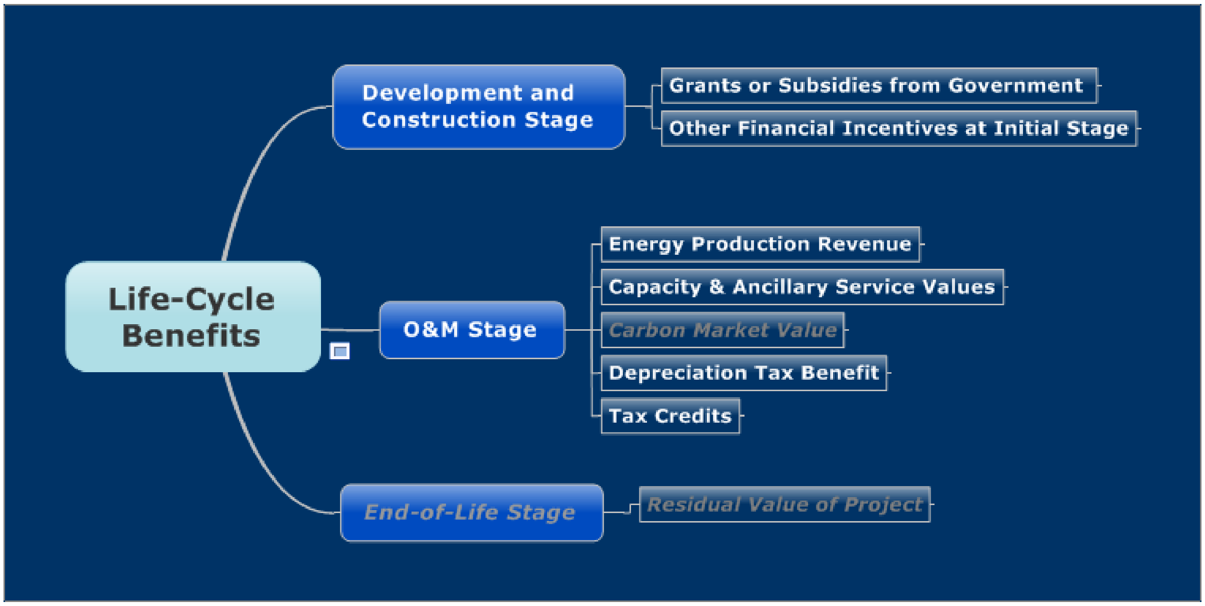


Table 6. Life-cycle benefits of a hydro project



5.3 LCOE CALCULATION

LCOE can be considered as the price of energy that will allow a generating project or technology to break even over its lifetime. LCOE analysis indeed involves a lifetime cost-benefit assessment for a generating project or technology, as defined in Eq. (15):

$$LCOE = \frac{Lifecycle\ cost}{Lifetime\ energy\ production} \qquad (15)$$

A simplified model for hydro LCOE calculation is developed and discussed in this section based on the model provided in the DOE funding opportunity announcement DOE-FOA-0000486 (DOE 2011). As shown in Eq. (16), the levelized present values of the total ICC (*ICC*), total O&M costs (*OMC*), and total periodic costs for replacement/rehabilitation (*RC*) over the lifetime of a project are incorporated into the life-cycle cost:

The variables in Eq. (16) can be described as follows:

(1) *AEP* = the average annual energy production at busbar, calculated by performing standard power studies using available flow and head data. The calculation should account for all hydraulic, mechanical, and electrical losses. Degradation of hydro generation capacity is negligible compared with a photovoltaic generation system. The variation in annual energy production depends mainly on yearly hydrological condition, and *AEP* should be averaged over multiple years.

$$LCOE = \frac{L(ICC) + L(OMC) + L(RC)}{AEP} \qquad (16)$$

(2) *ICC* = the total ICC of a project, including all direct and indirect costs (as shown in Table 5). In this model, the total amount of *ICC* is levelized via fixed charge rate (*FCR*). The equivalent annual cost of *ICC* is

$$L(ICC) = ICC \times FCR \tag{17}$$

FCR, also referred as the capital charge rate or capital recovery factor, represents the fraction of the total capital cost that is paid each year to finance the plant:

$$FCR = \frac{r}{1 - \frac{1}{(1+r)^N}} = \frac{r}{(1+r)^N - 1} + r \tag{18}$$

where r = the real discount rate, using r =5.5% in this report; N = project lifetime (years) as it is designed, usually N=50 years for an SHP.

Note: In most financing models for SHPs, ICC consists of both equity and debt. The levelized annual cost of *ICC* is the sum of equity annual payment and debt annual payment. The annual payment for the equity portion is calculated using the agreed/expected ROE (rate of return to equity); and the annual loan/debt payment includes the principal and interest paid each year, calculated by agreed loan terms and interests.

(3) *OMC* = O&M costs, as shown in Table 5, including employee salaries, insurance, standard parts, and so forth, as well as the costs for 3–5 year routine machine checkups and overhauls. The O&M costs in different years are summed and converted to a total present value:

$$PV(Total\ OMC) = \sum_{i=1}^{i=N} \frac{OMC(i)}{(1+n)^i} = Annul\ OMC \times \frac{1 - \frac{1}{(1+n)^N}}{n} \tag{19}$$

where i = 1, 2, …, N. It is then levelized via the *FCR*: $L(Total\ OMC) = PV\ (Total\ OMC) \times FCR$.

In Eq. (19), the nominal discount rate n is used because the O&M cost will occur in future years and thus the inflation rate should be considered. The nominal discount rate n equals the sum of the real discount rate, r, and the inflation rate, 2.5% (that is, $n = r + 2.5\%$).

Note: The projected *Annual OMC* is often estimated as a percentage of total *ICC*, which is assumed as the equivalent annual costs for O&M, that is, $L(OMC)$, and thus directly used in Eq. (16) for LCOE calculation.

(4) *RC* = periodic replacement and rehabilitation cost. Electrical and mechanical equipment tears up and wears out over time, and the civil works/structures may need rehabilitation after decades of operation. This model assumes that after every 25 years of operation, the turbine-generator will be replaced or rehabbed at 50% of the original cost; after every 10 years of operation, control and accessory electrical equipment will be replaced at 50% of original cost; and after every 50 years of operation, the penstock and intake structures will be completely rebuilt.

The periodic replacement costs are levelized as though the funds for the major overhaul (less asset depreciation) were paid into a reserve fund in the years prior to the replacement (which occurs in year T_R), so that

$$Annual\ Reserve\ Payment\ (ARP) = \frac{Replacement\ Cost\ \times (1 - D)}{T_R} \tag{20}$$

Here D = depreciation tax shield factor. These annual reserve fund payments (*ARP*) are then converted to a present value:

$$PV(ARP) = \sum_{i=1}^{i=T_R} \frac{ARP}{(1+n)^i} = ARP \times \frac{1 - \frac{1}{(1+n)^{T_R}}}{n} \qquad (21)$$

(where $i = 1,\ 2,\ ....,T_R$)

Then the present value of ARP is levelized via FCR: $L(RC) = PV(ARP) \times FCR$

The core LCOE assumption in this model is the real discount rate r. It is a compromise value resting between modeled discount rates for an independent power producer and a large regulated utility. This standardized rate is loosely realistic and does not reflect any expectations for project financial structure (DOE-FOA-0000486 2011).

5.4 RECOMMENDATION FOR LCOE UNCERTAINTY ANALYSIS

When developers, investors, regulators, and national or regional energy planners make their decisions associated with energy generation, they often use LCOE as the most important performance indicator to compare among renewable or traditional generation technologies, or to make choices among different projects and design alternatives. However, there are great uncertainties in the input parameters in hydropower LCOE calculations (even for an individual project). The uncertain parameters include discount rate, projected annual O&M cost, projected periodic replacement costs, initial construction cost, project lifetime, depreciation and amortizing years, and annual capacity factor. In currently established LCOE calculations, inputting single numbers for those parameters to get a definite LCOE number could give a misleading sense of certainty and even hide some key assumptions beneath the LCOE numbers. Misrepresentation of LCOE may result in a wrong or biased decision among different technology alternatives.

To account for variations and uncertainties among input parameters and the output LCOE, a stochastic model for LCOE analysis is proposed using a Monte Carlo simulation tool, similar to that developed by DOE to characterize solar photovoltaic cost uncertainty. To ensure an energy cost comparison is comparing “apples with apples,” uncertainty analysis and stochastic modeling should also be performed for hydro LCOE assessment. In such a model, parameters with great uncertainties would be treated as random variables. A probability distribution of random parameters would be developed based on best knowledge or available data, e.g., a probability distribution of capacity factor can be provided based on statistics for existing plants in the same region (power balance area and/or water basin); a probability distribution of discount rates can be based on projections made by the Financial Forecast Center (http://www/forecast.org/ffund.htm) for the Fed Funds interest rate. The stochastic model will result in probability distributions and statistics for LCOE output, from which the average LCOE, the upper bound (best case) and lower bound (worst case) of LCOE with confidence levels, will be reported for individual or aggregated projects. Sensitivities of input parameters to the LCOE result would be provided as well. The more informative and objective LCOE results would help decision-makers understand the risk level and risk sources.

This proposed future research aims to develop a leading LCOE analysis tool for the US hydro industry. The impacts from different assumptions (e.g., renewable incentives) and accounting methods will also be studied to obtain insights for many contingencies and problems incurred in regional planning or early stages of project development, such as the following:

- How will the renewable incentives (governmental grants and subsidies, carbon market value, and tax credits) affect the LCOE and thus affect hydro investment decisions?
- How will the capacity value and ancillary service benefits of hydro generators be appropriately reflected in LCOE calculations?

- How should equity and debt portions of the ICC be accounted for?
- How should periodic replacement costs be projected?
- What depreciation method and tax rates should be used?
- What are the different considerations for large utility owners and small private developers?
- How can the model be used to help in planning regional development or assessing basin opportunities?

