Development Engineering 7 (2022) 100097

Contents lists available at ScienceDirect

Development Engineering

journal homepage: www.elsevier.com/locate/deveng

Cost estimation of micro-hydropower equipment in Nepal

Joe Butchers [a,*], Sam Williamson [a], Julian Booker [a], Topaz Maitland [b], Prem Bikram Karki [c], Bikram Raj Pradhan [d], Suman Raj Pradhan [d], Biraj Gautam [c]

[a] Electrical Energy Management Group, University of Bristol, UK
[b] Science and Technology Facilities Council, Swindon, UK
[c] People, Energy and Environment Development Association, Kathmandu, Nepal
[d] Nepal Yantra Shala Energy, Kathmandu, Nepal

ARTICLE INFO

Keywords:
Micro-hydropower
Costing
Locally manufactured
Benchmark
Nepal

ABSTRACT

Selecting the appropriate technology for providing electricity to rural communities depends upon evaluating the cost of a potential installation. For some rural communities, locally manufactured technology, in the form of wind and hydropower, can be effective. However, often the cost of these locally manufactured technologies is largely unknown. Access to costing data allows the economic viability of a site to be compared with other options. Furthermore, it enables benchmarking, allowing the expected total cost of an installation, or individual sub-systems, to be compared with quotations. This paper attempts to address the current lack of publicly available costing information for locally manufactured micro-hydropower equipment. A methodology is presented where quotations are provided by micro-hydropower manufacturing companies in Nepal for randomly generated sites. Using that information, they provided a quotation for various sub-systems. This data allows comparison of the cost of major components and the influence of turbine type. Through a linear regression model, expression have been developed that can be used to determine the expected cost for both Pelton and Crossflow turbine installations. The accuracy of these expressions is compared with previous costing models, the outcomes of the work and their significance in the context of Nepal and elsewhere is discussed. The key contribution of this work is establishing numerical expressions which allow proposed costs of micro-hydropower equipment to be rapidly evaluated.

1. Introduction

In 2019, 759 million people worldwide did not have universal access to affordable, reliable, sustainable and modern energy services (IEA et al., 2021). Of these, 84% were living in rural areas. This highlights the ongoing challenge associated with rural electrification. In many rural locations, the typical trend of grid extension is hampered by a variety of challenges including high cost, lack of resources, weak infrastructure, conflict, and political instability (Urmee and Md, 2016; Palit and Chaurey, 2011; Bhattacharyya and Palit, 2014). Various renewable energy technologies that act as standalone systems, micro- or mini-grids, have been shown to be a necessary and viable alternative. These sources have been particularly effective in delivering electricity services to “last mile” communities, located far from national gridlines. To enable the ongoing electrification of rural areas, it is the responsibility of national governments to determine the most appropriate technology. Often this decision is based upon assessing the technical, social, environmental, and economic viability of the range of available technologies, at their various scales.

Therefore, to make this judgement, decision makers must have access to detailed information regarding the overall cost of project development. For grid extension or the development of large-scale renewable projects, expected costs are usually well reported with historical data available that can be used for estimation. For many standalone systems, micro- and mini-grids that rely on mass produced technology, costs can also be predicted with relative ease. For some rural communities, locally manufactured technology, in the form of wind and hydropower, has been shown to be effective, with their relative strengths and limitations often discussed (Ferrer-Mart í et al., 2012; Arter, 2011; Cromwell, 1992; Kumar et al., 2015; Leary et al., 2012;

Abbreviations: EUR, Euros; ID, internal diameter; IRENA, International Renewable Energy Agency; kVA, kilovolts-amperes; kW, kilowatts; MW, megawatts; NPR, Nepali Rupee; PCD, pitch circle diameter; R, correlation coefficient; USD, United States Dollar.

* Corresponding author.
E-mail address: joe.butchers@bristol.ac.uk (J. Butchers).

https://doi.org/10.1016/j.deveng.2022.100097
Received 22 December 2021; Received in revised form 12 May 2022; Accepted 23 June 2022
Available online 1 July 2022

Reinauer and Hansen, 2020). However, local variation and a lack of publicly available information often makes the overall cost difficult to estimate. As a result, they can be overlooked by decision makers as a viable alternative to other energy options.

In Nepal, locally manufactured micro-hydropower (generation at <100 kW) has been used for rural electrification since the 1960s (Meier and Arter, 1989; Conroy and Litvinoff, 2013). From this time, a local manufacturing industry has developed with companies producing hydro-mechanical and electrical components, installing the equipment, and empowering communities to construct the civil structures. The benefits, drawbacks and sustainability of these plants has frequently been explored (Bhandari et al., 2018; Gurung et al., 2011, 2012; Poudel et al., 2021; Butchers et al., 2020). In the last 10 years, government focus on micro-hydropower has reduced with greater attention directed towards mini- (<1 MW) and small-hydropower (<10 MW) (Consulting, 2017). The annual number of newly constructed micro-hydropower projects (MHPs) decreased accordingly, from over 3000 per year between 2011 and 2014, down to 1245 in 2016 (Centre, 2021). Table 1 shows recent data for the fiscal years between 2017 and 2021. The table shows the target and actual figures for rehabilitation and installation of mini-/micro-hydropower projects (M/MHPs) jointly by the Alternative Energy Promotion Centre (AEPC) and the National Rural and Renewable Energy Program (NRREP). The AEPC and NRREP are, respectively, the government institution focused on renewable energy development, and a programme focused on the development of rural living standards using renewable energy (Alternative Energy Promotion Centre, 2018). Whilst the original NRREP officially concluded in 2017, a number of programmes and projects funded by the government and foreign donors are still implemented under the NRREP heading (Alternative Energy Promotion Centre, 2021). In all categories and in each year, it can be seen that the annual targets have not been met. For new installations, the targeted amount of installed mini-/micro-hydropower has been falling. Meanwhile, the repeated failure to meet the targeted amount of rehabilitation for earthquake affected and partially finished MHPs suggests that there remains work to be completed. It should be noted that the authors are aware of ongoing refurbishment of MHPs funded by local government, which is not covered by the data presented.

The reduction in micro-hydropower development in Nepal can be explained by increased coverage of the national grid. It is estimated that grid-based electricity served approximately 85% of total households in Nepal in the fiscal year 2020/21 (Nepal Electricity Authority, 2021). The ongoing development of Nepal Electricity Authority (NEA) grid lines will continue to reduce the regions where smaller scale hydropower is applicable. There remains potential opportunity in a number of remote districts which have little or no grid coverage. In particular, the districts of Bajura, Jumla, Manang, Mugu and Mustang, where there are no current or planned sub-stations, or grid lines (Nepal Electricity Authority, 2021). In these districts, and remote parts of other districts, renovation of existing MHPs and construction of new plants can be cost effective in comparison to grid extension, and may be required to provide universal electricity access in Nepal (Sovacool et al., 2013).

Where the grid has encroached on existing MHPs, grid connection is an option. Following an agreement between the AEPC and NEA in 2014 (Kumar et al., 2015), several micro-hydropower plants have been connected to the national grid. Since the 23 kW rated Syaure Bhumi MHP in Nuwakot (Kumar et al., 2015), three further grid connections have been completed: Leguwa Khola MHP (40 kW) in Dhankuta, Chimal Khola MHP (90 kW) in Taplejung, Midim Khola MHP (100 kW) in Lamjung, and Tara Khola MHP (380 kW) in Baglung (Interview with Alternative Energy Promotion, 2022). There are four further projects currently undergoing connection to the grid with more planned. For MHPs located where the grid has arrived after the plant's construction, grid connection provides an opportunity for income generation. Electricity generated at the plant can be sold to the NEA. Where a community has invested time and effort in the development of an MHP, the lifespan of the project can be extended through income generation.

