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Article

A Methodology for Renovation of Micro-Hydropower Plants: A Case Study Using a Turgo Turbine in Nepal

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ABSTRACT

For off-grid communities, micro-hydropower continues to provide affordable and reliable electricity access across the world. In Nepal, despite ongoing development of large-scale hydropower projects and the extension of the national grid, there remain many off-grid communities that depend on micro-hydropower plants. Over time, these systems are prone to erosion from sediment in the water, which, together with other degrading mechanical and environmental effects, may lead to reduced reliability and potential failure. Extreme weather and natural disasters can also cause catastrophic failure of the plant and its infrastructure. In such cases, Nepali micro-hydropower companies are best placed to conduct renovation works.

Where renovation is required, the selection of a different turbine type could be beneficial. Recent work has demonstrated the potential of the Turgo turbine for use in Nepal due to several advantageous features. In this paper, a methodology is applied to explore the feasibility of a site for refurbishment considering environmental, social, technical, economic, and legal factors. Subsequently, a series of design and costing activities are used to demonstrate that the Turgo turbine can be implemented. A Turgo turbine design is scaled appropriately and manufactured by a Nepali company. The turbine demonstrated an increase in power generated, from 18 kW for the existing turbine to 32 kW for the newly installed turbine. The potential for Turgo turbines at other sites around Nepal is analysed, demonstrating it could be used to renovate and improve energy production at many sites across the country.

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INTRODUCTION

The 2015 Nepal earthquake was estimated to have damaged 262 micro-hydropower plants (MHPs, plants with power outputs < 100 kW) in the districts surrounding the earthquake's epicentre, impacting over 37,000 households [1]. Small-scale natural disasters are also prevalent in Nepal, such as landslides, flooding and avalanches, and these can often affect MHPs due to their location in the base of valleys near water courses. Even without extreme events, commissioned sites often do not last as long as the 50 years that could be expected. Sites can fail for many reasons but generally due to poor maintenance [2]. The impact of a failed community MHP can be severe, impacting lifestyle, health and income generation [3]. These failures provide an opportunity to renovate, refurbish and upgrade hydropower sites, using updated designs and technology to provide an improved service to the community [4].

Around the world, there is significant activity in the renovation and refurbishment of existing hydro sites. In Europe, some 350,000 small and micro-hydropower sites (including historic mills) are estimated to be abandoned, with over 24,000 restored recently, some adopting new turbine technologies [5]. Upgrading existing watermills with a generator for electricity generation has been a successful strategy in some Asian countries [6]. In Japan, the potential is being reassessed to include less conventional sites from existing infrastructure facilities, such as dams, weirs, irrigation channels, water supply and sewerage systems, to avoid environmental impacts [7].

Whilst many guidelines exist for the development of small-scale hydropower plants [8,9], there are limited resources regarding the renovation of plants. Documents such as a European Union commissioned handbook that offers guidelines for the renovation process [5] and a World Bank report [10] that discusses important economic technical issues, are the exceptions here. Within academia, several studies have focused on various considerations related to renovation. It has been found that it is difficult and expensive to extend an existing system and often, the whole system has to be re-built to improve power output [11]. In Croatia, Bojic et al. [12] considered that the refurbishment option for a small hydropower plant, was the most favourable option across a number of technical and economic indicators, such as improved reliability, and increased electricity production with the lowest investment cost. Quaranta et al. [13] presented a techno-economic analysis to aid users considering repowering vertical axis water mills. Across all these sources, community ownership, a key aspect present in Nepal, is not considered.

Previous work has explored some of the challenges associated with the development and operation of community owned micro-hydropower projects. As a site's geographical features affect seasonal waterflow and frequency of landslides and flooding, design and construction of civil structures is important. In Nepal, poor design and low quality of construction have been reported [14], and whilst installation companies are responsible for directing communities in construction, but often the results are poor [15]. At the operational stage, training of maintenance staff and finances have been identified as important factors affecting economic sustainability of plants [16]. In particular, the availability of trained operators for plants is a universal problem and was identified 30 years ago by Faruqui [17]. The remote location of sites has an impact on many of these issues, reducing the availability of trained operators, affecting the provision of spare parts, and reducing the opportunity for income generation. In plant renovation, these pre-existing challenges should not be overlooked.

Regardless of ownership status, when considering sites for renovation, it is important to consider multiple technology options and determine the most viable, particularly for the turbine (and the complete electromechanical sub-system). A comparison of key indicators such as return on, and amount of, capital investment cost, and predicted power output (and efficiency) against the previous installation is useful for decision making [18]. Essentially, these indicators provide both economic and technical drivers for final selection. In general, despite some efforts [19], cost modelling of civil works is challenging. For electro-mechanical sub-systems, however, the cost of component replacement can be more accurately estimated meaning the benefits of higher efficiency and reliability can be evaluated. Therefore, an important choice is the turbine and generator set, as it not only represents a large cost commitment [20–22], but also is crucial in determining the potential performance at the existing site (see Figure 1). Costing approaches have been developed for many different turbine types: Pelton [18,21,23], Francis and Kaplan [21,22], Crossflow [18] and Turgo [13]. Other important considerations will also need to be made, such as reliability of flow, nearby utilisation of generated electricity, environmental factors and water quality [24].

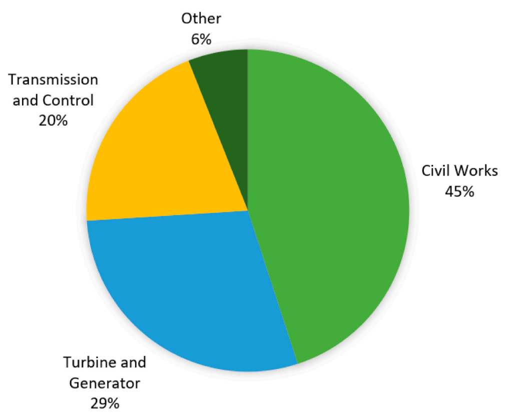

Figure 1. Median cost contribution to micro-hydro power installations. Civil works include the penstock cost. Adapted from references [18,21,22,25].

The option of renovation and repowering a site can enable new turbine designs to be installed to improve the performance. In the Nepali context for micro-hydropower turbines, historically there have been only two designs that are locally manufactured, that of the Crossflow and the Pelton, both introduced by international development agencies [26]. However, over the past ten years, three additional designs have been developed that can be manufactured locally in Nepal: a propeller turbine [27], Francis turbine [28] and Turgo turbine [16]. The Turgo turbine is especially interesting, as it can easily be retrofitted into existing infrastructure with minimal adaptation for both Pelton and Crossflow sites. Furthermore, it can bridge between the typical operational ranges (e.g., head and flow rate limits) of the Pelton and Crossflow.

In this paper, the use of a Turgo turbine will be investigated for the renovation an existing micro hydropower installation site in Nepal. A methodology is developed for assessing the viability of the renovation, and the process of renovation and its outcomes are presented. The efficacy of the methodology and the potential for the implementation of the Turgo turbine elsewhere are also discussed.