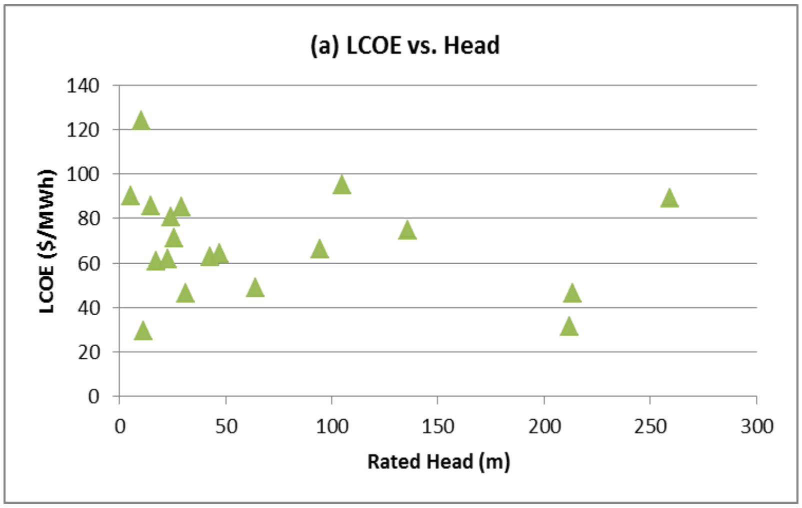
5.5 LCOE DATA TRENDING

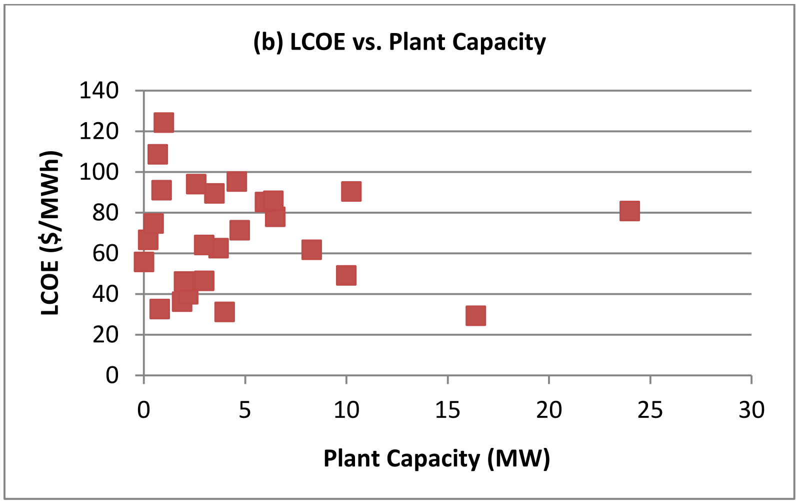
Excluding new site projects, 28 LCOE data sets were obtained from FERC *Order Issuing Licenses*, of which only 19 projects supply the head data. Figure 24 shows the project LCOE varies somewhat with the head, installed capacity, and capacity factor. Figure 24 (a) shows the LCOE tends to decrease with increasing head. Because the LCOE is reversely related to energy production, and annual energy production depends on both the capacity and the capacity factor, the relationships between LCOE vs. capacity (kilowatt) and LCOE vs. capacity factor are shown in Figure 24 (b) and (c), respectively. The LCOE seems more sensitive to the capacity factor than to the capacity itself (Note: Capacity factor is defined as the ratio of the total amount of energy the plant produced during a period of time and the amount of energy the plant would have produced at full capacity).

Regression analyses were tried, but no acceptable results were obtained for any correlation between LCOE and head, capacity, or capacity factor (all with very low R^2). The weakness in correlations may arise from (1) the limited size of sample data—more project data must be collected to perform a meaningful regression analysis for LCOE; or (2) complexity in LCOE calculation—compared with ICC, there are many more factors that could affect the LCOE of a project. Further data collection and LCOE modeling would reveal more evidence and insights for estimate and reduction of LCOE.

5.6 LIFE-CYCLE COST DRIVERS

LCOE was calculated for multiple projects using the method described in Section 5.3 and detailed project data was collected. It was found that ICC is the major contributor to LCOE (around 51–73%), annual O&M cost is the second-highest contributor (around 23–46%), and periodic replacement is the smallest contributor (3–8%). (The LCOE breakdown examples are shown in Figures 26 and 28 in Section 6.) In other words, ICC is the major driver of energy cost for small hydro generation, so any technology advancements or strategies that could reduce initial investment would help reduce LCOE. The influence of annual O&M cost saving is not insignificant to LCOE reduction, although there is no “fuel” cost for hydropower generation.





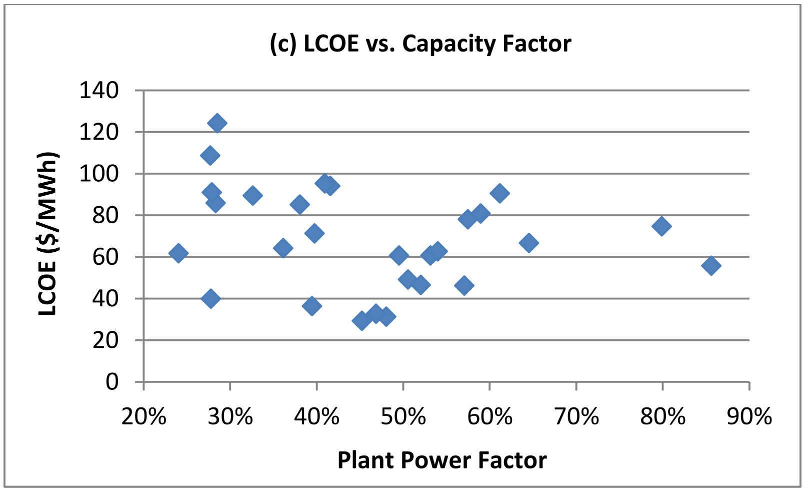


Figure 24. Trend of LCOE vs. head, plant capacity, and capacity factor.

6.0 COST COMPARISONS FOR NEW AND TRADITIONAL TECHNOLOGIES

To understand the cost performance of innovative small hydro technologies, this section analyzes and compares both LCOE ($/MWh) and ICC ($/kW) for two sets of projects:

- Turbinator—an integrated turbine system that eliminates powerhouse construction (for more detail see Section 7.2) vs. traditional turbine technologies (all with medium heads)
- A modular, removable powerhouse at existing locks for generation during navigation season only vs. traditional powerhouse designs (all with low heads)

6.1 TURBINATOR VERSUS TRADITIONAL TURBINE TECHNOLOGIES

Studies were performed to compare the cost performance of Turbinator turbines with those of traditional turbine technologies (Francis and Kaplan). All the LCOE data used in the comparison were calculated using the LCOE model described in Section 5.3 of this report, and the detailed capital and O&M cost data were obtained from FERC license documents and project developers. For this study, the projects within the medium range of hydraulic heads (96–155 ft) and small power scales (3–6 MW) were selected from the collected project database. The basic project information and calculation results are summarized in Table 7 and plotted in Figures 25 and 26.

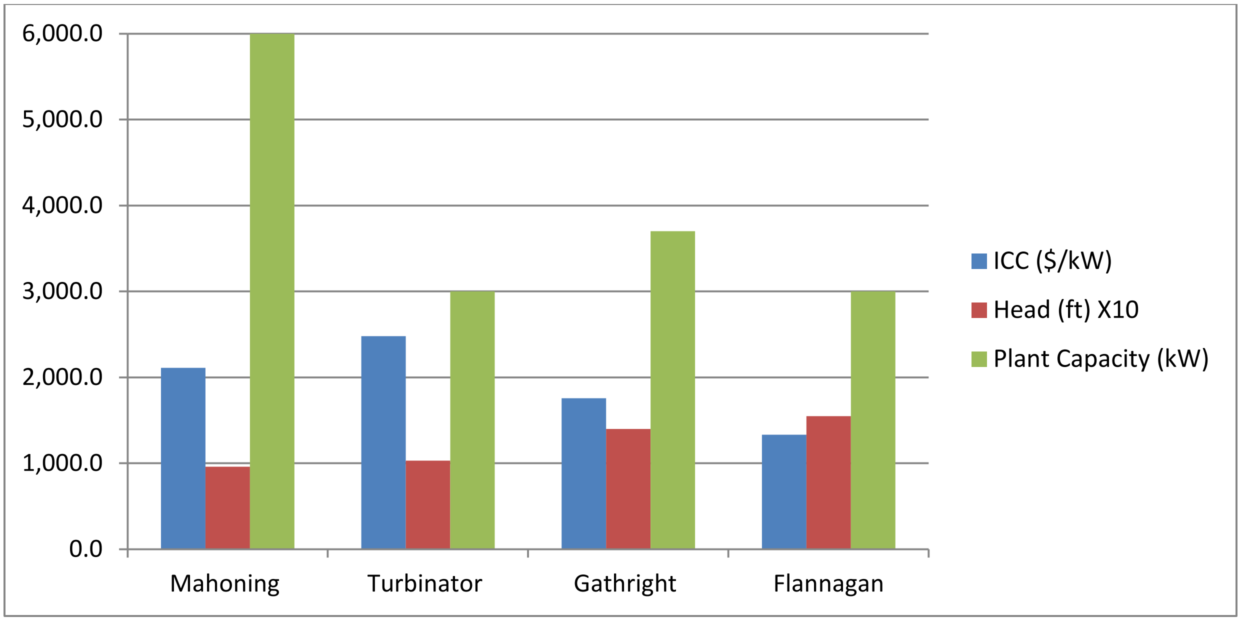
Table 7. Comparison for Turbinator project

Project name	Mahoning	Turbinator	Gathright	Flannagan
ICC ($/kW)	2,109.8	**2,480.9**	1,756.8	1,333.3
LCOE ($/MWh)	62.2	**46.4**	43.4	44.3
Head (ft)	96.0	**103.0**	140.0	155.0
ICC ($)	12,659,000.0	**7,442,792.0**	6,500,000.0	4,000,000.0
Plant capacity (MW)	6.00	**3.00**	3.70	3.00
Annual generation (MWh)	20,000	**13,675**	17,500	9,500
Capacity factor	38.1%	**52.0%**	54.0%	36.1%
Turbine types	V. Kaplan	**Turbinator**	Francis	Francis
Project/site type	Existing dam	**Existing canal**	Existing dam	Existing dam