Micro-hydropower will continue to play a role in electrification in Nepal. This will include construction of new projects in remote areas, rehabilitation of existing projects, and grid-connection of encroached projects. In all of these cases, to be competitive against other electrification options, it is important that the cost of micro-hydropower is known. For a given site, rapid cost estimation allows the economic viability of a site to be compared with other options. Cost estimation also enables benchmarking, allowing the expected total cost of an installation, or individual sub-systems, to be compared with quotations. Specific to Nepal, within the micro-hydropower manufacturing industry, there has been a recent trend of new companies providing extremely low quotations, to secure a contract and receive the corresponding subsidy (Butchers, 2020). Benchmarking of cost can provide an expected envelope which can be used to identify quotations at the high and low extremes. An additional benefit is that it allows the cost of new technologies to be evaluated. Within locally manufactured micro-hydropower, both generally, and particularly in Nepal, the Pelton and Crossflow turbines have been become predominant in the market (Paish, 2002). A study of 163 sites conducted by the AEPC included 45% Pelton and 55% Crossflow turbines (Interview with Alternative Energy Promotion, 2022). Whilst the extent to which this study was representative is unknown, it provides an indication of the potential proportion of each turbine type. Without costing information readily available in the public domain, it is difficult to evaluate the opportunity to use other turbine types. Both the Francis (Ghimire et al., 2019) and Turgo (Butchers et al., 2021) turbines have been suggested for potential use in Nepal.

This paper attempts to address the current lack of publicly available micro-hydropower costing information. To do so, a methodology has been developed; established micro-hydropower manufacturing companies in Nepal were provided with random site characteristics of head and flow rate. Using that information, they provided a quotation for various sub-systems. This data allowed comparison of the cost of major components and the influence of turbine type. Through a linear regression model, it was possible to develop expressions to determine the expected cost for both Pelton and Crossflow turbine installations. Subsequently, the accuracy of these expressions is compared with previous costing models, the outcomes of the work and their significance in the context of Nepal and elsewhere is discussed.

2. Background to hydropower costing

The overall cost of hydropower installations is often discussed in relation to other major sources of electrical power. As a result, the typical focus is upon larger scale hydropower projects. Often the differentiation is placed between small (<10 MW) and large (>10 MW). At these scales, in a 2020 International Renewable Energy Agency (IRENA) report, for small hydropower projects, the average was 2459 $/kW

Table 1
Data regarding hydropower installations and rehabilitation between 2017 and 2021. Data extracted from (Alternative Energy Promotion Centre, 2018, 2019, 2021).

		17/18		18/19		19/20		20/21	
		Aim	Complete	Aim	Complete	Aim	Complete	Aim	Complete
Rehabilitation of earthquake affected MHPs	(kW)	2000	259	2000	157	200	112	–	–
Rehabilitation/completion of partially finished MHPs	No.	40	25	20	15	20	0	15	6
New mini/micro-hydropower installations	(kW)	2200	1249	3000	1453	2000	870	1500	1116

whilst the range between the 5th percentile and 95th percentiles was 1374 to 5272 $/kW (IRENA and Renewable Power Generation Costs, 2021). Whilst for large hydro, the average was 1865 $/kW and the 5th to 95th percentile range was 1046 $/kW to 7582 $/kW (IRENA and Renewable Power Generation Costs, 2021). These values indicate that whilst, on average, large hydro is less expensive, there is a greater potential range of overall cost. This is likely associated with variation in the cost of civil works of large hydropower projects. Between 10 MW and 500 MW, for a range of turbine types, the quantity of steel, cement and associated construction time can vary hugely depending on whether the project is high or low head. These recent costings are useful in understanding what micro- and mini-hydropower can be compared against. General worldwide cost averages are more difficult to obtain at these smaller scales. For a nominal 50 kW plant, an earlier IRENA report from 2012 places the cost between 3500 $/kW and 5500 $/kW (IRENA, 2012). Specific to Nepal, data published by the Alternative Energy Promotion Centre places the average cost per kilowatt of 38 micro-hydropower projects at 4459 $/kW, with an approximate range of 3200 $/kW to 6400 $/kW (Williamson, 2013). A more recent study from 2022 of 175 MHPs in Nepal found an average investment cost of 5074 $/kW with a standard deviation of 1802 $/kW (Poudel et al., 2022).

Alongside assessment of overall cost, some literature provides a breakdown for individual sub-systems and other headings. Table 2 shows the proportional cost of hydropower sub-systems from a number of sources. Whilst derived from different scales of hydropower, there is reasonable consistency in the cost of electro-mechanical equipment with a total range of 20%. Amongst large hydro projects, civil works contribute the largest cost. Typically, larger scale projects require significant civil works to install dams and tunnels. Smaller schemes, which are often run-of-the-river, do not require the construction of these elements. For the values derived from micro-hydropower in Nepal, the source does not indicate the type of turbine, nor the rated power. It does not indicate where the cost of the transmission and distribution network is included.

The large variations in the potential cost of hydropower schemes (at all scales) and, in particular, a lack of costing data for mini- and micro-hydropower has led to the development of a range of methods to estimate cost. Whilst it has been acknowledged that it is difficult to accurately predict cost using simplified models (Cavazzini et al., 2016), many approaches for cost estimation have focused on using expressions that are based upon numerical quantities associated with a site, e.g., rated power, head and flow rate. In (Cavazzini et al., 2016), a detailed comparison of 10 different cost functions is described. The accuracy of these expressions are tested across the micro-, mini- and small hydropower range: the range of rated power is from 9.4 to 2753 kW. All of the studies rely on turbine data from Europe or North America and are dated between 1979 and 2016.

A significant trend amongst all of the cost functions is that they focus on the cost of electro-mechanical equipment alone. The cost of civil structures is extremely site specific and dependent on particular local geography (Cavazzini et al., 2016). Therefore, accurate estimation depends upon the knowledge of site details which enable the calculation of particular civil costs, e.g. the volume of concrete and quantity of reinforcing metal that is required (Cavazzini et al., 2016). Furthermore, accurately predicting civil costs is challenging due to the impact of local factors: availability and cost of labour, access, and the cost of steel and cement. An exception is (Singal et al., 2010), where the authors use a rigorous method to develop equations for the estimation of all major civil structures for low head (<20 m) small hydropower installations. The results are compared to actual costs for 24 installations in India. The predicted total civil cost is reasonably accurate with a deviation of $\pm$11%, however, the accuracy of the estimated costs for individual sub-systems is unknown. In general, studies rarely provide an itemised breakdown of expected costs based on their available datasets. Ogayar and Vidal (2009) show a pie-chart which separates the total investment cost (into civil works, turbo generator set, construction and engineering management, and electrical regulation and control equipment) but the source is not provided. In (Aggidis et al., 2010), data was obtained from global manufacturing companies perhaps unwilling to show the various cost contributions. The result is that the majority of studies are unable to provide cost for the various components. In (Cavazzini et al., 2016), the authors argue that their expression (which uses head, flow rate and power terms) allows the estimated hydro-mechanical and electrical costs to be disaggregated, however, the accuracy of this is not evaluated.