TURGO TRUBINE

In Nepal and other countries in the Global South with significant hydropower resources, local companies produce hydro-turbines at the micro-scale. Typically, these companies manufacture Pelton turbines to serve sites with high head, and Crossflow turbines for sites with low head. Whilst these turbines can accommodate many different sites, an extended range of designs could provide advantageous features and cost benefits.

Using data from existing sites in Nepal from [29] and data collated by the authors, Figure 2 shows the flow rate and head for a selection of Crossflow and Pelton sites. The site characteristics for the renovated site are also included. The general trend is that Crossflow turbines are used at sites with head less than 50 m, and Pelton turbines for those with a higher head. By applying several constraints, it is possible to identify the region with greatest uncertainty in turbine selection. That is, a region where for the same site characteristics, either turbine could be selected. The region is generated between horizontal lines passing through points corresponding to the lowest head for a Pelton site and highest head for a Crossflow site, and between vertical lines corresponding to the lowest flow rate for a Pelton site and highest flow rate for a Crossflow site. Consequently, the region represents the combination of head and flow rate where, based on the site data, there is no substantial preference for either turbine type. It should be noted that the dataset is limited in size. From the literature, it is suggested that at the interface between the turbine types, Peltons are large (i.e., expensive), and Crossflows are narrow (i.e., difficult to manufacture) and inefficient [30]. For sites at the interface, the Turgo turbine could provide a viable alternative. The Turgo turbine operates similarly to a Pelton turbine, the change of momentum of a jet interacting with a blade is used to generate torque. The difference is that the jet enters and exits on opposites sides of a runner (as shown in Figure 3a). An isometric drawing of a Turgo turbine runner is shown in Figure 3b.

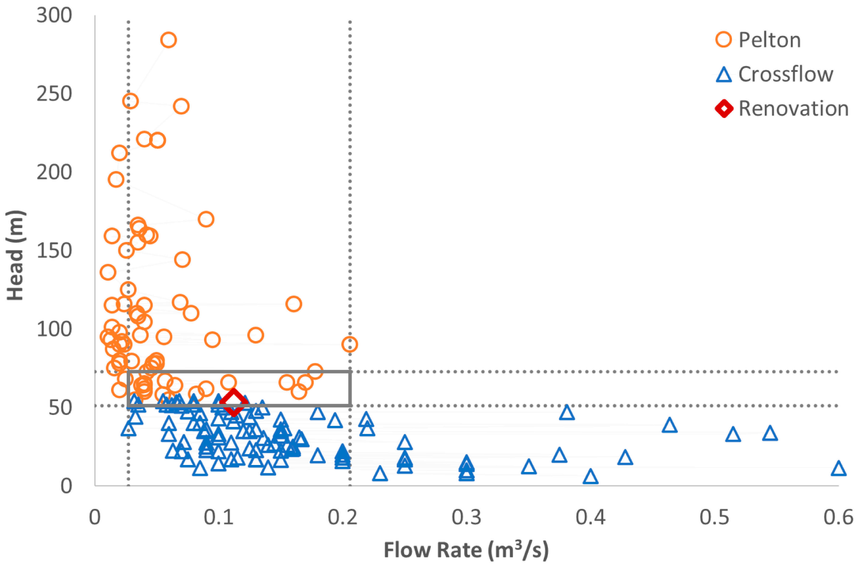

Figure 2. Flow rate vs. head for Pelton and Crossflow installations in Nepal. Adapted from reference [29].

A standardised design for a small-scale Turgo turbine has been the focus of research by the authors for the last decade [27]. The intention was the design would be scalable, open source and, to a large extent, manufacturable by local companies, and this was found to be the case as reported here. Other studies suggest that the manufacturing technology is available in Nepal to adequately produce Francis turbines too [28]. Increased local manufacture has the potential to promote sustainable supply chains and system reliability through access to skills and spare parts.

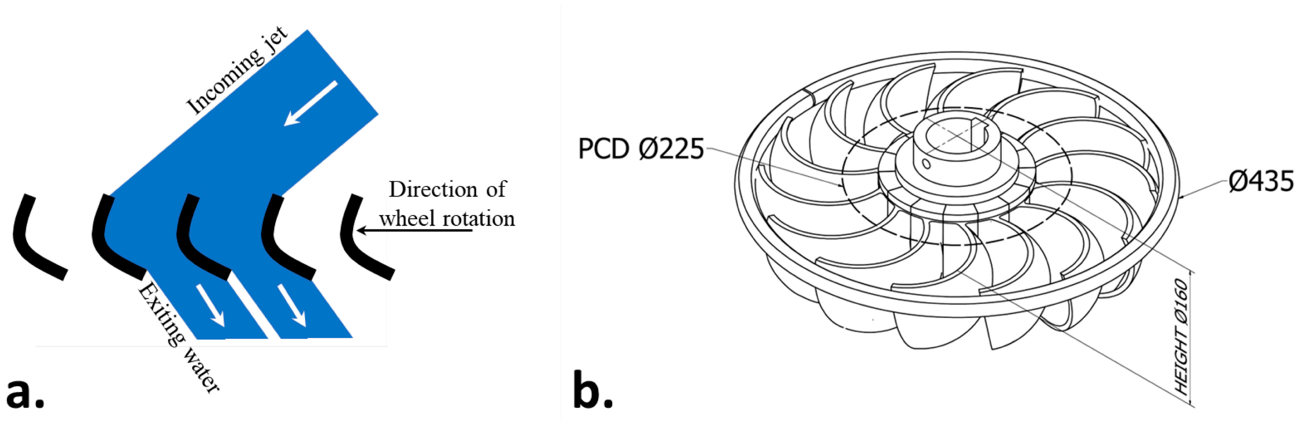

Figure 3. **(a)** Diagram showing Turgo turbine operation adapted from [31] and (**b**) isometric drawing of a Turgo runner including dimensions (in mm) for the installation described in this paper, PCD indicates the pitch circle diameter.

METHODOLOGY

In order to demonstrate that the Turgo turbine could be used to renovate a MHP, it was necessary to find a feasible site. In this case, the intention was to identify a site that would be appropriate for the Turgo turbine. Despite this, the methodology presented here can still be applied at any existing micro-hydropower plant to determine the feasibility of a site for renovation. Figure 4 summarises the methodology. As indicated in the literature, the development and operation of MHPs is complex, depending on social, technical, environmental, and economic factors alongside legal and governmental considerations. The methodology considered these five areas. An initial phase involved data collection to address key questions relating to the characteristics of the site, its present condition and information that would help determine feasibility. The information collected could then be used to complete a series of actions, shown in the green boxes, that would ultimately determine whether a site was feasible for renovation.

It involved a phase of data collection followed by preliminary design and costing. The yellow boxes indicate the key questions to be answered that determined the site's feasibility and its characteristics. The information collected could then be used to complete the subsequent actions.