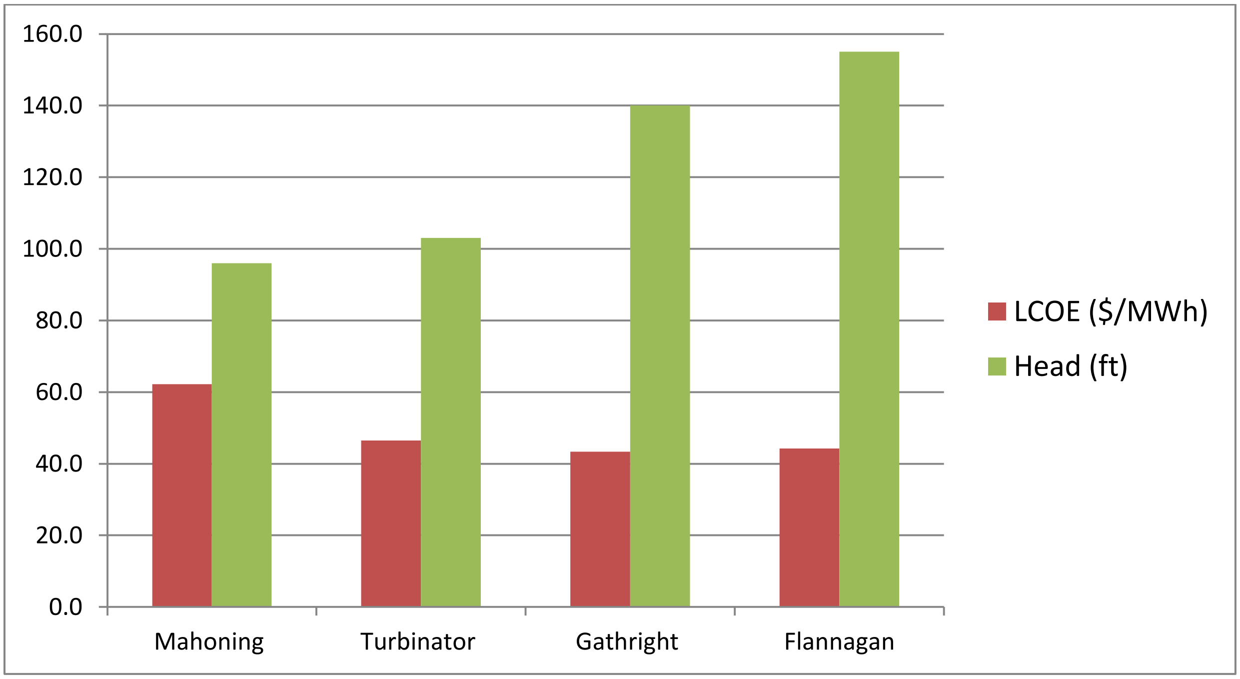
Among the projects listed in Table 7, the Turbinator project initially spends more in terms of cost per kilowatt of capacity. The cost savings on powerhouse construction seem to be being offset, because

- The turbine-generator package is purchased and shipped from Europe.
- The design includes desirable but more expensive features for a control and automation system.
- Because it is the first application of Turbinator in the United States, there is more expense for studying and testing.

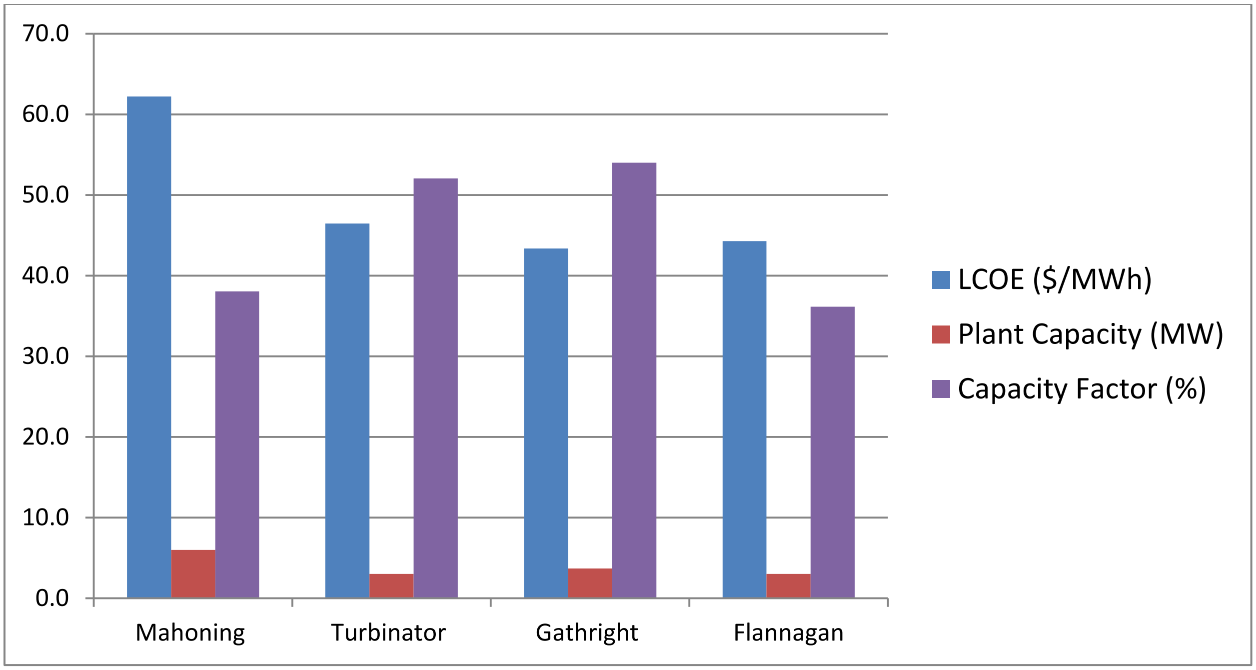
However, the LCOE of the Turbinator project is modest, benefiting from lower projected operating expenses because of the absence of on-site routine duty staff. Figure 25 (b) charts the correlation between LCOE and head.



(a) ICC vs. head and plant capacity



(b) LCOE vs. head



(c) LCOE vs. plant capacity and capacity factor

Figure 25. Cost comparison for Turbinator vs. traditional turbine technologies (all with medium head).

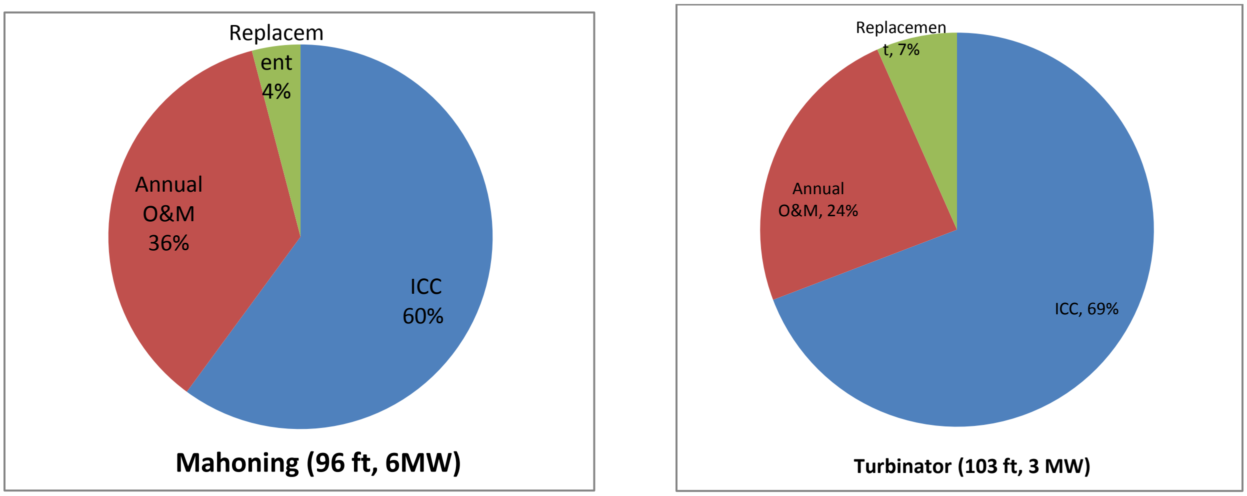


Figure 26. LCOE components of Turbinator and other medium-head projects.

6.2 REMOVABLE POWERHOUSE VERSUS TRADITIONAL POWERHOUSE DESIGN

Studies were performed to compare the cost performance for the emerging technology of removable powerhouses with traditional powerhouse designs. All the LCOE data used in the comparison were calculated using the LCOE model described in Section 5.3, and the project detailed capital costs and O&M costs were obtained from FERC license documents and engineering consultants. For this study, the projects within the low range of hydraulic heads (10–18 ft) and similar power scales (5.0–10.3 MW) were selected from the collected project database. The basic project information and calculation results are summarized in Table 8 and plotted in Figures 27 and 28.