Amongst the studies, many provide a generic expression to determine estimated cost irrespective of turbine type. Meanwhile, in (Cavazzini et al., 2016; Ogayar and Vidal, 2009; Aggidis et al., 2010), the expressions developed are particular to turbine type. Ogayar and Vidal argue that the type of turbine is crucial to the determination of accurate constant values in the cost expressions (Ogayar and Vidal, 2009). Aggidis et al. (2010) argue that differentiation between turbine types is necessary to reflect how the costs of manufacturing processes scale differently depending on the turbine type. In most approaches, regression analysis is used to calculate costing terms based on power and head alone without using flow rate. Given rated power is directly proportional to head and flow rate, it appears that use of all three terms is generally considered unnecessary. An exception is (Cavazzini et al., 2016) where flow rate is included and expressions are derived using a particle swarm method. When comparing the accuracy of this method with the 10 other approaches, the authors find that their own approach and that of Ogayar and Vidal (2009) provide greater accuracy. The authors observe that most studies are characterised by good accuracy with their original data set but have significant deviation when used with data sets of hydropower sites from other sources (Cavazzini et al., 2016).

Previous studies have resulted in the development of expressions that can be used to predict the total cost of electro-mechanical components at mini- and micro-hydropower installations. Few studies have attempted to include the cost of civil structures due to its site-specific nature and challenges associated with its estimation. In addition, the majority of studies provide only a total cost; the cost of individual electrical and mechanical sub-systems is unknown. Where the accuracy of different methods has been compared, it appears that many tend to have lower accuracy when applied to other datasets. These findings indicate that the use of existing expressions is unlikely to be applicable in Nepal and that currently, there is a lack of evidence that provides a breakdown of the cost of individual sub-systems for micro-hydropower.

Table 2
Proportional cost of hydropower sub-systems (as percentage of the total cost).

Sub-system	25 projects of unknown size	Large hydro (<10 MW)	Small hydro (>10 MW)	Micro-hydropower (<100 kW) in Nepal
Civil works	45%	50%	30%	20%
Electro-mechanical equipment	33%	30%	40%	53%
Grid connection	6%	5%	10%	–
Other	19%	15%	20%	27%
Source	IRENA and Renewable Power Generation Costs (2021)	IEA and Hydropower Special Market Report (2021)	IEA and Hydropower Special Market Report (2021)	Kumar et al. (2015

3. Methodology

In this study, the methodology focused on collecting a breakdown of costs for micro-hydropower sites from Nepali manufacturers. This allowed the cost of individual sub-systems to be compared and the data to be used to estimate total cost based on site characteristics. In Nepal, when quoting for projects, micro-hydropower manufacturers provide a detailed breakdown for costs of the various sub-systems that are specified within bidding documentation (Alternative Energy Promotion Centrea; Alternative Energy Promotion Centreb; Alternative Energy Promotion Centrec). Consequently, rather than attempting to use historical data (which the authors concluded would be difficult to access), it was decided to survey manufacturing companies to provide expected costs for prospective sites. Using the form of the bidding document as a template, the survey requested the expected cost for the turbine, power transmission system (typically a belt drive), penstock, butterfly valve, generator, control & protection system, and installation & commissioning.

Table 3 lists the questions in the cost survey for each random site. In relation to the cost of a complete installation, there were two notable omissions. First, as discussed earlier, the significant variation in the cost of civil structures and the challenges associated with estimating these costs meant that they were not considered. Second, the cost of the transmission and distribution network was not evaluated. Similarly to civil structures, the cost depends significantly on the local geography, e.g., topography, number of households and the distance between them.

Potential participants from manufacturing companies, operating in Nepal for at 10 least years, were identified through the Nepal Micro Hydropower Development Association. Due to their length of time in service, it was assumed these established companies would be likely to provide realistic quotations. In total, representatives of 7 manufacturing companies confirmed that they were willing to participate. Two limitations of the study were that it relied on assuming that the quotations provided were realistic, and that the quality of equipment produced by the manufacturing companies was similar. This first assumption was justified on the basis that due to their length of time in service, these established companies would be more likely to provide realistic quotations. For them, there was no commercial benefit associated with providing an unrealistic quotation. The second assumption was based on the experience of the authors. During the data collection process, the authors were able to observe the type of manufacturing equipment that each manufacturer owned. Whilst it was not possible to assess the quality of finished products, access to similar equipment of similar age was assumed to indicate that broadly the potential quality was the same for all manufacturers. Ethical approval for the study was provided by the University of Bristol, with participants informed that identifying data would not be collected and that the information that they provided was to be used for the purpose of research alone. Using information from (Butchers et al., 2020) and (Dutta et al., 2007), typical ranges in head and flow rate were identified for Pelton and Crossflow turbine sites in Nepal. Using these ranges, a selection of 100 randomly generated site details was produced, equally split between Pelton and Crossflow sites. From this list, each manufacturing company was provided with the characteristics (head and flow rate) for 4 sites, chosen using a random number generator. As penstock angles can vary depending on site geography, for simplicity, it was assumed that for all the random sites that the penstock angle was fixed at 45°. The data collection occurred between March and May of 2019. Participants were provided with the information regarding the 4 sites, a hard copy of the information shown in Table 3, and a briefing statement. In person, explanation was provided in English or Nepali. In their own time, the respondents completed the survey and returned a scanned or photographed copy by email. When processing the data, an average exchange rate for 2019 of 1 NPR (Nepali Rupee) = 0.0088 USD (United States Dollar) was applied (X-Rates, 2021).

Table 3
Cost survey questions for each random site.

Item	No.	Question
-	1.1	Specify the rated power for this micro-hydro plant (kW).
Turbine	2.1	Specify the type of turbine for this site.
	2.2	Specify the approximate runner PCD (in mm).
	2.3	Specify an approximate price for the turbine (in NPR).
Power transmission system	3.1	Specify the type of belt used for power transmission.
	3.2	Specify an approximate price for the power transmission system (in NPR).
Penstock	4.1	Specify the ID of the penstock pipe.
	4.2	Specify the wall thickness of the penstock pipe (in mm).
	4.3	Specify an approximate price for the total cost of all penstock pipes (in NPR).
Butterfly valve	5.1	Specify the ID of the butterfly valve (in mm).
	5.2	Specify an approximate price for the butterfly valve (in NPR).
Generator	6.1	Specify the kVA rating of the generator.
	6.2	Specify the approximate price for the generator (in NPR).
Control, instrumentation and protection system	7.1	Specify an approximate price for the control, instrumentation and protection system (in NPR).
Installation and commissioning	8.1	Specify an approximate price for mechanical and electrical installation and testing (in NPR).

4. Results and discussion

The results were used to evaluate the total costs and how they varied in response to the rated power of the site. Fig. 1 shows the overall cost in USD per kilowatt (kW) against the rated power for the sites quoted by manufacturers. The figure demonstrates that as the rated power increases, the cost per kilowatt decreases considerably: the range is more than 600 $/kW. A trendline is fitted to the results with reasonable correlation (the correlation coefficient, $R = 0.868$). The shape of the line indicates that as the rated power increases, the rate of change of the cost decreases. Fig. 2 compares the cost per kilowatt for the Crossflow and Pelton sites. The mean cost per kilowatt for Crossflow and Pelton sites was 505 $/kW and 605 $/kW respectively. Across the power range, the results suggest that Crossflow sites tend to be lower cost. For both types, the results follow a similar trend, with the difference in cost between them decreasing as the rated power increases. There is less variation in the trend amongst the Crossflow ($R = 0.922$) than the Pelton sites ($R = 0.907$). Amongst both turbine types, it can be seen that there are some sites that vary from the trend. The outliers with most deviation are found amongst sites with Pelton turbines. Amongst both turbine types, an accurate prediction of cost is not possible from rated power alone. There is a dependence upon other factors: head, flow rate and penstock length. It is more appropriate to assume that there exists a feasible band of cost either side of the predicted trend.