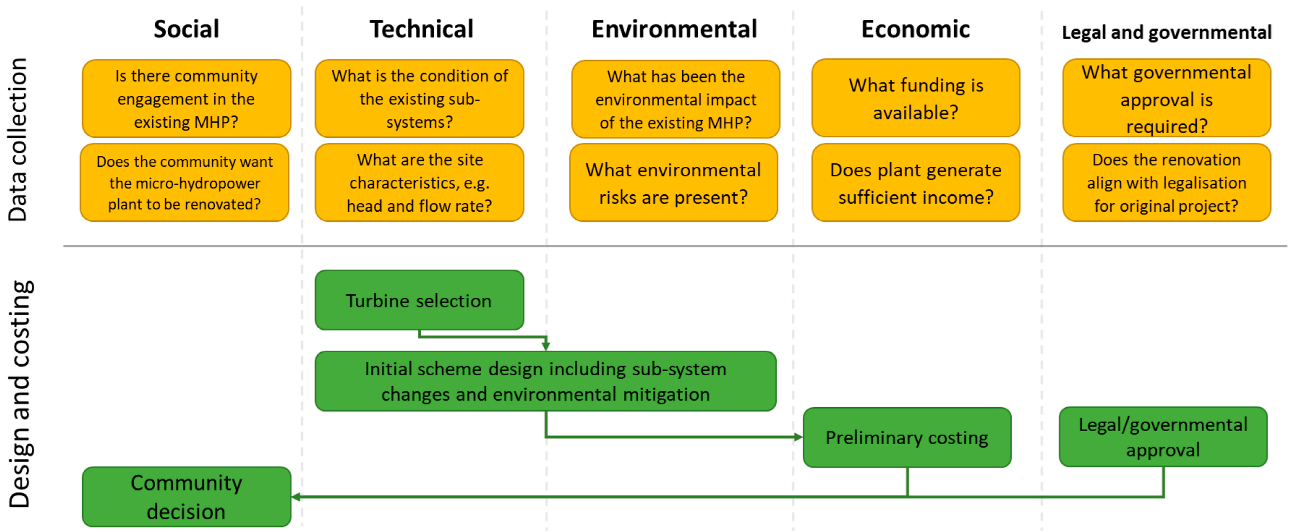

Figure 4. Methodology for site renovation feasibility.

At the final stage, if the project was deemed feasible by the community, typical steps of the project cycle could be followed, e.g., detailed design, manufacture, community mobilisation for construction, testing and commissioning, as described in [15,32]. In the following sections, the data collection, and design and costing phases for the project are described.

Data Collection

A potential site for renovation called Mangmaya Khola I MHP (referred to here as Mangmaya), was identified in Sangu, Taplejung district. The site was identified by Nepal Yantra Shala Energy (NYSE, a project partner and turbine manufacturer) who had installed a turbine in the local area. Table 1 lists important features of the MHP.

Table 1. Key details of Mangmaya Khola I MHP.

Name	**Mangmaya Khola I MHP**
Location	Sangu, Taplejung
Year of installation	2005
Rated power	27 kW
Design flow (Q_{max})	112 l/s
Design head (H)	53 m
Canal length	480 m
Ownership	Community owned with 11 members on the committee

Over time, the power output of the plant had reduced to approximately 18 kW. It was observed that the existing turbine was leaking which contributes to reduced power output. The turbine was not disassembled but it can be assumed that due to the length of time in operation, the Crossflow turbine blades will have been eroded. This contributes to decreased power output due to deviation of the blades from their original form. The inside of the powerhouse including key components is shown in Figure 5.

To establish site feasibility, staff from the People, Energy and Environment Development Association (PEEDA, a project partner and non-governmental organisation) were sent to conduct the data collection methods outlined in Table 2. Using these methods, data was collected that allowed the key questions to be answered. A summary of the collected data is shown in Table 3.

Figure 5. Inside of the powerhouse at Mangmaya Khola I including turbine (1), inlet valve (2), belt drive transmission (3), generator (4) and control panel (5).

Table 2. Methods for collecting data.

Method	Description
Site assessment	An evaluation of the MHP sub-systems using the methodology explained in [32].
Interview with plant operator	An interview with plant the operator was to understand the plant's current status, historical performance and the approach to maintenance taken.
Interview with MHP manager/chairperson	An interview with the MHP manager and chairperson was used to collect data regarding the current financial status and the plant's management strategy.
Community meeting	A meeting with MHP committee members and MHP beneficiaries to gauge community perspective of the existing MHP and to collect opinions on the potential renovation.
Site data collection	Data collection regarding site characteristics and measurement of relevant dimensions.

Table 3. Summary of collected data from Mangmaya Khola MHP.

Question	Outcome
Is there community engagement in the existing MHP?	The plant is run by a committee with 11 members, including 4 women. A public audit and general meeting are conducted on an annual basis.
Does the community want the micro-hydropower plant to be renovated?	The output of the existing turbine had reduced from 27 kW to 18 kW. Due to the impact upon community, strong interest in renovating the MHP. The nearest location of the national grid is 2 hours walk away.
What is the condition of the existing sub-systems?	Most civil structures in an acceptable condition. Some places where small cracks are present in concrete structures and vegetation is overgrown. The condition of ballast tank was very poor with leakage and rusting. The quality of powerhouse maintenance and cleanliness was poor.
What are the site characteristics?	For the existing turbine, rated conditions are head of 53 m and design flow 112 l/s. Water source is from the tailrace of another MHP. When flow rate is low, additional water can be extracted from a canal fed by a river.
What has been the environmental impact of the existing MHP?	No significant environmental impact of the existing MHP. The powerhouse is located in a safe position in relation to the river. It is placed well above the flood plain and set at least 5 m away from the river edge. In general, the MHP is located within a steep sided valley, therefore landslides remain a risk, however, the plant itself has not significantly affected this. When monsoon flooding occurs, the temporary intake structure is rebuilt. Where the water is returned to the river, the tailrace is reasonably effective in slowing the water flow down with no evidence of river erosion seen. The water speed could be slowed further by using stone pitching which would reduce the erosion downstream.
What funding is available?	Funding was available from EnergizeNepal Program (ENEP) [33] to cover the costs of turbine installation. The community were willing to contribute in-kind labour but reluctant to offer a cash contribution.
Does plant generate sufficient income?	Typically, approximately 60% of the expenses for the plant (employee salaries) were collected each month. Productive end uses often paid their tariffs on a half annual basis meaning salaries had to be paid in arrears. As a result, additional costs for repair and maintenance have been managed on an ad-hoc basis. There is no additional charge for late payment. Accounting records of expenses and income are kept.

Design and Costing

Turbine selection

As explained in [9], the primary considerations for turbine selection are head and flow rate. The performance requirement under part-flow conditions and the operational speed of the turbine are also factors that require consideration in the selection process, particularly at sites where more than one turbine could be implemented. As demonstrated in Figure 2, in the context of Nepal, particular combinations of head and flow rate may result in the selection of different turbines. As a result, as part of renovation, it should not be assumed that a turbine with the same dimensions should be installed. Furthermore, environmental (e.g., reduced rainfall) or social changes (e.g., alternative water use) may have changed the volume of water available.