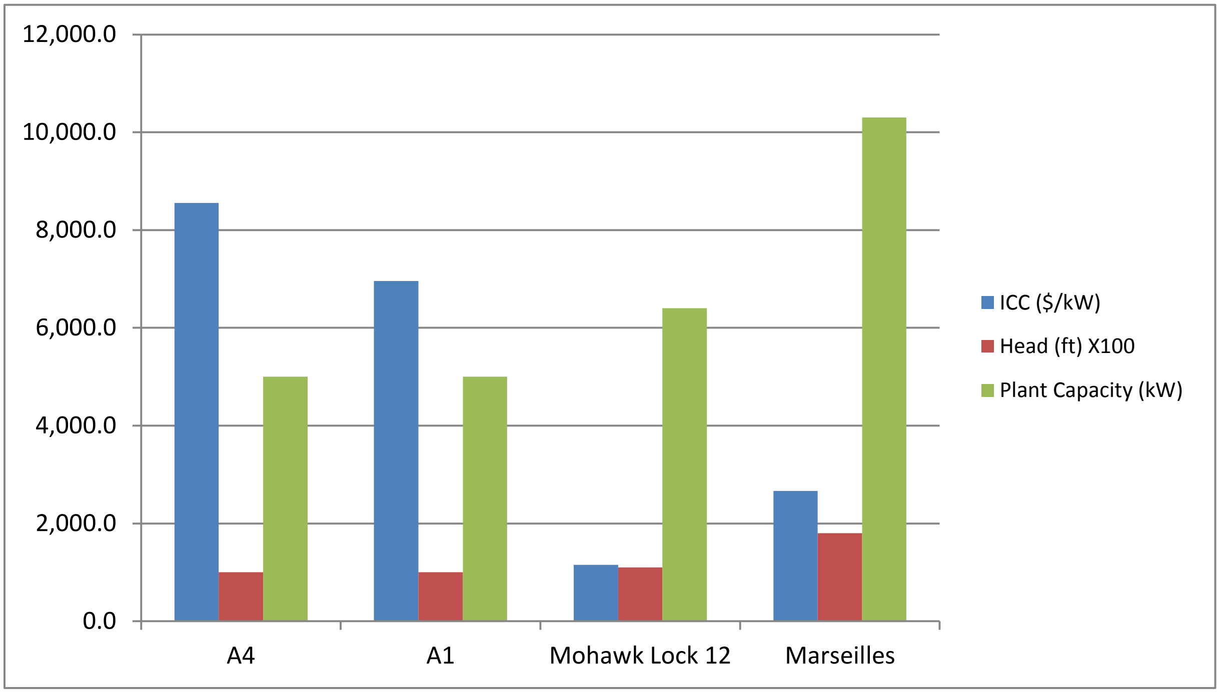
The removable powerhouse project initially cost less because almost no civil work was required, but the LCOE was not correspondingly low because of the shorter lifespan of the removable facility and higher maintenance costs. Figure 27 shows a good correlation between the ICC ($/kW) and LCOE ($/MWh) with the project head and capacity, which indicates the costs of low-head projects are more sensitive than others to site features (head, capacity and utilization of existing facility).

Table 8. Comparison for removable powerhouse project

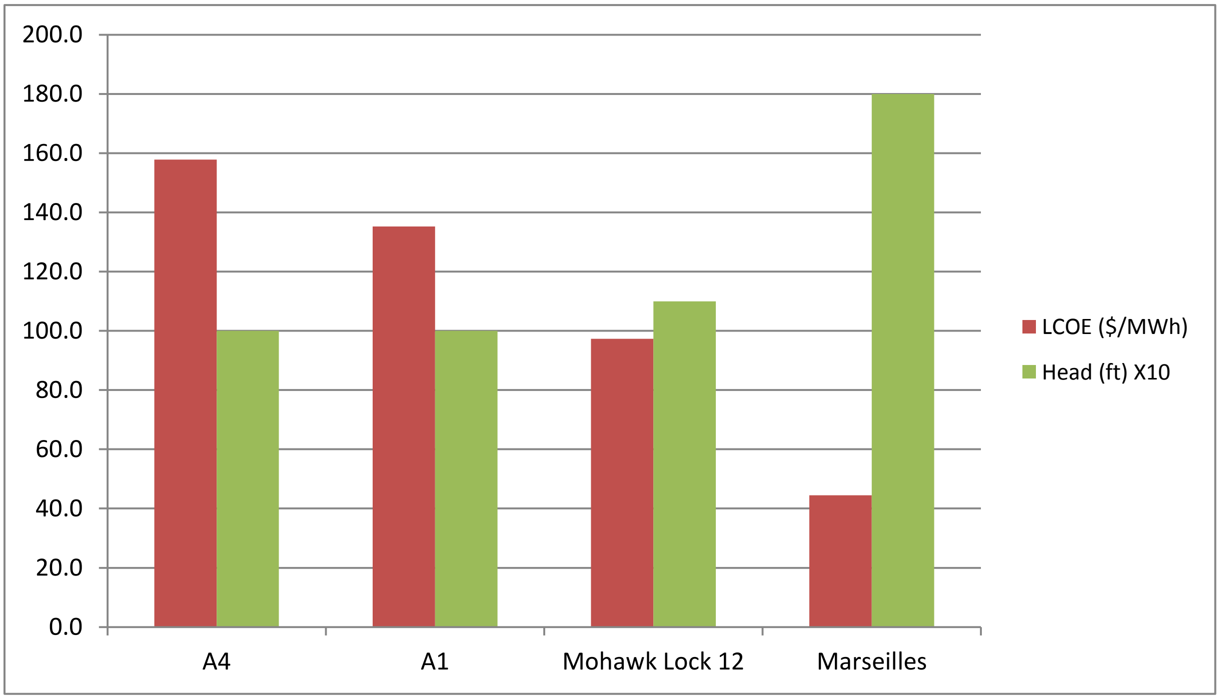
Project name	**A4**	**A1**	**Mohawk Lock 12**	**Marseilles**
ICC ($/kW)	8,557.9	6,957.6	**1,156.3**	2,665.4
LCOE ($/MWh)	157.8	135.2	**97.3**	44.5
Head (ft)	10.0	10.0	**11.0**	18.0
ICC ($)	42,789,594.9	34,787,945.8	**7,347,400.0**	27,347,400.0
Plant capacity (MW)	5.0	5.0	**6.4**	10.3
Annual generation (MWh)	21,900	21,900	**12,461**	55,000
Capacity factor (%)	50.0	50.0	22.4	61.2
Project life (year)	50	50	**20**	50
Turbine type	Kaplan	Kaplan	**Modular PH**	Pit Kaplan
Project/site type	New dam	Existing dam	**Existing lock dam**	Existing dam

6.3 COST PERFORMANCE OF NEW TECHNOLOGIES

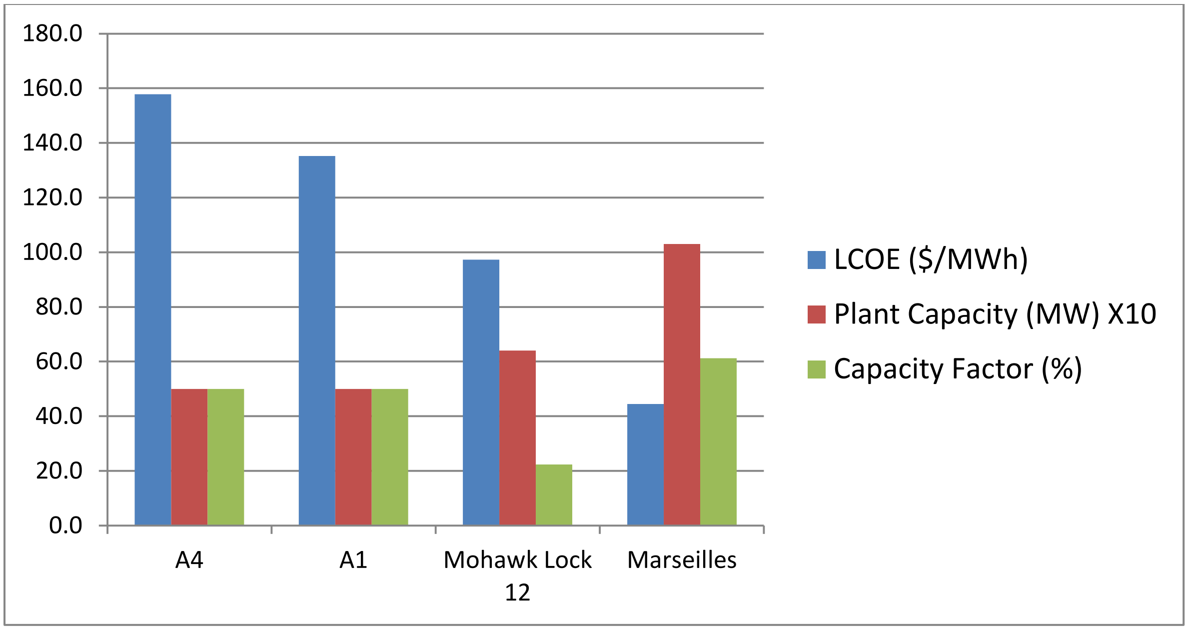
The initial investment is the key cost driver for any project with new or traditional technologies. However, ICC ($/kW) alone cannot fully represent the cost-effectiveness or cost performance of a project or a technology. The LCOE, taking into account lifetime costs and energy production, would be a more important indicator of the cost-effectiveness of a new technology. Thus, as already suggested in Section 5.4, a statistical model for LCOE analysis should be developed for uncertainty and contingency consideration and quantification.



(a) ICC vs. head and plant capacity

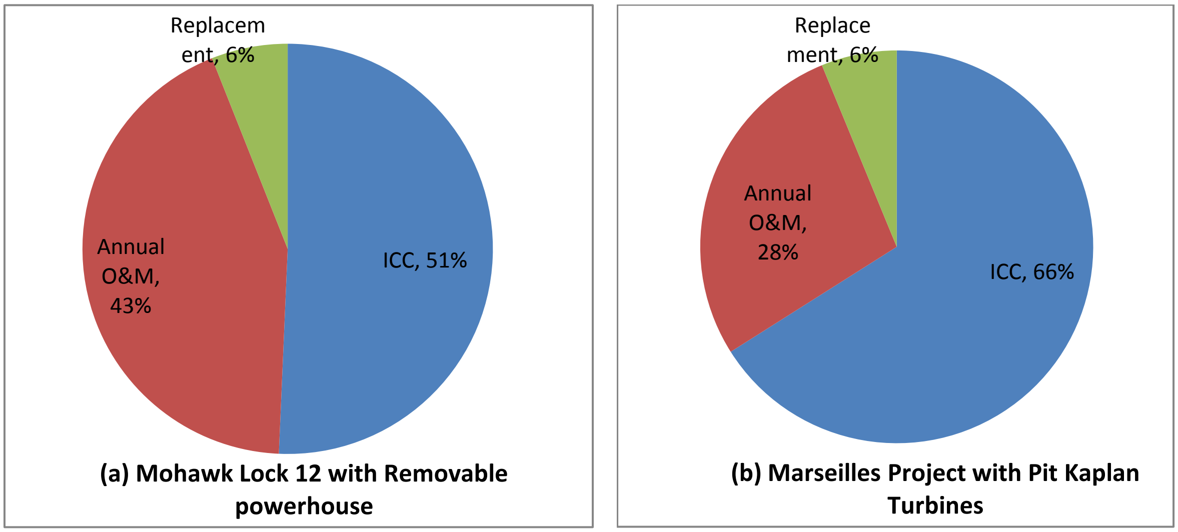


(b) LCOE vs. head



(c) LCOE vs. plant capacity and capacity factor

Figure 27. Cost comparison for removable powerhouse vs. traditional powerhouse designs (all with low heads).