To broadly explore the relationships between cost and key site details, it was possible to evaluate the individual linear correlations. Table 4 plots the linear correlation between overall cost and several key site details: rated power, head, flow rate, and penstock length. The results allow identification of site details which have the strongest linear correlation (i.e., an R value = 1) with overall cost. Amongst the Crossflow sites, all of the site details are strongly linearly correlated with the overall cost. It can be assumed that each of these site details alone could be used to predict the overall cost with reasonable accuracy. For Pelton sites, rated power is the only factor that has a strong linear relationship with overall cost. The flow rate has some correlation with cost, whilst penstock length and head have weak and extremely weak relationships with cost, respectively. Amongst Crossflow micro-hydropower sites in

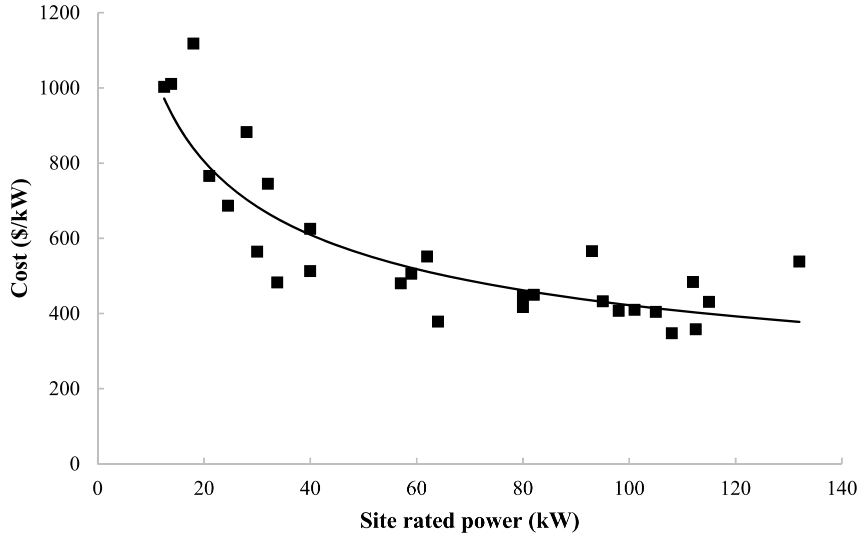

Fig. 1. Cost per kilowatt for all sites.

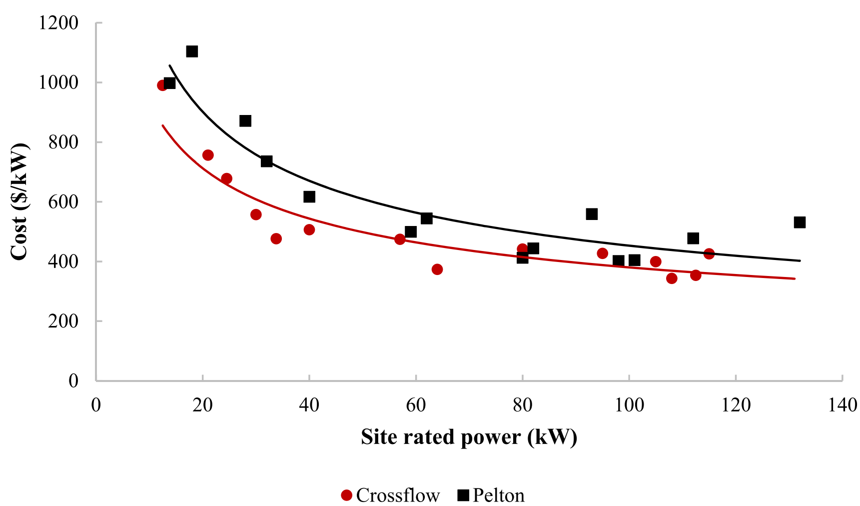

Fig. 2. Cost per kilowatt comparing Crossflow and Pelton sites.

Table 4
Linear correlation between overall cost and key site details.

Turbine type	Relationship	R	Significance
Crossflow	Power and cost	0.973	4.77 E−09
	Head and cost	0.852	1.08 E−04
	Flow rate and cost	0.937	7.80 E−07
	Penstock length and cost	0.850	1.17 E−04
Pelton	Power and cost	0.933	1.12 E−06
	Head and cost	0.078	0.789
	Flow rate and cost	0.746	0.002
	Penstock length and cost	0.267	0.356

Nepal, generally, as the power (and therefore cost) increases, the head and flow rate increase to deliver higher power. For the Pelton sites, the relationship is more variable. In Nepal, it is possible to find Pelton sites with lower head and higher flow that deliver power equivalent to a site with far higher head and lower flow. In this example, whilst the overall cost could be similar, there is unlikely to be a similar trend between cost and the other site details. The results demonstrate that considering linear relationships alone, rated power can provide the most accurate estimate of overall cost. To obtain a more accurate prediction of overall cost, the combined relationship of multiple site details requires consideration.

Between the two turbine types, there is also different contributions from the various sub-systems. In Fig. 3 and Fig. 4 the average cost of each item is broken down for each turbine type. In these figures, it can be seen that the generator, penstock, and turbine sub-systems contribute at least half of the total cost for both types of turbine. Particularly amongst the Pelton turbine sites, the cost of the penstock becomes very significant, contributing on average 30% of the total cost alone.

In Fig. 5, Fig. 6 and Fig. 7, the cost per kilowatt is plotted against the site rated power for the three most costly sub-systems: penstock, turbine, and generator respectively. In Fig. 5, it can be seen that for equivalent rated power the specific cost of the Pelton penstock is considerably higher. This can be attributed to the longer length of penstocks required for Pelton sites where the head will be higher. Comparing a Pelton and Crossflow site of the same rated power, the Pelton penstock will need to be longer and will therefore require a substantially larger amount of

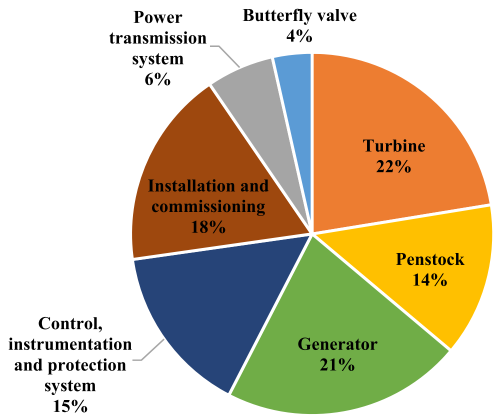

Fig. 3. Average proportional cost by sub-system for Crossflow sites.