As the objective of this project was to install a Turgo turbine, the selection was focused on assessing the feasibility of the Turgo turbine alone. In other cases, it is likely that turbine manufacturers will employ their own methods for determining what is the most appropriate turbine to install at any given site. Examples of selection methods can be found in [9] and, specific to Nepal in [34]. Previous work by the authors has focused on the design and optimisation of a Turgo turbine runner for manufacture in Nepal. This has included experimental testing of a small-scale 1 kW prototype [35], and subsequent optimisation using computational fluid dynamics (CFD) resulting in an improvement in efficiency from 69% to 81% [36]. The resulting optimised design could then be scaled using non-dimensional numbers derived from the outputs of computational modelling. Site parameters could then be used to determine whether a Turgo turbine could be installed. For hydropower turbines, commonly used dimensionless groups are the flow coefficient (C_Q), head coefficient (C_H), power coefficient (C_P), and the specific speed (C_ω), which is derived from the power and head coefficients.

$$C_Q = Q/(\omega D^3) \quad (1)$$

$$C_H = gH/(\omega^2 D^2) \quad (2)$$

$$C_P = P/(\rho \omega^3 D^5) \quad (3)$$

$$C_\omega = C_P^{0.5}/C_H^{1.25} = (\omega P^{0.5})/(\rho^{0.5}(gH)^{1.25}) \quad (4)$$

where, Q is the flow rate in m^3/s, ω is the rotational speed in rad/s, D is a length dimension in m (typically the pitch circle diameter (PCD), the tangential diameter at which the centre of the jet impacts the runner [37]), g is the acceleration due to gravity in m/s^2, and H is the head in m. Specific speed is a dimensionless parameter associated with the maximum efficiency of dimensionally similar turbines and is commonly used in scaling [38]. Using the head and flow rate of the site, it was possible to calculate that a Turgo turbine could be scaled from the existing size to a PCD of 0.225 m and expected rotational speed of 1270 rpm. Based on [37], it was decided that the chosen design could be used in a direct drive configuration operating at 15% less than a rated generator speed of 1500 rpm.

Initial scheme design

The design of all sub-systems impacts upon the plant's performance; both efficiency and reliability are affected by the scheme's design. In Nepal, there is evidence from multiple sources of poorly designed or constructed civil structures, e.g., de-silting bays and canals [15,27]. When defective, these sub-systems are likely to increase the volume of debris that passes through the civil works and the turbine, resulting in more erosion. In general, renovation can provide an opportunity to identify and address issues with the plant with the objective of improving overall energy production [11]. Even where considerable design changes (other than the turbine) are not required, the enforced system downtime can allow for maintenance activities that support improved energy generation.

Based on the site assessment, several site improvements were identified to improve the plant's reliability. These improvements were:

- Low flow rate into canal—Due to a temporary intake structure, design flow rate was not achieved consistently. It was proposed to re-direct flow from another source into the canal.
- Debris in canal—Throughout the length of the canal, there were stones and silt deposited. These reduce flow rate through the canal and can increase erosion. It was proposed that the canal was shut off and the debris removed along its length.
- Leakage in forebay tank—In the forebay tank, there were several places where there was leakage in the stone masonry. It was proposed that the forebay tank is drained and cement is used to repair the cracks.

In addition to these improvements, based on the site assessment and the interviews, it was decided that the powerhouse and penstock could be adapted to allow the new turbine to be installed alongside the existing turbine. The motivation for this was to allow the existing turbine to be used if the new turbine faced any issues during its testing and commissioning. Measurements were taken at the powerhouse to confirm that this adaptation would be possible.

Preliminary costing

For energy projects, in general, cost is a crucial driver when assessing project feasibility. When deciding to refurbish a project, accurate prediction allows the cost of refurbishment to be compared with the installation of alternative energy technologies. For hydropower, a number of different costing methods have been developed for different turbine types. In general, the cost of hydro-mechanical and electrical components is more predictable than for civil structures, which can vary significantly depending on local geography [22]. Consequently, where refurbishment focuses on hydro-mechanical or electrical components alone, cost estimation can be performed based on limited information.

Similar methods for costing for hydropower (at a range of sizes) have been demonstrated in [18,21,22]. For the Mangmaya site, where the renovation included the turbine, transmission system, generator, and butterfly valve, the costing could be estimated using the method and data from [18]. A regression analysis was used to predict the total cost of these sub-systems based on data from 28 quotations from micro-hydropower manufacturers in Nepal. The resulting expression related the site rated power to the expected cost. Unlike the expressions presented in [18] and [21], it was found that due to a p-value of greater than 0.05 for the head, the cost could be estimated with reasonable accuracy using the site rated power alone. The resulting expression (where P is site rated power in kW) was in United States Dollar (USD):

$$COST = 1217P^{0.605} \quad (5)$$

The expression is the estimated purchase cost for the turbine, transmission system, generator and butterfly valve. It was derived from quotations for Pelton and Crossflow turbines and thus provided a reasonable benchmark for the equipment cost in Nepal, rather than a direct estimation for a Turgo turbine. The data was collected in 2019 and the average exchange rate for 2019 of 1 NPR (Nepali Rupee) = 0.0088 USD was applied [39]. For the assumed rated power of 30 kW, the estimated cost was $9527.

Legal/governmental approval

The mechanism for approval of hydropower projects varies between countries, however, projects generally must meet certain legislative and governmental requirements. In Nepal, at the micro-hydropower scale, the process of subsidy application ensures that new projects meet with the expected requirements [15]. The process ensures that projects have a certificate of registration for water use from the District Water Resources Committee. The community must also register as a Micro-Hydropower Functional Group, cooperative or a private company. During the subsidy application process, local governmental approval is required, and to be awarded the subsidy funding depends on approval from the Alternative Energy Promotion Centre, the national government agency focused on renewable energy. For the refurbishment of micro-hydropower projects in Nepal, a subsidy is also available. For the site at Mangmaya, a subsidy was not required. Regardless, approval was sought from local government for the project. Prior to a final community decision, an agreement between the committee, PEEDA and NYSE was signed.

Community decision

Community owned renewable energy projects have proven success in providing electricity and providing developmental benefits. It has also been emphasised that the sustainability of these projects depends on creating responsibility for them amongst the users, managers and local staff [40,41]. Whilst achieving this can be challenging, financial contributions, labour and participation in decision making by local residents have all been identified as supportive activities. In the case of Mangmaya, a committee for the MHP had been formed during the development of the existing project. PEEDA's site visit had ascertained that there was evidence of reasonable engagement in the MHP: attendance of committee members at the meeting, payment of tariffs and the results of interviews were all informative. To achieve interest and develop ownership in the renovated project, the community was involved in the decision-making process. Following all other stages of data collection, design and costing, the complete proposal for the project renovation was presented to the community. Based on the information provided, the committee decided, as a collective, to proceed with the renovation.