(a) Mohawk Lock 12 with Removable powerhouse

(b) Marseilles Project with Pit Kaplan Turbines

Figure 28. LCOE components of low-head projects.

7.0 COST-CUTTING TECHNOLOGIES AND TRLS

The viability of a small hydro project is usually determined by the energy to be produced (i.e., revenue) vs. the funds to be invested (i.e., cost), and much of the recent technical effort in the small hydro industry has been focused on cost-effectiveness and environmental performance. To this end, potential cost-cutting technologies and their technology readiness levels (TRLs) are reviewed and discussed in this section, which focuses on the key cost drivers identified in previous sections.

7.1 TRL DEFINITIONS IN THE SMALL HYDRO DOMAIN

TRLs are defined to measure the maturity of a technology. The popular definition of nine-level TRLs was based on aerospace technology development and uses descriptions that are not suitable for small hydro technology development procedures. Therefore, TRLs for the small hydro domain are adjusted, as shown in Table 9, to evaluate the maturity of the small hydro cost-cutting technologies discussed in this report.

Table 9. Definition of TRLs in the small hydro domain

	Descriptions
TRL1	Ideas to form R&D proposals
TRL2	Formally funded R&D proposals
TRL3	Conceptual design—technical feasibility demonstration through theoretical analysis and/or computer modeling
TRL4	Physical model validation in laboratory
TRL5	Field validation and demonstration
TRL6	Pilot plant operation
TRL7	Verification and validation completed and ready for commercialization
TRL8	Successfully applied and well performed in some countries/regions
TRL9	Mature technology—good performance has been proved for decades

7.2 COST-CUTTING TECHNOLOGIES

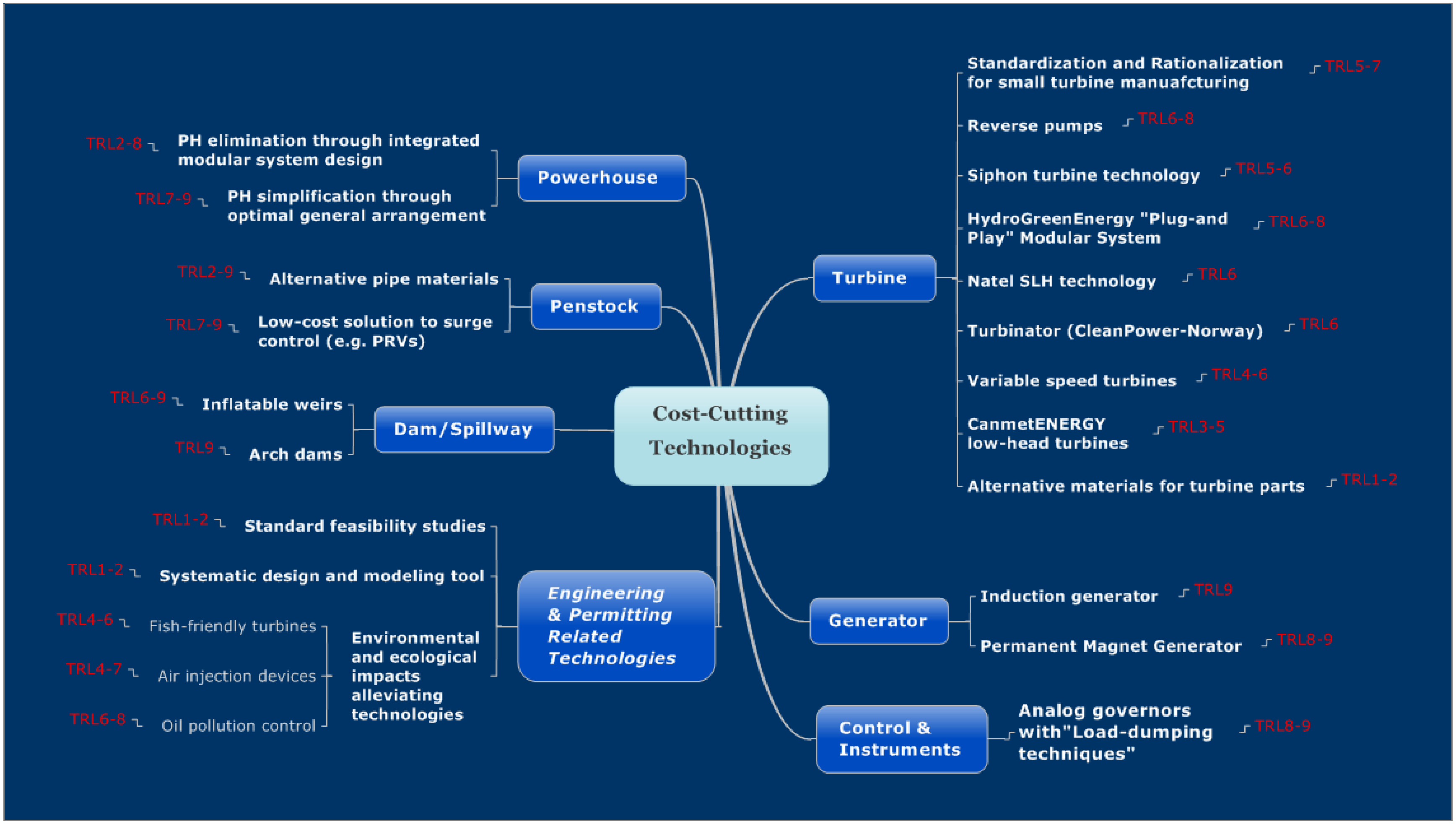
Based on the identified cost drivers for small hydro generation, potential cost-cutting technologies are listed and categorized in Table 10, in which the TRLs are largely indicated. This section explains and reviews the listed technologies. Knowledge has been acquired based on different resources, including books, magazines, web sites, and personal experiences; some specific references are omitted owing to respect for business-sensitive information.

7.2.1 Turbine Cost-Cutting Technologies and Strategies

The turbine is the most costly item of equipment and a major cost component of the total capital investment. The total project cost and LCOE may be considerably reduced through turbine cost reduction. The current and emerging technologies/strategies for cost-cutting purpose are reviewed below (Paish 2002).

- **Standardization and rationalization of turbine manufacturing:** Traditional turbine technologies for low to medium heads have achieved 85–93% efficiency, leaving little room for efficiency improvement through further improvements in design and technologies. Standardization of turbine design and manufacturing is more likely to reduce turbine cost by economies of scale. Standard turbines are applicable to mini/micro sites at which cost is more sensitive than efficiency. AF Kaplan turbines, particularly, have high efficiencies across wide ranges of flow and head. In other words, one standard-size turbine can be applied at different sites with a wide range of flow and head conditions with little sacrifice in efficiency. This feature makes it possible to keep an inventory of a series of standard-size small turbines for cost-competency and quick availability. However, at relatively larger sites, the turbine still needs to be individually sized and the major parts (runner and high-pressure parts) need to be individually designed, although the design procedure, general arrangement, and most elements can be standardized for quality assurance and cost reduction.
- **Siphon intake and variable-speed siphon propeller turbine:** Siphon intake is a good solution for powering NPDs to reduce civil work costs, and it allows for the penstock and equipment to be prefabricated and prepackaged. The micro-siphon turbine technology, developed by IT Power with Derwemt Hydro and GP Electronics, has been deployed in the UK for around a decade. It is a low-cost solution for sites with existing dams and extremely low heads (1–3 m), aimed at power output in the range of 5–100 kW. A suction pump primes the siphon by drawing the upstream water level up to the intake until it starts flowing down through the turbine. There is no need for an intake shutdown valve; instead, the machine is shut down by opening a valve and breaking the siphon. In this turbine system, the generator is installed above the water level, and variable-speed control allows the turbine to extract maximum power in different hydraulic conditions. To promote the siphon design, more studies might be needed to understand whether the air intervention would cause problems during the operation or negatively impact on the cavitation and efficiency of the turbine.