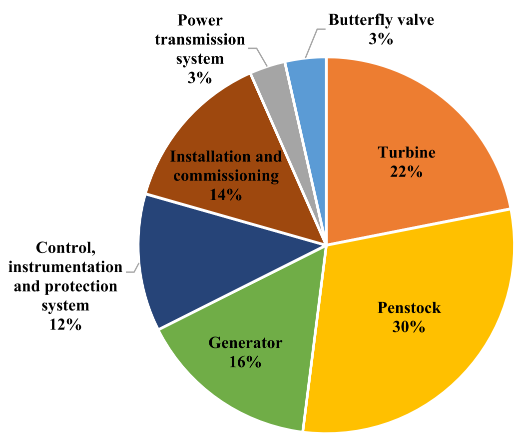

Fig. 4. Average proportional cost by sub-system for Pelton sites.

material. For the Crossflow sites in Fig. 5, there is almost no variation in the cost per kilowatt of the penstock as the rated power increases. For Pelton sites, there is a general trend of cost per kilowatt decreasing as rated power increases. However, the 2 sites with highest rated power are an exception to this. There is no clear explanation for these results although an error in quotation or the application of a 'premium' price due to the higher power rating are possible reasons. In Fig. 6, it can be seen that the cost per kilowatt for the turbine decreases for higher rated powers. There are similar trends for the Crossflow and Pelton turbines, although generally the Crossflow turbines tend to be lower cost. For the generator, Fig. 7 shows that there is a trend of decreasing cost per kilowatt with increasing site rated power. The relationship is similar for the two turbine types and a line of best fit is used to show the trend irrespective of the turbine type.

Of all the components, the penstock and turbine both require skilled workmanship to produce new components from stock material. Figs. 3 and 4 show that the turbine accounts for the same proportion of the total cost for both Crossflow and Pelton sites. Typically, Pelton turbines require a smaller volume of metal, however, their runners are cast at separate companies which adds an extra cost. The similarity in cost per kilowatt for the two turbine types can be seen in Fig. 6. Similarly, for the cost per kilowatt of the generator, Fig. 7 shows that there is little difference between the two. One would expect that there would be no difference in the cost of generators between the different types of site; manufacturers tend to use 1500 rpm 4-pole synchronous machines in conjunction with a transmission system. The relationship between rated power and the cost of the penstock is much more difficult to predict. As shown in Fig. 5, there is only a small variation in the cost of the penstock for Crossflow turbines, with all sites lying in the range of 40–90 $/kW. For the Pelton sites, the cost per kilowatt decreases for higher rated power sites but remains highly variable. The flow rate and head determine the dimensions of the penstock, specifically the wall thickness and diameter. Using the values quoted by the manufacturers for thickness, diameter, and penstock length, it is possible to calculate the overall volume of material required. Using this information, Fig. 8 plots the volume of material per metre against the cost per metre. In this figure, as expected, there is a strong positive linear correlation ($R = 0.987$) between the volume of material per metre and the cost per metre. As the quotations for penstock cost should be directly proportional to the cost of steel, the figure can be used to identify penstock prices that vary significantly from the expected price.

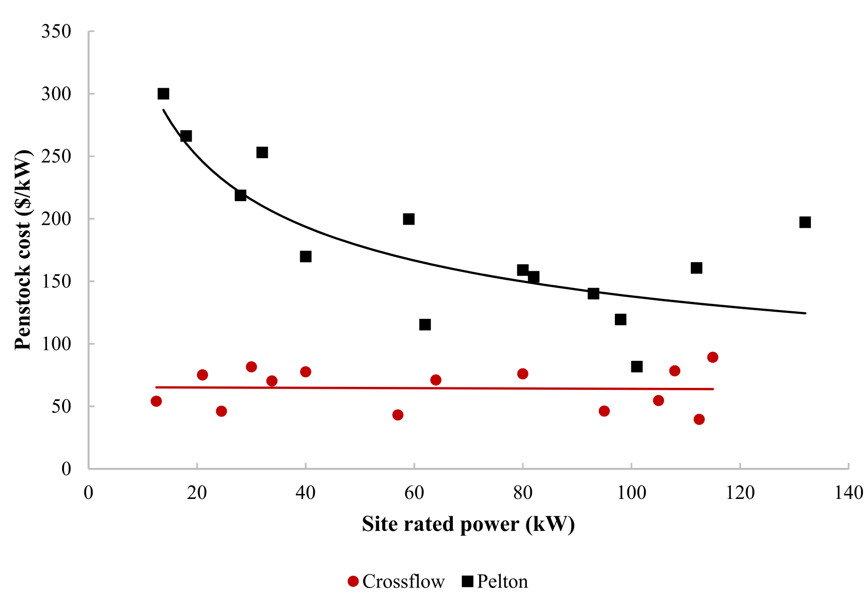

Fig. 5. Cost per kilowatt for penstock.

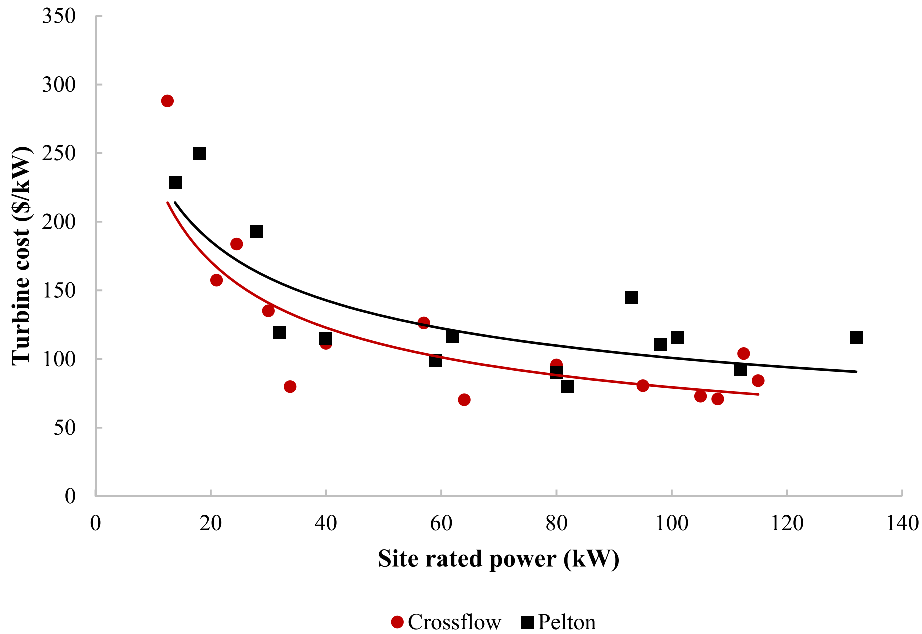

Fig. 6. Cost per kilowatt for the turbine.

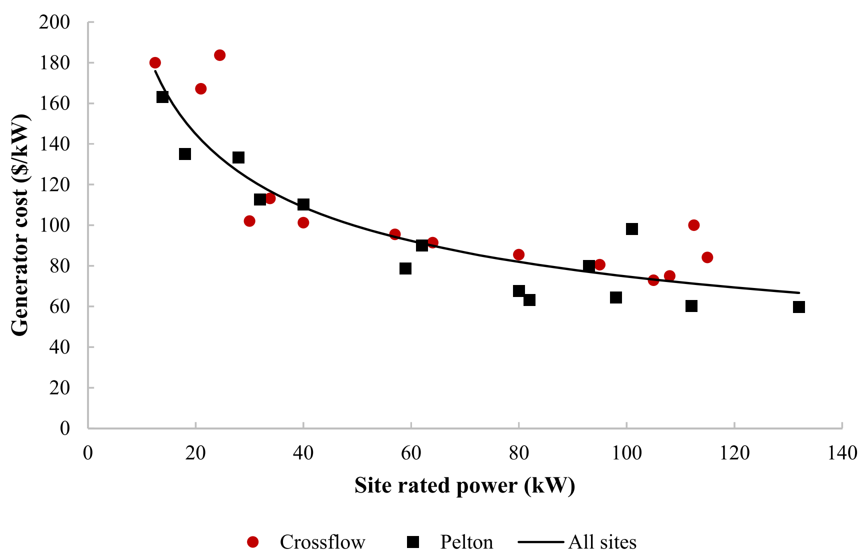

Fig. 7. Cost per kilowatt for the generator.