RESULTS

Design and Manufacture

The development of the design for the Mangmaya turbine took place collaboratively between the first author and NYSE. Based on an existing design that was optimised using computational fluid dynamics [29] and manufactured and tested in Nepal, the turbine runner was scaled up. A full package of engineering drawings was developed for the scaled runner and all other components of the turbine. The design for the turbine was developed such that it was appropriate for manufacture in Nepal. For example, the blades of the runner were designed for sand casting (see Figure 6a,b) with the mould developed from 3D printed parts. The individual blades were then fabricated together to develop the complete runner, as shown in Figure 6c,d. All components including the turbine casing, inlet pipework and spear valve assembly (see Figure 6e,f) were manufactured at NYSE. The cost of the installed components was NPR 930,000, approximately $7812 using an average exchange rate for the year of manufacture (in 2021, 1 NPR = $0.0084) [39].

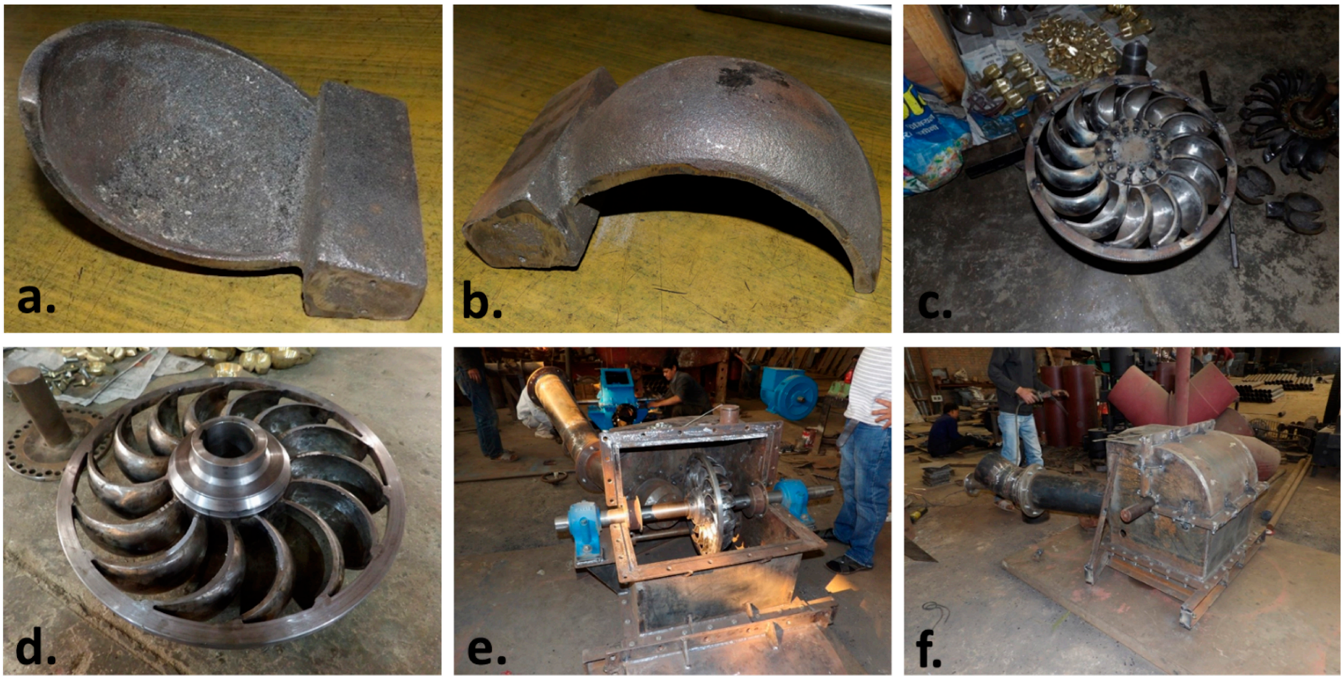

Figure 6. Components of the Turgo turbine during manufacture, (**a**) leading edge of the sand cast runner blade, (**b**) trailing edge of the sand cast runner blade, (**c**) turbine runner during fabrication, (**d**) turbine runner after machining, (**e**) turbine casing, runner and inlet pipe, (**f**) turbine with cover on.

Field Installation

To prepare the powerhouse for the installation of the new turbine, it was necessary to dig a new tailrace channel. Subsequently, the turbine base frame could be anchored and concreted into position (see Figure 7a). The y-section of penstock pipe was installed allowing the flow to be directed to either of the turbines (see Figure 7b). This adaption was intended to minimise disruption to the local community; when the new turbine was not operational, the old turbine could be used to generate power. It required a new hole to be made in the wall of the powerhouse to accommodate the new pipework. A direct replacement of the turbine would have required less work. Figure 7c shows the Turgo turbine installed in the powerhouse. Site works were completed by NYSE with support from community members. During these works, NYSE staff provided clear directions to community members to ensure the quality of work completed. The installation took place during the COVID-19 pandemic. As a result, there were some delays as the project team responded to locally imposed restrictions.

Figure 7. Site works for the renovation, (**a**) installed y-section of penstock pipe, (**b**) cementing of new turbine frame, (**c**) installed Turgo turbine in the powerhouse.

Field Testing

Upon completion of the installation, representatives of the Turbine Testing Laboratory at the Kathmandu University conducted field testing at the site. During testing, the flow rate was varied using the turbine's spear valve. The static head of the system remained approximately constant, however, there may have been some small variations in the forebay tank. The measurement of head was taken on the inlet pipe section directly preceding the nozzle. The rotational speed of the turbine was controlled by an electronic load controller (ELC). Using the electrical frequency, the ELC adjusts the load to maintain the rotational speed of the turbine at the generator's rated speed [37], in this case 1500 rpm. Table 4 lists the measurands and the equipment used.

Table 4. Measurands and equipment used in field testing.