Table 10. Potential cost-cutting technologies and technology readiness levels



- **Natel Schneider Linear HydroEngine (SLH) turbine system (US):** The SLH system is an impulse type of turbine, designed for low-head applications. The product line offers two standard sizes: The SLH10 is rated to a maximum power of 50 kW at 20 feet (6 meters) of head, passing 38.5 ft3/s (1.1 m3/s), and the SLH100 is rated to a maximum power of 500 kW at 20 feet (6 meters) of head, passing 357 ft3/s (10.1 m3/s). This technology has been tested by commercial pilot projects in Indonesia and the United States (Buckeye, AZ). The SLH has 10,000 hours of test operation and a few pilot plants (http://www.natelenergy.com). Currently, it lacks a performance assessment (including durability, reliability, and lifespan) provided and validated by an independent party—a common phenomenon for innovative technologies developed by private and emerging companies.
- **Reverse pumps:** These mass-produced pumps are used for reverse operation as turbines. This practice has been used for several decades and could be further examined for cost reduction benefit vs. efficiency sacrifice.
- **Turbinator (CleanPower–Norway):** The Turbinator is a compact unit integrated a low-head axial turbine with a permanent magnet synchronous generator. The turbine, designed by Evald Holmén of Sweden, has fixed runner blades with adjustable or fixed wicket-gates. In the generator, designed by CleanPower, the rotor is fixed directly to the outside of the turbine runner (tip driven) so that the entire turbine-generator assembly is one single rotating piece. The fully sealed generator allows the unit to be submerged and cooled by water flow. On the upstream side, the Turbinator has a simple bolted flange connection to the pipe, and downstream is a suction pipe for water release. The powerhouse is eliminated and other civil construction minimized. The first full-scale demonstration model was piloted at the Hegset dam in Norway in August 2010 for 28 m of design head and 280 kW of capacity. Now a 3 MW project is to be installed at the North Unit Irrigation District’s Main Canal, in Culver, Oregon. Earth By Design, Inc., and its partners (including ORNL) are undertaking the planning, design, engineering, construction, operation, performance monitoring, and cost/benefit assessment of the project.
- **HydroGreenEnergy “plug-and-play” technology (US):** HydroGreen Energy, LLC, is a privately-held renewable energy development company with proprietary hydropower technology. The technology is a modular small hydro system combining a modified bulb turbine design, which minimizes the civil work, time, and costly installation process of conventional hydropower systems. Deployment is focused at low-head NPDs and lock sites (head less than 30 ft); presently 28 hydropower projects in 14 states are ongoing.
- **Variable-speed turbines (Canada):** This next-generation turbine is designed to operate at optimal rotational speed with varying flow rates to increase efficiency, improve fish survival, and reduce overall costs. The variable-speed turbine was tested at Hydraulic Machinery Laboratory (LAMH) at Laval University, and a 300 kW prototype turbine was manufactured and installed in Ontario, Canada (NRCan 2007, Warren-Nickle’s Network 2007).
- **CanmetNERGY low-head turbines:** An unregulated vortex propeller turbine was proposed by Natural Resources Canada’s CanmetENERGY and its industry and university partners in Canada and France. This turbine design would eliminate costly civil work by using larger but simpler runners, rotating slowly like windmills; it would promote applications at navigation canals, irrigation canals, and municipal intakes. It will be tested at a site in France after being tested in LAMH.
- **Alternative materials for turbine components:** with advances in materials science and technology, plastics, carbon fiber composites, and other new anti-corrosion materials offer possible low-cost turbines for low-head micro-scale development. Although an informal survey revealed a 50 kW Pelton turbine made from polycomposite materials has been installed at a site,

so far there is no formal public report regarding the use of low-cost alternative materials for turbine components. The durability and deflection at high rotational speed and flow velocity are the major issues with plastics and Fiberglass. But these issues won't exclude the future application of these materials in low-speed turbines.

7.2.2 Generator Cost-Cutting Technologies

- **Induction generator:** For pico/micro/mini -scale hydro, a stand-alone induction generator system has been successfully developed using low-cost electronic controls. Two systems were developed: one provides dc power to charge batteries and the other provides standard ac power for general use. The frequency control is precise, allowing the use of electronic equipment on the circuit. The system advantages include lower costs due to the induction motors, more rugged construction and general availability; greatly reduced short-circuit energy; ability to withstand 100% overspeed; and good sinusoidal power wave form with low harmonics and high efficiency in the range of 86–96%.
- **Permanent magnet generator (PMG):** Low-head hydro installations are almost always characterized by great variations in flow and head, which require a generator that can accommodate the variations. Should frequency/speed regulation and voltage control be required, double regulation and external excitation systems are often needed; these result in complexity of turbine and generator and considerable expense to the developer. The PMG, in which the excitation field is provided by a permanent magnet instead of a coil, supplies continuous power to the exciter through the voltage regulator, which varies with speed (that is, with head and flow variations) regardless of the generator voltage. In addition, the axial flux permanent magnet (AFPM) generator has been widely applied in wind turbines and electric vehicles but rarely in hydropower applications. With proper design, the AFPM could significantly reduce the size and cost of generators for pico-hydropower applications.

7.2.3 Control and Instrument Cost-Cutting Technology

- Analog electronic "load-dumping" governors have been widely used in mini-scale hydro plants (<500 kW) since the 1980s; they cost at least ten times less than a traditional hydraulic-mechanical governor. In this governing mechanism, the load and speed changes of the unit are no longer adjusted by the opening of wicket gates and the rate of inflow; this arrangement allows the turbine wicket gate to be fixed, which will further reduce the cost with simplified switchgear. A bank of thyristors controls the load current, which flows through a bank of resistive loads. This in-house load is electrically in parallel to the external load. When the external load is reduced, the prime mover tends to speed up, generating an error voltage that increases the current through the in-house "dummy" load. In this way, the turbine-alternator system "sees" an invariant load. This design philosophy is called "load-dumping" because generating capacity in excess of consumer demand is dumped on the in-house bank of resistors. This type of governor provides precise frequency control and greater stability with rotating equipment. In addition, redundancy can be built into the controller at low cost and maintenance can be simplified by modular design. This type of controller can also be a voltage regulation device and, with some modifications in circuitry, can be used on isolated systems or in systems synchronized to a local grid supply.

7.2.4 Powerhouse Cost-Cutting Technologies and Strategies

- **Powerhouse elimination through integrated modular system design:** In recent years, the integrated design concept has been used with mixed success with the Turbinator, Natel SLH, "Plug-and-Play" modular, CanmetEnergy low-head turbine, and other systems. Additional assessments should be conducted for pre-fabricated and pre-assembled system designs integrated with modified bulb turbine technology for efficient, fish-friendly, fast, low-cost applications dedicated to vast sites with low head (2–10 m) and mini scales (<1 MW) to pursue scale-up for economical deployment.

- **Powerhouse simplification through optimal general arrangement:** By using advanced computerized design tools (e.g., CFD, CAD), flexible water inlets and outlets, turbine-generator shaft orientations, and overall power plant layouts can be attained to simplify and minimize powerhouse construction (e.g., the "open-flume" configuration). This design strategy is extremely useful for low-head sites combining AF turbine technologies.

7.2.5 Penstock Cost-Cutting Technologies

- **Alternative pipe materials:** Conventional penstocks have usually been made of pre-stressed concrete or high-strength steel. Steel pipe is expensive, and concrete pre-stressing techniques are suitable only if adequate facilities exist nearby. Alternative materials (PVC, polyethelene, Fiberglass-reinforced polyester, and asbestos cement) are currently being used to achieve large cost reductions in penstocks (Minott and Delisser 1983).

– PVC pipes can be supplied to withstand heads of over 150 m so long as an appropriate method of making joints is used to guarantee proper sealing. But PVC has low impact resistance and becomes fragile from prolonged exposure to ultraviolet solar radiation, so underground installation of penstocks is recommended to increase its lifespan. One advantage of using PVC piping is easy adaptation to the desired penstock profile because each pipe length can readily accommodate up to 5° of flexure. Another advantage is that joints need no welding, so the cost of welding is virtually obviated. In addition, the low weight of PVC piping facilitates and saves costs in transportation, need for supports and anchoring, and installation time. Total installation of PVC penstocks can save up to 50% compared with steel penstocks.

– The wood stave penstock is an old and well-tried type of conduit that requires a minimum of leveling and foundation work and may undulate through rugged terrain with a curve radius of as little as 60 times the pipe diameter. The smoothness of the pipe interior which, unlike in steel pipes, often increases over time, ensures very low friction losses. If manufactured from quality materials and professionally assembled, such penstocks will normally have a long life. Note that the steel hoops are the carriers of the water pressure. Wood stave penstocks are more likely feasible in developing countries where wood for penstocks is still in relatively great abundance and the manufacturing labor cost is lower.

– Polyethelene pipe is a good choice for small hydro projects. It can withstand heads of up to 150 m. Joints are made with special steel accessories and may not withstand high levels of pressure drop. The high flexibility of polyethelene penstocks results in reduced need for excavation and surface modifications. Very little anchoring is necessary. Pipe lengths may be selected to facilitate ease of transportation, and relatively large diameters of pipes (up to 12 in.) can be supplied.

– Penstocks made of Fiberglass-reinforced polyester can be used for heads of up to 150 m and may have internal diameters of up to 80 in. They are recommended that for low-head applications, as the cost of steel and steel fabrication for these low pressures far exceeds the cost of an equivalent Fiberglass penstock.

– Asbestos cement penstocks need to be considered for low-head applications. The main advantages of using asbestos cement piping include (1) ready adaptation to overland profiles because deviations of up to 5° can be easily accommodated at joints without causing leaks, (2) lack of need for expansion joints since the unions can be designed to obviate most expansion effects, and (3) relatively low friction head losses because of the smoothness of the piping.

  - As alternative materials are developed, a coordinated effort among materials suppliers, standard and code organizations, and regulatory bodies is critical to ensure sufficient material data and design codes for the safety and integrity of penstocks.

- **Low-cost solutions to surge control:** For mini- and micro-scale plants and low-head small hydro plants, the low-cost solution to waterhammer control may be to use pressure release valves instead of surge tanks. But careful and specialized waterhammer and transient analysis cannot be avoided because it is needed to predict and lower the risk of load rejection and transient failures.

7.2.6 Dam and Spillway Cost-Cutting Technologies

- **Inflatable weirs:** Thousands of rubber dams have been installed worldwide for various purposes. Water-filled rubber dams are more stable but more expensive and complicated than air-filled dams (Zhang, Tam, and Zheng 2002). Water-filled rubber weir crests are being used to raise the available head on micro-hydro or low-head sites; they can deflate to allow flood water to pass through. They are also used for water impoundment with certain foundation requirements. A US patent (2010) has been granted for fish passage using inflatable weirs.

- **Arch dams:** Computerized structural design/analysis and advanced construction technologies offer opportunities for using arched and multiple-arch dams to reduce the volume of concrete needed while maintaining a high degree of reliability and safety.