Various literature (Ogayar and Vidal, 2009; Voros et al., 2000; Gordon, 2003) has suggested that a reasonable estimate of the cost can be determined from the power (P) and head (H) of the site using an expression in the form:

$$COST = aP^{b}H^{c} \tag{1}$$

where a, b and c are coefficients to be determined. Based on the analysis of cost estimation methods in (Cavazzini et al., 2016), a linear regression method was applied to derive an expression in the form of Eq. (1). To allow comparison with other methods which focus on the electro-mechanical equipment alone, the cost of the penstock was excluded. Applying the linear regression method resulted in the following expressions:

$$COST_{Crossflow} = 5399P^{0.837}H^{-0.530} \quad (\$) \tag{2}$$

$$COST_{Pelton} = 7765P^{0.552}H^{-0.237} \quad (\$) \tag{3}$$

In predicting the cost, the expression for Crossflow sites has R = 0.961 and the error between the actual and predicted costs range from −15.8% to 23.2%. For Pelton sites, the expression has R = 0.917 and the errors range from −23.2% to 27.7%. The coefficients in the expressions for the two turbines indicate how the overall cost varies depending on site conditions. The power coefficient (*b* in Eq. (1)) is positive for both Crossflow and Pelton. It's larger value for Crossflow sites indicates that the rate of change of cost increase is higher compared to Pelton sites. In both cases, as the value is less than 1, the rate of change of cost decreases as power increases, agreeing with the relationship shown in Fig. 2. The head coefficient (*c* in Eq. (1)) is negative in both cases, indicating that the overall cost is inversely proportional to the head. This means that for a constant power, if the head were varied, a reduction in the head would increase the overall cost. To generate the same power, at a reduced head,

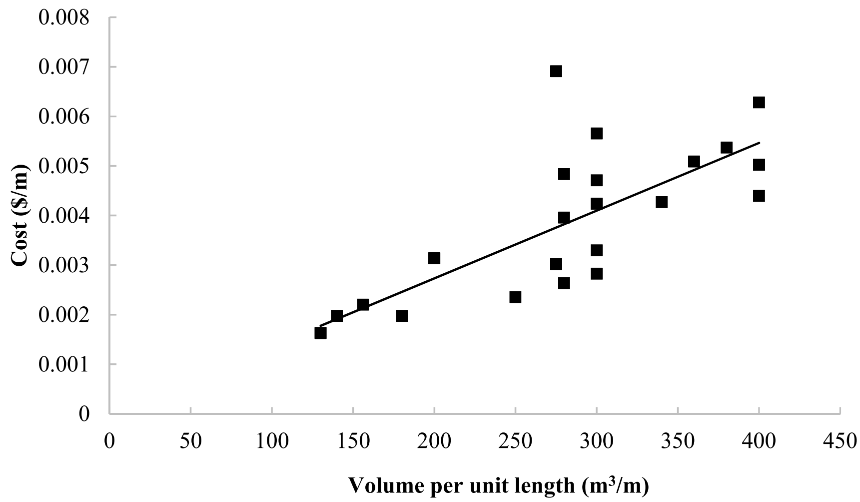

Fig. 8. Cost per metre of penstock material against volume per metre.

requires a larger volume flow rate, therefore larger equipment is generally required, at a higher cost. As head decreases, the length of the penstock is, in fact, likely to decrease, however, this is coupled with an increase in the diameter. Similar to the power coefficient, the head coefficient's absolute value is greater for Crossflow turbines. This means that for a constant power, as head increases there will be a greater proportional reduction in cost for Crossflow sites compared to Pelton sites.

These expressions were used to compare with the costs predicted by the expressions developed by Cavazzini et al. in (Cavazzini et al., 2016) and Ogayar and Vidal in (Ogayar and Vidal, 2009). In both of these publications, the authors provided expressions specific to turbine type. Whilst no expression was present for Crossflow turbines, it was possible to compare the expected cost for Pelton turbines using the generated site data. These earlier publications both provided expected cost in Euros (EUR). For ease of comparison, all values have been converted into USD. Historic annual average exchange rates have been used to change values from Euros to USD at the time of the studies (i.e., 2009, 1 EUR = 1.12 USD, and 2016, 1 EUR = 1.22 USD (OFX. Yearly Average Rates, 2021)) with changes in inflation (2009–2019, 19.2% (Official Inflation Data, 2021) and 2016 to 2019, 6.52% (Official Inflation Data, 2016)) applied subsequently. This follows the method for conversion of currency values described in (Turner et al., 2019). Fig. 9 plots the results showing the specific costs predicted by 3 expressions for all of the sites.

It can be seen that all three cost models show a trend of decreasing specific cost for increasing rated power. The expression developed in this study provides a good match to the quoted costs. The other expressions show a similar trend, specific cost decreases for higher rated powers, but overestimate cost by a factor greater than 2.5. There are a number of reasons that could account for the large difference between the predicted costs and the quoted costs. In general, the expressions from the other literature and derived from European site data predict a far higher cost for the sites. Therefore, it can be assumed that for equivalent rated powers, the cost of electro-mechanical equipment is significantly less in Nepal than Europe. This could be accounted for by both cheaper labour and materials. An International Labour Organisation report published in 2020 placed the monthly minimum wage of Nepal at $119 (Office, 2020). In the same report, amongst the European countries

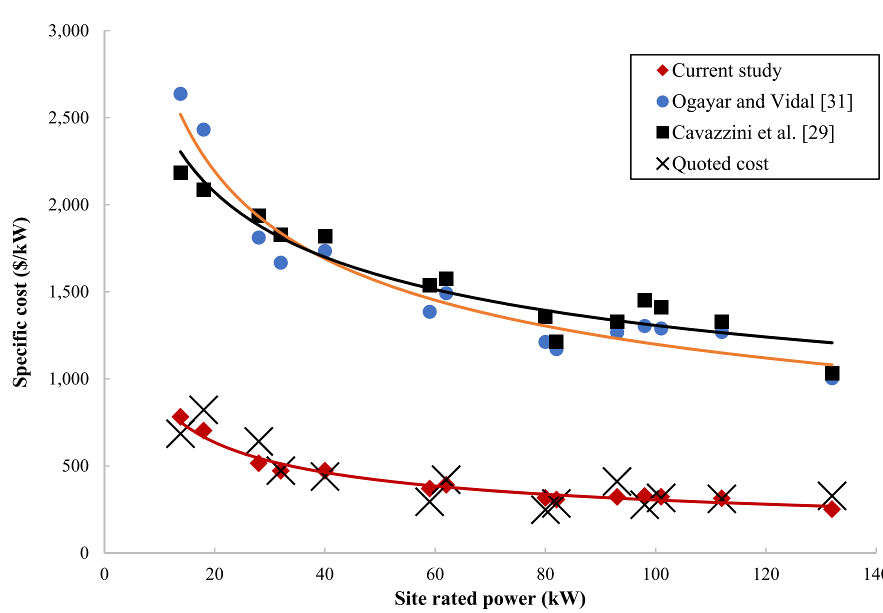

Fig. 9. Comparison of original data with cost estimation methods for the randomly generated sites.

included, the range of minimum wage was from $232 in Bosnia and Herzegovina to $2339 in Luxembourg. For the cost of materials, the cost of steel (in Nepal predominantly imported) from India is typically lower. For example, in 2019, the price of hot rolled coil steel was on average 458 EUR/tonne in Europe and 392 EUR/tonne in India (Medarac et al., 2020). The material costs are further compounded by cheaper transportation costs: lower driver wages and fuel prices.