Measurand	Units	Equipment	Specification	Accuracy
Head (H)	m	Pressure sensor	Aplisens APC-2000ALW	±0.075% [42]
Flow rate (Q)	m^3/s	Ultrasonic flow meter	Isoflux IFX-P200	±3% [43]
Rotational speed (ω)	rad/s	Infrared sensor	Sunrom infra-red sensor	N/A
Current (I)	A	Clamp meter	UNI-T UT 203	±2% [44]
Voltage (V)	V	Clamp meter	UNI-T UT 203	±0.8% [44]
Power factor (PF)	N/A	Powerhouse control panel	N/A	N/A

The power and water-to-wire efficiency were calculated from the product of the measured current and voltage in each phase, and then compared to the power available at the nozzle of the turbine using the measured head at the turbine inlet. The measured current in one phase of the electric generator was found to be unreliable during post-processing of the data, so the average power in the other two phases was scaled to calculate the expected power output from the turbine. Using the measured data, the power input and power output (both with units of watts), and the efficiency were calculated using the following expressions:

$$P_{IN} = \rho g Q H \tag{6}$$

$$P_{OUT} = 1.5PF(I_1V_1 + I_2V_2) \tag{7}$$

$$\eta = \frac{P_{OUT}}{P_{IN}} \tag{8}$$

where most terms and units are defined in Table 4, and ρ, the density of water is assumed to be 1000 kg/m^3, and g, the acceleration due to gravity is assumed to be 9.81 m/s^2. It should be noted that the expression for P_{OUT} uses only two of the three phases of the generator; the third phase is assumed to be an average of the other two, resulting in the coefficient of 1.5 in Equation 7. The manufacturer's stated accuracy for measuring equipment can be used as an approximation of the systematic uncertainty. Using the method described in [45], the total systematic uncertainty can be approximated as the square root of the sum of the squares of the individual uncertainties. Therefore, the total systematic uncertainty for the efficiency is equal to 3.8%. It should be noted that the uncertainty in the measurement of the power factor (read from the system's control panel) is unknown. The measured output power and efficiency of the turbine are shown in Figure 8 across a range of flow rates. On the graph, 2 data points are considered to be anomalous due to current readings that are substantially higher than the trend, and so have not been included.

For increasing flow rate, the head loss at the turbine nozzle increases. This occurs due to increased friction losses caused by the increase in the velocity of the flow through the penstock [46]. The head loss at the turbine nozzle and the normalised flow rate can be calculated using the following expression:

$$H_L = H_{max} - H \tag{9}$$

$$Normalised\ flow\ rate = \frac{Q}{Q_{max}} \tag{10}$$

where, H_L is the head loss, H_{max} is the measured head at the lowest flow rate and H is the head (all with units of m), and Q_{max} and Q are the maximum measured flow rate and the flow rate respectively (both with units of m^3/s). The head loss at the turbine nozzle, compared to the maximum measured head in the system, can be seen in Figure 9. This loss in head in the penstock causes a reduction in the overall system efficiency, and increases quadratically with the flow rate, causing the efficiency of the overall system to drop off at higher flow rates, as is seen in Figure 8.

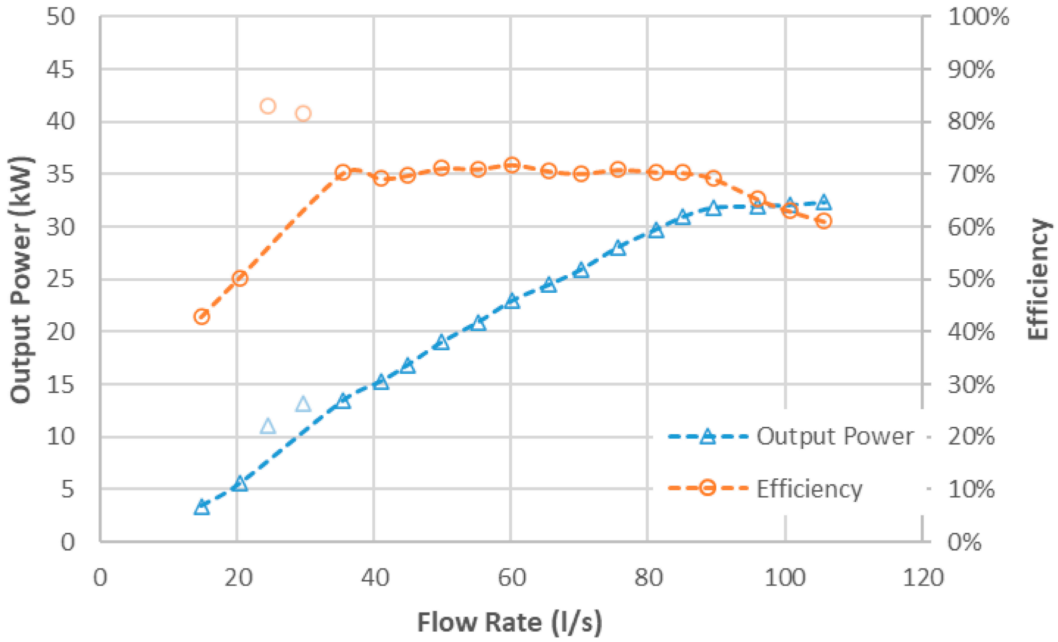

Figure 8. Expected output power and efficiency vs. flow rate.

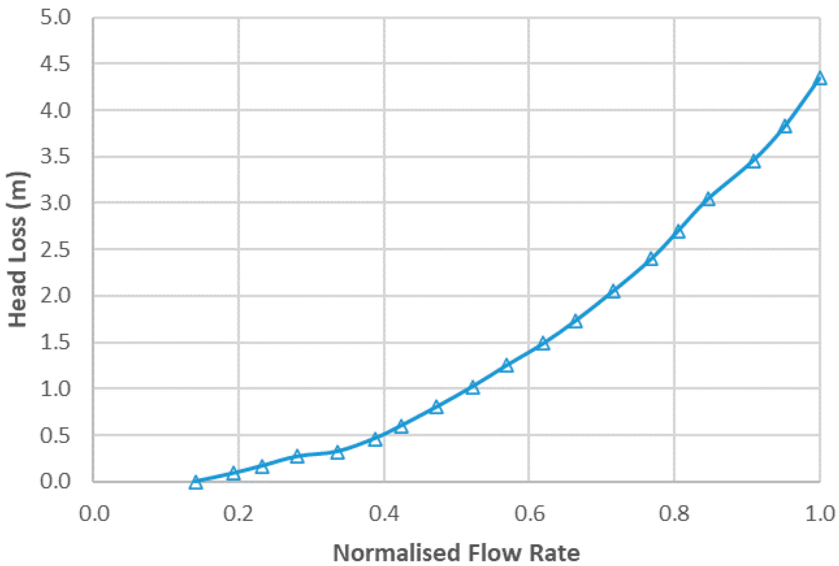

Figure 9. Normalised flow rate vs. head loss at the turbine nozzle exit compared to the maximum head measured.

DISCUSSION

The discussion section will focus on three elements. Firstly, the outcomes of the implementation at Mangmaya and the extent to which the methodology was effective. Second, the lessons learnt from applying the methodology and its potential for application elsewhere. Third, the opportunity to use the Turgo turbine both in Nepal and elsewhere.