7.2.7 Engineering and Permitting Cost-Cutting Technologies

- Standardized feasibility studies and systematic design and modeling tools could reduce the engineering costs of small hydro projects. Section 8 of this report will discuss this topic in more detail.

- Technologies to improve the level of downstream dissolved oxygen concentration DOC) and fish survival would not only alleviate the environmental and ecological impacts and improve the generating performance of small hydro projects, but also ease the permitting process and even aid the evolution of permitting/licensing requirements and eventually reduce investment costs at early stages of development.

- The use of oil lubricants could be eliminated to prevent water pollution. Water-lubricated or self-lubricated turbine guide bearings have been applied to eliminate water contamination concerns. The hub of a Kaplan turbine typically is filled with pressurized oil to equalize pressure compared with the outside water pressure, as well as to lubricate internal mechanisms. The servomotor uses oil as a hydraulic fluid. One common reason for oil leakage from these units is failure of the blade trunnion seals. Although this risk is low, technologies are being developed to reduce the risk of oil pollution, including replacing the oil in the hub with air or water, installing an electric servomotor, and using hydrostatic water guide bearings (Falkenhem, Nakagawa, and Havard 2011, Ingram and Ray 2010).

8.0 RESEARCH AND DEVELOPMENT PROPOSALS AND STRATEGIES

More R&D funding is recommended to promote the strategies and technologies that enable cost-effective development of smaller-scale and lower-head resources. In addition to “solid” cost-cutting strategies through advancements in industrial technology, the following “soft” strategies should be promoted, which could reduce not only direct costs but also indirect costs for design, engineering, and the permitting process. The following list is a summary of R&D proposals associated with small hydro development and acceleration.

- **Hydropower cost database and modeling:** A robust cost database should be established, by collecting raw data from major hydro consulting companies/equipment suppliers/developers and project owners, for a large number of hydropower projects that have been constructed, designed, or studied in the United States. A set of more reliable cost estimating tools could then be developed through regression analysis, using the project-based cost data to build new cost equations or update/refine/verify existing cost equations for various project categories (NPDs, in-canal sites, new greenfield sites, existing plant expansions, and pumped storage projects) and different ranges of hydraulic heads (high, medium, and low) and project scales (large, small, mini/micro).
- **Uncertainty analysis of hydropower LCOE:** A leading LCOE analysis tool in the US hydro industry should be developed to address the uncertainty issues in LCOE calculation. There are great uncertainties in the input parameters in hydropower LCOE calculations (even for an individual project). A stochastic model would take into account the variations and uncertainties in input parameters and would result in probability distributions and LCOE statistics from which the average, the upper bound (best case), and the lower bound (worst case) LCOE, with confidence levels, would be reported for individual or aggregated projects. More informative and objective LCOE results would help decision makers understand risk levels and risk sources. In addition, the impact from different scenario assumptions (e.g., renewable incentives) and accounting methods would be studied to develop insights for many contingencies and questions in regional planning or early stages of project development.
- **Systematic design and modeling tool for SHPs:** There are often a number of trade-offs in the preliminary design of a hydropower project. A comprehensive design and modeling tool would be useful to simulate all components of an SHP to optimize the overall plant performance (i.e., minimizing the installation cost in $/kW and LCOE in $/MWh). An embedded CAD design module could test different selections of potential components (e.g., speed increaser or direct turbine-generator coupling) and layout arrangement (e.g., surge tank or higher penstock class to prevent excessive waterhammer pressures) and might also test for different operating modes (e.g., fixed speed or variable speed with a frequency converter) and corresponding energy production levels to determine the best arrangement and design of a project. This tool would compare with and improve upon the RETScreen Tool for Small Hydro Generation Projects.
- **Innovative integrated small hydro system for low-head site applications:** The innovative, integrated small hydropower system will combine two viable technologies: the AF bulb turbine and the concept of modular/compact system design. The design is aimed for broad and fast deployment in the United States at low-head small hydro sites, specifically for a head range of 2–10 m and a capacity of up to 1.2 MW. Reduction of the installation and operation costs will be achieved mainly through standardized system design and broad site implementation. As an initial stage of this innovative system development, the proposed R&D efforts will focus on (1) study of the potential deployment scale in the United States and the feasibility of commercialization, (2)

development of the conceptual design of the integrated low-head small hydropower system, and (3) validation and improvement of turbine system performance through numerical modeling.

- The proposed system design is inherently fish-friendly because of the slow rotational speed of the 3–4 blades of the bulb turbine for low-head applications ranging from 2 to 10 m. It eliminates the powerhouse, so on-site environmental disturbance and construction cost will be significantly reduced. To further reduce the environmental footprint and construction cost, the system layout will be optimized by integrating system components. Through hydraulic and structural numerical simulation, the existing design of bulb turbine components and water passage will be slightly modified to incorporate more proven fish-friendly features and to fit in a limited space while maintaining the turbine's high efficiency and flow capacity. The automation system will be studied to enhance the stability and reliability of power generation and reduce operation and maintenance costs. Some special issues and constraints that could arise from the limited space inside the system container are recognized but are considered resolvable, such as electromagnetic disturbances from different devices, the large size of low-speed generators, and cooling and temperature controls. The slightly higher cost of a bulb type turbine is expected to be offset by its efficient generation and high readiness for design standardization (due to its suitability for a wide range of flows and head variability).
- Based on a recent ORNL assessment of US national hydropower resources, within the given head range of 2–10 m there are more than 45,000 NPDs with average annual flows of 2.3 m3/s and total output potential of 8.5 GW. Thousands of them fall within the flow range of the proposed integrated system design. When other low-head sites are accounted for, the market scale of this proposed design must be sufficient for commercialization. A series of four to five physical sizes, combining several system and modular designs, will be determined to cover the whole range of target applications. Each of these standard products will be applicable to hundreds and perhaps even thousands of sites, effectively realizing the objective of reducing costs via economies of scale. Such an invention will potentially increase the US renewable generation fleet on the gigawatt scale in 5–10 years, and the manufacturing and engineering associated with these new integrated small hydro systems will bring business opportunities and job creation.

- **Bottom-up life cycle manufacturing cost model for one specific low-head turbine technology:** For the AF Kaplan turbine, for example, the cost is relatively high. This proposal is for a data-based life-cycle cost analysis for hydro turbine manufacturing to identify which technologies (including material and machining technologies) could be applied to reduce hydro equipment costs. The assessment will include upstream supply chains for turbine component manufacturing. The timelines and costs for replacing turbine components (e.g., bearings and seals) during the O&M stage may also be included in this study.

- **Technical and economic assessment of small hydro restoration projects:** This proposal aims to identify the opportunities for hydropower capacity restoration at desolated or under-used, aging facilities through a nationwide investigation and assessment. (Note: federal hydro owners have done a similar assessment for large hydro). The restoration projects won't cause additional environmental concerns, and existing civil works may be partially used. This R&D proposal is not only to assess the additional water power resources but also to study the technical and economic feasibility of individual restoration projects.

- **Nationwide energy assessment in existing conduits:** Except for NPD and new greenfield sites, the potential water energy in existing canals, municipal water supply pipelines, and wastewater outlets should be assessed across the United States to measure nationwide water power potential and allow various stakeholders to prioritize the level of investment in different waterpower resource. Municipal water systems are usually nearby load centers, and thus little investment in transmission is required. Meanwhile, the existing pipelines and valve house can be utilized for power generation to save the cost of civil works.

- **An improved site screening and assessment tool:** Leveraging the efforts and results from NHAAP by inputting site-specific hydrological and other basic site information, a site screening and assessment tool would generate flow and power duration curves and determine the turbine technology, design capacity, annual production, installation costs, and other economic indices to screen potential hydro sites across the United States. Aligned with the statistics for potential power scales and costs for different site features and applicable technologies, this study would help prioritize R&DD efforts for cost-cutting hydro technologies and aid industry in making strategic decisions on investment opportunities.
- **Standards of feasibility studies:** The site validation and permitting processes are costly in the United States and other western countries. Standards for the requirements and methodology for SHP feasibility studies need to be streamlined (harmonizing with permitting/licensing procedures). This effort also involves the standardization of a series of technical criteria for planning, design, construction, installation, testing and acceptance, operation, and other activities to ensure quality, improve efficiency, and help popularize new technology and innovative products.
- **SHP design workshops**: Many design issues for smaller projects are mostly due to limited budgets. Smaller projects are usually designed by smaller consultants with limited experience, and some common mistakes/deficiencies in small hydro design could be avoided by workforce training.

9.0 REFERENCES

Aggidis, G. A., Luchinskaya, E., Rothschild, R. and Howard, D. C. (2010). The costs of small-scale hydro power production: Impact on the development of existing potential. Renewable Energy, Vol. 35, Issue 12, pp. 2632–2638.

DOE (US Department of Energy) and INL (Idaho National Laboratory) (2003). *DOE and INL Estimation of Economic Parameters of U.S. Hydropower Resources*.

DOE (US Department of Energy) and INL (Idaho National Laboratory) (2004). *Water Energy Resources of the United States with Emphasis on Low Head/Low Power Sources*. DOE-ID-11111. http://hydropower.inel.gov/resourceassessment/pdfs/03-11111.pdf

DOE (US Department of Energy) and INL (Idaho National Laboratory) (2006). *Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants*. DOE-ID-11263. http://hydropower.inl.gov/resourceassessment/pdfs/main_report_appendix_a_final.pdf

DOE (US Department of Energy) (2011). Appendix E in "2011 Advanced Hydropower Development Funding Opportunity Announcement" (DE-FOA-0000486).

ESHA (European Small Hydro Association) (2004). *Guide on How to Develop a Small Hydropower Plant*. European Small Hydro Association.

Falkenhem, R., Nakagawa, N. and Havard, D. (2011). Technologies for eliminating oil in Kaplan turbines. http://www.hydroworld.com/articles/print/volume-18/issue-6/articles/turbine-mechanical-components/technologies-for-eliminating-oil-in-kaplan.html, (accessed March 2013).