The expressions developed in Eqs. (2) and (3) provide a rapid method for estimating the cost of electro-mechanical equipment in Nepal. For both the Pelton and Crossflow turbine, they could be used to determine a reasonable envelope of expected costs. As such, they allow communities and government stakeholders to evaluate the viability of quotes by identifying values that are infeasibly low or high. It should be noted that the expressions were developed using a total of 14 sites for each turbine type. By surveying 7 manufacturing companies, it was hoped that some of the inherent variability in costing was accounted for. The ongoing collection of cost data from actual sites could be used to increase the accuracy of the expressions.

The results of the cost survey are useful in a number of other ways. They have established the typical proportion of costs of various subsystems of the electro-mechanical equipment. Within all forms of hydropower, the penstock and its cost are often a source of attention. The results here suggest that particularly for Pelton turbines, concentrating effort on the penstock could be the simplest route to reducing cost. Typically in Nepal, where steel penstocks are used, manufacturing companies produce them using rolled steel sheet (Butchers, 2020). As such a large cost contributor, exploring alternative options, e.g., procuring ready-made pipes, could be appropriate. Beyond individual components, the data has established typical expected costs for electro-mechanical equipment in Nepal. The data means that in the development of new projects and even the introduction of new turbine types, e.g., the Francis and Turgo, there is a target cost to aim for. The survey was limited to the micro-hydropower range, however, the results may still provide a useful insight into the expected costs for production of mini-hydropower equipment. In Nepal, at the mini-hydropower scale, turbines are often imported from abroad. The results here can be used to estimate expected costs at the mini-hydropower scale in Nepal. When compared with expected prices for the foreign turbines, evaluation of the difference could be used to understand additional cost that could be incurred in the pursuit of increased quality.

The results of the survey can also be used in comparison with other electrification options, e.g., solar (PV) installations. In making such comparisons, it should be noted that the total cost of micro-hydropower also includes civil structures and the transmission and distribution network. The range for electro-mechanical equipment from this study was from 256 $/kW to 948 $/kW, with a mean of 447 $/kW. Referring back to Table 2, it is possible to estimate a total cost. Using the highest (53%) and lowest values (30%) for the proportional contribution of the electro-mechanical components, and applying them to the mean, the range in specific cost is 843 $/kW to 1490 $/kW. These values should be used with caution; however, they can be used to compare with the average specific costs provided earlier for small hydro and large hydro, 2459 $/kW and 1865 $/kW respectively. Considering other options for rural communities, the cost can also be compared with that of solar. In (Poudyal et al., 2021), costing is provided for a 3 kW off-grid solar supply system and ancillary equipment (including a battery). The total cost for the system is $2841 giving a specific cost of 947 $/kW. It appears that the cost of micro-hydropower compares favourably with larger scale hydro installations. Against solar, the results suggest that more expensive (likely lower rated power) sites struggle to be cost competitive with solar. For larger sites, based on these estimations, micro-hydropower can be competitive and provides the benefit of day-long power and the ability to sustain larger industrial loads. These values allow some estimation of the additional contribution of civil costs, however, their accuracy is unknown. Further work is required to evaluate the contribution of civil structures and the transmission network to the overall cost of MHP installations in Nepal.

With the collection of additional data regarding the cost of civil structure and distribution networks, the complete cost of micro-hydropower installations could be more accurately predicted. For all technologies, it is worth considering economic factors beyond the capital cost. In the case of Nepal, rural communities are rarely able to afford to pay capital costs upfront and with banks unwilling to provide loans, the development of micro-hydropower has relied upon subsidies (Kumar et al., 2015). This work has helped to benchmark some of the capital costs, however, beyond installation there are ongoing costs associated with operation and maintenance (Butchers et al., 2020; Winrock International, 2017). The longer-term sustainability of micro-hydropower has been discussed in the context of Nepal and elsewhere. For the locations where it is an economically feasible choice, there remains work in identifying financial structures that make it viable for local communities. With better information regarding operational income and cost for MHPs, it would be possible to conduct more extensive financial analysis. Break even and return on investment analysis would aid comparison of micro-hydropower with other technologies. This is the case regardless of country context. The work presented here has shown that with a simple and repeatable methodology, it was possible to establish the cost of electro-mechanical equipment. If replicated in multiple country contexts, there may be a greater opportunity to demonstrate that locally manufactured hydropower technology can continue to play a role in rural electrification.

5. Conclusions

Whilst locally manufactured micro-hydropower provides an option for rural electrification, its associated costs are reported with far less frequency than larger forms of hydropower and other electrification options. In this paper, a simple methodology has been used to collect expected cost data for electro-mechanical, hydro-mechanical equipment and their installation for MHPs in Nepal. The results indicated a mean cost per kilowatt for Crossflow and Pelton sites of 505 $/kW and 605 $/kW respectively. The results have allowed identification of the most expensive sub-systems and the relative costs between them. Based on methods applied in previous work, expressions have been developed which allow prediction of costs for Pelton and Crossflow turbines based on inputs of rated power and head. When compared with existing methods, the expressions developed here predicted cost with far greater accuracy. The comparison demonstrated that costing expressions rely on local data to capture regional differences in cost. The results could be used to evaluate the acceptability of quotations, both at the sub-system level and overall. The key contribution of this work is establishing numerical expressions which allow proposed costs of micro-hydropower equipment to be rapidly evaluated. This can help to ensure that rural communities in Nepal are provided technology at fair and appropriate prices. Repetition of the methodology elsewhere can establish an improved understanding of the cost of locally manufactured hydropower technology worldwide.

Data availability

Data is available on request.

Funding

This research was funded through a PhD studentship from the Engineering and Physical Sciences Research Council, award reference 188052 and through Energize Nepal, project reference number ENEP-RENP-17-01.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aggidis, G.A., et al., 2010. The costs of small-scale hydro power production: impact on the development of existing potential. Renew. Energy 35 (12), 2632–2638.

Alternative Energy Promotion Centre, Progress at a Glance: A Year in Review FY 2074/75 (2017/18), 2018.

Alternative Energy Promotion Centre, Progress at a Glance: A Year in Review FY 2075/76 (2018/19), 2019. Nepal, Kathmandu.

Alternative Energy Promotion Centre, Progress at Glance: Year in Review FY 2076/77 (2019/20) and FY 2077/78 (2020/21), 2021. Nepal, Kathmandu.

Alternative Energy Promotion Centre, Bill of quantities and specifications of electro-mechanical equipment and installations jhumara Khola micro hydro project (11KW) laha-06, jajarkot alternative energy promotion Centre, Editor., Government of Nepal: Kathmandu, Nepal.

Alternative Energy Promotion Centre, Bill of quantities and specifications of electro-mechanical equipment and installations manpang Khola II micro hydro village electrification project (11 kw). Alternative Energy Promotion Centre: Kathmandu, Nepal.