From a technical perspective, the project resulted in the installation and commissioning of the Turgo turbine at Mangmaya Khola I MHP. The installed turbine provided increased power output (32 kW) in comparison to the existing turbine's recent power output (18 kW) and its original rated power (27 kW). The increase in power generated from the system is due to the increased efficiency of the Turgo system over the Crossflow at the rated conditions. The water-to-wire efficiency of the Turgo of approximately 70% for flow rates between approximately 25 and 90 l/s (22% and 80% of Q_{max} respectively) is comparable with typical micro-hydropower installations in Nepal [47]. Above 90 l/s, the efficiency dropped. Field based testing is inherently difficult and subject to variabilities and as mentioned in the results section, the current results for one phase of the generator were unreliable. Alongside this, the results suggest that the variation in rotational speed may have also affected the system's efficiency. When performing turbine scaling, it was assumed that a small difference (~15%) between turbine operational speed and rotational speed of the generator would be acceptable (e.g., reducing overall efficiency by several percent). Due to instability in the ELC, there was some variation in the rotational speed of the turbine. As the flow rate was increased from the lowest to the highest value (as shown in Figure 8), the rotational speed increased from 1385 up to 1493 rpm. Therefore, as more water flowed through the turbine, the rotational speed increased linearly in relation to increasing power output. At higher output powers, as the control system brought the rotational speed closer to 1500 rpm, the turbine was operating further from its design speed at 1270 rpm. This difference will have contributed to reduced efficiency at higher flow rates, along with the increased loss in the penstock. Considering the turbine's fluid mechanics, variation of the rotational speed means it will operate away from its ideal velocity ratio (the ratio between rotational speed and jet velocity). Also, when the turbine operates with the highest flow rates, there is greater potential for turbine performance to be affected by splashing and secondary flows. The runner design was scaled directly based on the optimised CFD design [38]. This direct scaling was intended to make use of all available head and flow rate, without altering the ratio between PCD and the blade's dimensions. Further computational work is required to explore varying this ratio so that, where appropriate, the PCD could be directly matched to the rated speed of the generator.

From a social and economic perspective, the project was implemented using the funding from EnergizeNepal and with contributions of labour from beneficiaries. The provision of funding meant that a local financial contribution was not required. Consequently, the community were keen to proceed with the project. Without grant funding, the community would have been responsible for the complete cost, perhaps with support from the Alternative Energy Promotion Centre and local government. Ideally, income from plant tariffs can be saved for the costs of repair and maintenance. In practice, challenges associated with tariff collection means that this does not happen universally [32]. Whilst the focus of the project team was the installation of the turbine, as part of the project implementation, a number of suggestions were made to the management committee relating to financial management. It was emphasised to the community that the frequency of tariff collection should be increased, income and expenditure should be recorded, and regular meetings of the management committee should be held. The costing method predicted a cost for the electro-mechanical components of $9527. In practice, the actual cost was lower at $7812. Due to the relatively small dataset (n = 28) used to predict cost and the one-off nature of the Turgo turbine construction, no major conclusions regarding the cost of the Turgo turbine can be drawn. However, the relatively small difference (~20%) suggests that the costing method offered a reasonable estimate. The expression for estimating renovation cost (Equation 5) should be validated by comparison with other hydropower site renovations in Nepal.

The methodology was successful in identifying the information required regarding the renovation. It depended on a site visit to assess the existing system and interview key stakeholders. The presence on site is useful for developing a tacit understanding and acceptance of a project, particularly when it is community owned and operated. The information collected under the environmental heading was done by PEEDA's employees. Whilst familiar with micro-hydropower and qualified engineers, they were not geological experts. If the renovation had required significant alterations to the existing civil structures, a redesign of the civil structures may have been required. The information collected was enough to allow the community to decide whether to proceed with the project. As noted previously, however, with the grant substantially covering the cost, the economics were less complex than for other renovation projects with more complex financing arrangements.

The lessons learnt from applying the methodology at Mangmaya can be used to inform applications of the methodology elsewhere. In general, the local knowledge and the experience of PEEDA and NYSE were important. If applied elsewhere, ideally similarly experienced local practitioners would be responsible for data collection. In relation to social, economic, and legal areas, there is greatest scope for variation in the local context and the impact that this might have upon renovation. For example, in a different country, legal requirements for the renovation of a hydropower plant may vary; locally based actors are best placed to support communities. In its current form, the presented methodology makes recommendations for key questions to be answered. In the case of Mangmaya, adapted versions of the methods explained in [34] were used to gather information. The methodology could be developed further to employ more prescriptive methods for collection of specific data. For example, a detailed analysis of the plant's income and expenditure, or an environmental risk assessment. Such information could be used to conduct more detailed analyses. A cost-benefit analysis would enable comparisons between renovation, construction of a new hydropower plant, and other technology choices (e.g., solar photo-voltaic). An environmental assessment could aid identification of climate proofing measures that could be implemented [48].

The renovation of the Mangmaya was the first documented example of the implementation of a Nepali manufactured micro-hydropower Turgo turbine. As such, alongside an understanding of the applied methodology, the outcomes relating to the use of the Turgo turbine can also be evaluated. Based on the manufacture and testing of a prototype (rated to 1 kW) [35], the turbine design was optimized using CFD [36] and scaled up. The resulting package of engineering drawings was used to manufacture the turbine at NYSE. Implementation at Mangmaya was complicated by the decision to install the new turbine in parallel with the existing one. The requirement to construct a new tail race, and manufacture and install the 'Y-section' of pipe were additional steps in the renovation process. As discussed above, the scaling procedure resulted in a difference between the turbine's rated speed and generator speed. In future, the impact of moving the pitch circle diameter of blades to match the turbine and generator rotational speeds should be explored. Analytical or computational methods could be used to explore the impact of this change. Engineering drawings and supporting tools for the present design are available online [49].

CONCLUSIONS

There are many challenges but also opportunities when considering renovating existing micro-hydropower sites, not just in Nepal, but around the World. These have been reviewed here, with literature sources and the experience of the authors used to develop a high-level methodology to assist in decision making. The potential benefits of renovating existing sites are many, but in terms of increased power outputs, higher efficiencies and plant reliability, the options around utilising modern turbine designs in particular are essential in order to achieve higher performance at investment and operating costs which are economically viable over the plant's lifetime. The methodology was successful in collecting the information required to carry out the renovation. An open source and scalable Turgo turbine design has been successfully installed and operated in an existing MHP site in Nepal. The increased power from a site has the potential for providing more people in the community with a stable electricity supply. Furthermore, with the potential to generate additional capacity, the current and future demands of the community can be met with potential for further benefits of new income generation opportunities.

Despite its success, the implementation at Mangmaya is currently the only example of this particular Turgo turbine design. Experience, particularly relating to use in other country contexts can be developed through applications of the design. In further developments, it is important to consider where the Turgo turbine can be applied and whether its application region can be expanded. With the existing Turgo design, scaling allows adjustment for different combinations of head and flow rate. The application region identified here is not intended to be exclusively for the Turgo turbine. Turbine selection involves evaluation of key trade-offs (e.g., cost, efficiency, part-flow efficiency) and further work is required to explore these. This understanding could be used to both, identify the best application region for the Turgo turbine and to optimise its design further.