Gordon, J. L. and Penman, A.C. (1979). Quick estimating techniques for small hydro potential. J. of Power Dam Constr., 31 (1979) pp.46–55.

Gordon, J. L. (1982). Estimating hydro stations costs. J. of Water Power Dam Constr., 33 (1982), pp.31–33.

Gordon, J. L. (1983). Hydropower cost estimates. J. of Water Power Dam Constr., 35 (1983), pp.30–37.

Gordon, J. L. and Noel, C. R. (1986). The economic limits of small and low-head hydro. J. of Water Power Dam Constr., 38 (1986), pp. 23–26.

Hatch (2008). *Low Head Hydro Market Assessment*. Hatch Energy and Natural Resources Canada, Ottawa, Ontario, Canada.

IDEA (1996). "Manuales de Energias Renovables: n°1 Minicentrales hydroelectricas." Altener Program, Madrid.

IEA-ETSAP (2010). "Technology Brief E12." May. (www.etsap.org)

INFORSE (2012). Hydro Power. http://www.inforse.org/europe/dieret/Hydro/hydro.html.

Ingram and Ray (2010). Hydro Review, "Bearings & Seals: Examples of Innovations and Good Ideas", Compiled by Elizabeth A. Ingram and Russell W. Ray. http://www.hydroworld.com/index/display/article-display/3519601978/articles/hydro-review/volume-29/issue-4/articles/bearings-_amp__seals.html

IRENA (International Renewable Energy Agency) (2012). *Renewable Energy Technologies: Cost Analysis Series—Hydropower*, Volume 1: *Power Sector*, Issue 3/5, June.

Kosnik, L. (2010). The potential for small scale hydropower development in the US. Energy Policy, 38, pp. 5512–5519.

Matthias HB, Doujak E, Angerer P. (2001). A contribution to ecological-economical aspects of hydro power plants. In: Honningswåg, et al., editors. Hydropower in new millennium. Lisse: Swets and Zeitlinger; 2001.

Minott, D., and Delisser, R. (1983). Cost reduction considerations in small hydropower development. United Nations Industrial Development Organization, Third workshop on small hydropower, Kuala Lampur, Malaysia, 1983.

Navigant (2006) *Statewide Small Hydropower Resource Assessment*. California Energy Commission. http://www.energy.ca.gov/2006publications/CEC-500-2006-065/CEC-500-2006-065.PDF.

Nexant (2006). *Assessment of Small and Mini Hydropower Stations—Afghanistan*. United States Agency for International Development.

NHA (National Hydropower Association), Oak Ridge National Laboratory, and Hydro Research Foundation (2010). *Summary Report of the 2010 Technology Summit Meeting on Small Hydropower*, Washington, D. C., April 7–8, 2010. http://www.esd.ornl.gov/WindWaterPower/SmallHydroSummit.pdf

NRCan (Natural Resources Canada) (2007). *Emerging Hydropower Technologies R&D in Canada: A Strategy for 2007–2011*, December.

Ogayar, B. and Vidal, P. G. (2009a). Cost determination of the electro-mechanical equipment of a small hydro-power plant. Renewable Energy, Vol. 34, pp. 6–13.

Ogayar, B., Vidal, P. G. and Hernandez, J.C. (2009b). Analysis of the cost for the refurbishment of small hydropower plants. Renewable Energy, Vol. 34, Issue 11, pages 2501–2509.

Paish, O. (2002). Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews, Vol. 6, pp. 537–556.

Papantonis, H. B. (2001). *Small Hydro Power Stations*, Simeon, Athens.

Singal, S. K. and Saini, R. P. (2008a). Analytical approach for development of correlations for cost of canal-based SHP schemes. Renewable Energy, Vol. 33, Issue 12, pp. 2549–2558.

Singal, S. K. and Saini, R. P. (2008b). Cost analysis of low-head dam-toe small hydropower plants based on number of generating units. Energy for Sustainable Development, Vol. 12, No. 3, pp. 55–60.

Singal S. K., Saini, R. P. and Raghuvanshi, C. S. (2010). Analysis for cost estimate of low head run-of-river small hydropower schemes. Energy for Sustainable Development, Vol. 14, Issue 2, pp. 117–126.

USBR (US Bureau of Reclamation) (2012). Hydropower Construction Cost Trends. US Bureau of Reclamation. http://www.usbr.gov/pmts/estimate/cost_trend.html.

Warren-Nickle's Network (2007). "Canada Developing Emerging Small Hydro Technology." Energy Evolution: April 23, 2007. http://www.airwaterland.ca/article.asp?id=1737.

Zhang, X. Q., Tam, P. W. M., and Zheng, W. (2002). Construction, operation, and maintenance of rubber dams. Canadian Journal of Civil Engineering, June, 29, 3, pp. 409–420.

APPENDIX A: PROSPECTUS FOR HYDROPOWER COST DATA COLLECTION

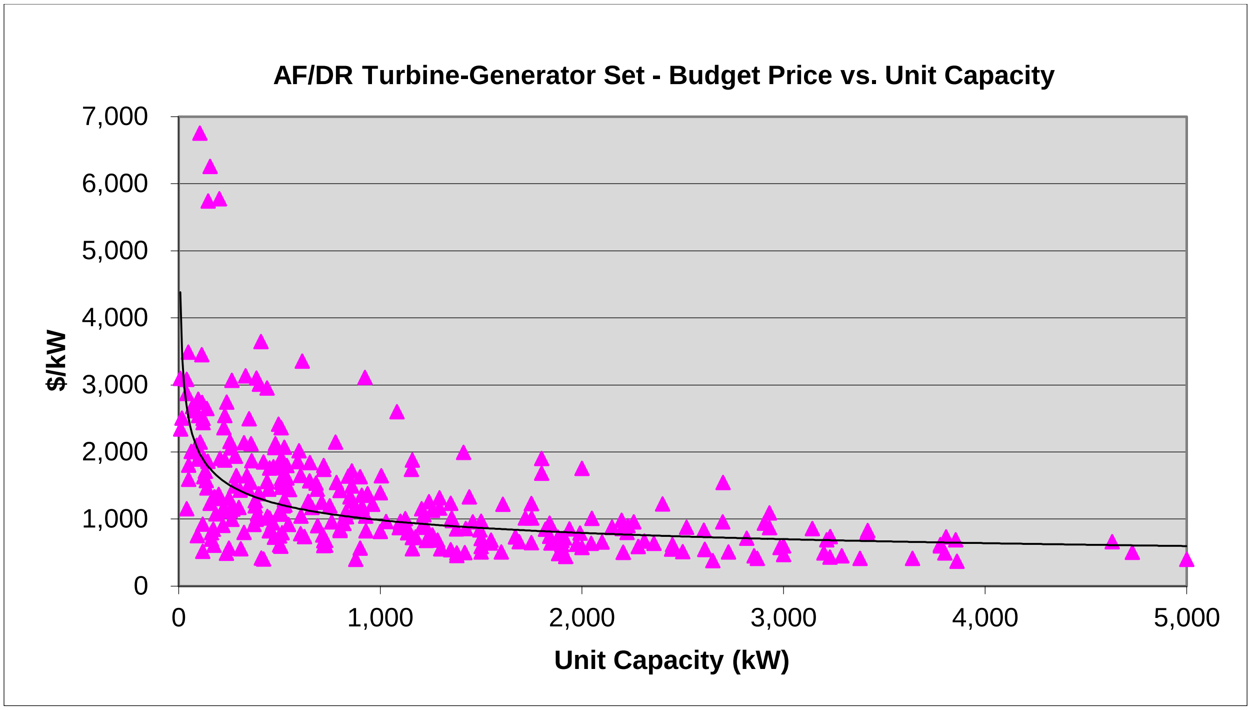
Purpose of Data Collection

Oak Ridge National Laboratory (ORNL) is assisting the US Department of Energy (DOE) Water Power Program in the development of a *Small Hydropower Cost Model*. The model will provide current (2012) costs for small hydropower facility development, including site preparation, construction, equipment acquisition, and equipment installation as functions of typical design variables (head, flow-duration), technology type, and other factors. DOE will use this information to inform its hydropower research and development programming, including the modeling of hydropower deployment in future capacity growth models and targeting of specific research to lower component costs that contribute to the levelized cost of energy (LCOE) for small hydropower production.

ORNL is requesting that your company, as an industry participant, contribute its knowledge of small hydropower development costs to this *Small Hydropower Cost equation* effort. Cost information gained through experience in developing, designing, or providing equipment for hydropower projects in the range of 100 kW to 30 MW is the primary focus of this request. The attached data collection form specifies the types of detailed data that are sought.

Use of Data Provided by Industry

ORNL understands that individual facility cost data are business-sensitive for facility owners, developers, and consultants. Such data that industry participants provide to ORNL will be protected from public release and will not identify costs with specific projects. To this end, the enclosed data collection form does not include project names—contributors identify projects by number instead. These cost data collected from all sources will be grouped by parameters such as facility type (e.g., new sites, non-powered dams, diversion/canal sites, conduit installations), hydraulic head (low, medium, high), and turbine technology (Francis, Kaplan, Pelton, other). The resulting charts and tables will reveal trends and distribution of costs among facility components and development activities, as in the following chart for axial-flow turbines.



Value to the Hydropower Industry

Insights gained from new cost data will replace publicly available empirical cost equations for small hydropower development that are outdated and do not incorporate state-of-the-art construction, hydraulic design, or manufacturing techniques. The LCOE analysis will identify which components associated with small hydropower design and development affect costs the most, and which components contribute the most to cost uncertainty. This information will enable ORNL and others to classify small hydropower technology research according to the potential to reduce LCOE. For example, research that helps reduce costs for site preparation, construction, structures, and environmental characterization and mitigations could yield LCOE reductions over different timelines and by different degrees compared with research focused on powertrain components.

The outcome of the data collection and analysis will eventually be publicly available through DOE dissemination channels for industry users, including small hydro consultants and other project stakeholders. This will help in economic assessments regarding site selection and project financing to reduce early-stage development costs and risks; it will also help in promoting the commercial development of small hydro projects.