Alternative Energy Promotion Centre, Bill of quantities and specifications of electro-mechanical equipment and installations sot Khola micro hydro project (28KW), surkhet Alternative Energy Promotion Centre: Kathmandu, Nepal.

Arter, A., 2011. Micro-Hydropower in Nepal: Enhancing Prospects for Long-Term Sustainability. Entec: st gallen.

Bhandari, R., Saptalena, L.G., Kusch, W., 2018. Sustainability assessment of a micro hydropower plant in Nepal. Energy. Sustainability and Society 8 (1), 3.

Bhattacharyya, S.C., Palit, D., 2014. Mini-grids for Rural Electrification of Developing Countries: Analysis and Case Studies from South Asia. Springer.

Butchers, J., 2020. Enabling sustainable and reliable energy using locally manufactured micro-hydropower technology. In: Mechaning Engineering. University of Bristol.

Butchers, J., et al., 2020. Understanding sustainable operation of micro-hydropower: a field study in Nepal. Energy for Sustainable Development 57, 12–21.

Butchers, J., et al., 2021. A rationalised CFD design methodology for Turgo turbines to enable local manufacture in the Global South. Energies 14 (19), 6250.

Cavazzini, G., et al., 2016. Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling. Energy 103, 746–757.

Centre, A.E.P., 2021. Mini/micro hydro. Available from: https://www.aepc.gov.np/statistic/minimicro-hydro. (Accessed 13 December 2021).

Conroy, C., Litvinoff, M., 2013. The Greening of Aid: Sustainable Livelihoods in Practice. Routledge, London, UK.

Consulting, P.A., 2017. Technical assistance for developing an enabling policy environment to accelerate development of clean energy through mini and small hydropower in Nepal. In: Practical Action Consulting. Nepal, Kathmandu.

Cromwell, G., 1992. What makes technology transfer? Small-scale hydropower in Nepal's public and private sectors. World Dev. 20 (7), 979–989.

Dutta, S., Sing, R.P., Thakali, H., 2007. Terminal review report, rural energy development programme. In: United Nations Development Programme. Nepal, Kathmandu.

Ferrer-Martí, L., et al., 2012. Evaluating and comparing three community small-scale wind electrification projects. Renew. Sustain. Energy Rev. 16 (7), 5379–5390.

Ghimire, A., et al., 2019. Opportunities and challenges of introducing Francis turbine in Nepalese micro hydropower projects. In: Journal of Physics: Conference Series. IOP Publishing.

Gordon, J., 2003. Determining "Ballpark"costs for a proposed project. Hydro Rev. 11 (1), 37–41.

Gurung, A., Gurung, O.P., Oh, S.E., 2011. The potential of a renewable energy technology for rural electrification in Nepal: a case study from Tangting. Renew. Energy 36 (11), 3203–3210.

Gurung, A., Ghimeray, A.K., Hassan, S.H., 2012. The prospects of renewable energy technologies for rural electrification: a review from Nepal. Energy Pol. 40, 374–380.

IEA, Hydropower Special Market Report, 2021. IEA. France, Paris.

IEA, et al., 2021. Tracking SDG 7: the Energy Progress Report. World Bank, Washington D.C.

Interview with Alternative Energy Promotion Centre Official, 2022.

IRENA, 2012. Hydropower, in Renewable Energy Technologies: Cost Analysis Series. IRENA.

IRENA, renewable power generation costs in 2020. In: International Renewable Energy Agency, 2021. Abu Dhabi.

Kumar, P., Tomoyuki, Karki, et al., 2015. Nepal-scaling up Electricity Access through Mini and Micro Hydropower Applications: a Strategic Stock-Taking and Developing a Future Roadmap. World Bank, Washington, USA.

Leary, J., While, A., Howell, R., 2012. Locally manufactured wind power technology for sustainable rural electrification. Energy Pol. 43, 173–183.

Medarac, H., Moya Rivera, J.A., Somers, J., 2020. Production Costs from Iron and Steel Industry in the EU and Third Countrie. P.O.o.t.E. Union, Luxembourg.

Meier, U., Arter, A., 1989. Solving problems of micro hydro development in Nepal. In: International Water Power & Dam Construction, vol. 41, pp. 9–11, 6.

Nepal Electricity Authority, A Year in Review Fiscal Year 2020/21, 2021. Nepal, Kathmandu.

Office, I.L., 2020. Global Wage Report 2020–21: Wages and Minimum Wages in the Time of COVID-19. ILO, Geneva.

Official Inflation Data, A.F. Value of $1 from 2016 to 2018. [Accessed 13 December 2021]; Available from:: https://www.officialdata.org/us/inflation/2016?endYear=2018&amount=1.

Official Inflation Data, 2021. A.F. Value of $1 from 2009 to 2018. Available from: https://www.officialdata.org/us/inflation/2009?endYear=2018&amount=1. (Accessed 13 December 2021).

OFX. Yearly Average Rates, 2021. Available from: https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/.

Ogayar, B., Vidal, P., 2009. Cost determination of the electro-mechanical equipment of a small hydro-power plant. Renew. Energy 34 (1), 6–13.

Paish, O., 2002. Small hydro power: technology and current status. Renew. Sustain. Energy Rev. 6 (6), 537–556.

Palit, D., Chaurey, A., 2011. Off-grid rural electrification experiences from South Asia: status and best practices. Energy for Sustainable Development 15 (3), 266–276.

Poudel, B., et al., 2021. Factors influencing the sustainability of micro-hydro schemes in Nepal. Renew. Sustain. Energy Rev. 151, 111544.

Poudel, B., Parton, K., Morrison, M., 2022. The drivers of the sustainable performance of renewable energy-based mini-grids. Renew. Energy 189, 1206–1217.

Poudyal, R., Loskot, P., Parajuli, R., 2021. Techno-economic feasibility analysis of a 3-kW PV system installation in Nepal. Renewables: Wind, Water, and Solar 8 (1), 1–18.

Reinauer, T., Hansen, U.E., 2020. How open-source hardware can succeed: a conceptual framework and case study of small wind turbines. In: 11th International Sustainability Transition Conference. Austria, Vienna.

Singal, S., Saini, R., Raghuvanshi, C., 2010. Analysis for cost estimation of low head run-of-river small hydropower schemes. Energy for sustainable Development 14 (2), 117–126.

Sovacool, B.K., et al., 2013. Peeling the energy pickle: expert perceptions on overcoming Nepal's electricity crisis. S. Asia 496–519.

Turner, H.C., et al., 2019. Adjusting for inflation and currency changes within health economic studies. Value Health 22 (9), 1026–1032.

Urmee, T., Md, A., 2016. Social, cultural and political dimensions of off-grid renewable energy programs in developing countries. Renew. Energy 93, 159–167.

Voros, N., Kiranoudis, C., Maroulis, Z., 2000. Short-cut design of small hydroelectric plants. Renew. Energy 19 (4), 545–563.

Williamson, S., 2013. Modular and Scalable Low-Head Pico-Hydro Generation for Off-Grid Networks. University of Bristol.

Winrock International, 2017. Baseline report of micro hydro plants (MHP) selected under sharing learning across projects: operating MHPs as commercially viable enterprises. In: Winrock International. Nepal, Kathmandu.

X-Rates, 2021. Exchange rate average (Nepalese rupee to US dollar in 2018). Available from: https://www.x-rates.com/average/?from=NPR&to=USD&amount=1&year=2018. (Accessed 15 December 2021).