NOTE

After operating for 18 months, the plant was badly affected by a landslide in the local area in July 2023. The landslide severely damaged the penstock and the powerhouse. The Nepali project partners are exploring how the plant can be restored to operation. As mentioned in the paper, the incident highlights the risk that landslides pose to MHPs in Nepal.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

JPB, SW, PK, SP, BP, BG designed the study and implemented the project. JPB, PK, SP, BP, and PS collected the data. JPB, SW, JDB and PS analysed the data. JPB, SW and JDB wrote the paper with input from all authors. Abbreviations: JPB—Joe Butchers, SW—Sam Williamson, JDB—Julian Booker, PK—Prem Bikram Karki, SP—Suman Raj Pradhan, BP—Bikram Raj Pradhan, BG—Biraj Gautam, PS—Prajwal Sapkota.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

1. Government of Nepal National Planning Commission. Nepal earthquake 2015: post disaster needs assessment. Available from: https://www.worldbank.org/content/dam/Worldbank/document/SAR/nepal/PDNA%20Volume%20A%20Final.pdf. Accessed 2023 Aug 26.
2. Agrawal S, Pandey R. Current Status of Small/Micro Hydropower in Nepal: A Case Study of Giringdi SHP. J Inst Eng. 2019;15(3):21-7.
3. Gautam B. The Success and Struggles of Nepal's Micro-Hydro Projects. Available from: https://www.wisions.net/the-success-and-struggles-of-nepals-micro-hydro-projects. Accessed 2023 Aug 26.
4. GlobalGiving. Rehabilitation & Upgrading of 30-KW Micro Hydro Project for Poor Fisherfolks in Brgy. Available from: https://www.globalgiving.org/pfil/7569/projdoc.pdf. Accessed 2023 Aug 26.
5. European Small Hydropower Association. Small and Micro Hydropower Restoration Handbook. Available from: https://www.restor-hydro.eu/documents/2014/12/small-and-micro-hydropower-restoration-handbook.pdf. Accessed 2023 Aug 26.
6. UNIDO. Projects for the Promotion of Small Hydro Power for Productive Use. Available from: https://www.unido.org/sites/default/files/2010-02/e-book_small-hydro_0.PDF. Accessed 2023 Aug 26.
7. UNIDO. World Small Hydropower Development Report. Available from: https://www.unido.org/sites/default/files/files/2020-08/WSHPDR_2013_Executive_Summary_English.pdf. Accessed 2023 Aug 26.
8. JICA. Guideline and Manual for Hydropower Development Vol. 2—Small Scale Hydropower. Available from: https://openjicareport.jica.go.jp/pdf/12024899.pdf. Accessed 2023 Aug 26.
9. Harvey A, Brown A, Hettiarach P, Inversin A. Micro-hydro design manual. London (UK): Intermediate Technology Publications; 1993.
10. Goldberg J, Espeseth Lier O. Rehabilitation of hydropower: an introduction to economic and technical issues. Available from: https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/518271468336607781/rehabilitation-of-hydropower-an-introduction-to-economic-and-technical-issues. Accessed 2023 Aug 26.
11. Drinkwaard WS. The diffusion of micro-hydro power for rural electrification in Bolivia a learning approach. Available from: https://pure.tue.nl/ws/portalfiles/portal/46939155/644017-1.pdf. Accessed 2023 Aug 26.
12. Bojić S, Bozic D, Pavlica M. Refurbishment of small hydro power plant. Available from: https://www.researchgate.net/profile/Srecko-Bojic/publication/261429926_Refurbishment_of_small_hydro_power_plant/links/595b66d14585151177419d6d/Refurbishment-of-small-hydro-power-plant.pdf. Accessed 2023 Nov 13.
13. Quaranta E, Pujol T, Grano MC. The repowering of vertical axis water mills preserving their cultural heritage: techno-economic analysis with water wheels and Turgo turbines. J Cult Heritage Manag Sustain Dev. 2023;13(2):269-87.

14. Gill A, Mosley P, Fulford DJ. Community Micro-Hydro in LDCs: Adoption, Management and Poverty Impact. Available from: https://assets.publishing.service.gov.uk/media/57a08d9840f0b652dd001a76/DFIDR7110.pdf. Accessed 2023 Aug 26.
15. Kumar P, Yamashita T, Ajoy K, Shrestha A, Yadav A. Nepal—Scaling up Electricity Access through Mini and Micro Hydropower Applications: A Strategic Stock-Taking and Developing a Future Roadmap. Available from: https://documentos.bancomundial.org/es/publication/documents-reports/documentdetail/527221467993505663/summary. Accessed 2023 Aug 26.
16. Butchers J, Williamson S, Booker J. Micro-Hydropower in Nepal: Analysing the Project Process to Understand Drivers that Strengthen and Weaken Sustainability. Sustainability. 2021;13(3):1582.
17. Faruqui NI. Small hydro for rural development. Can Water Resour J. 1994;19(3):227-35.
18. Butchers J, Williamson S, Booker J, Maitland T, Karki PB, Pradhan BR, et al. Cost estimation of micro-hydropower equipment in Nepal. Dev Eng. 2022;7:100097.
19. Singhal MK, Kumar A. Cost benching for civil structures of micro/mini hydro electric projects located in Uttaranchal. Available from: https://www.researchgate.net/profile/Arun-Kumar-266/publication/267149964_Cost_benching_for_civil_structures_of_micromini_hydro_electric_projects_located_in_Uttaranchal/links/565145cb08ae4988a7abdf64/Cost-benching-for-civil-structures-of-micro-mini-hydro-electric-projects-located-in-Uttaranchal.pdf. Accessed 2023 Nov 13.
20. Balkhair KS, Rahman KU. Sustainable and economical small-scale and low-head hydropower generation: a promising alternative potential solution for energy generation at local and regional scale. Appl Energy. 2017;188:378-91.
21. Ogayar B, Vidal PG. Cost determination of the electro-mechanical equipment of a small hydro-power plant. Renew Energy. 2009;32(1):6-13.
22. Cavazzini G, Santolin A, Pavesi G, Ardizzon G. Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling. Energy. 2016;103:746-57.
23. Meier T, Fischer G. Assessment of the Pico and Micro-Hydropower Market in Rwanda. Available from: https://energy4impact.org/sites/default/files/pico-hydro_market_in_rwanda.pdf. Accessed 2023 Aug 26.
24. Loots I, van Dijk M, Barta B, van Vuuren SJ, Bhagwan JN. A review of low head hydropower technologies and applications in a South African context. Renew Sust Energ Rev. 2015;50:1254-68.
25. ISSF. Stainless Steel in Micro Hydro Turbines. Available from: https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_in_Micro_Hydro_Turbines.pdf. Accessed 2023 Aug 26.
26. Cromwell G. What makes technology transfer? Small-scale hydropower in Nepal's public and private sectors. World Dev. 1992;20(7):979-89.
27. Butchers J, Cox J, Williamson S, Booker J, Gautam B. Design for localisation: A case study in the development and implementation of a low head propeller turbine in Nepal. Dev Eng. 2020;5:100051.

28. Ghimire A, Dahal DR, Pokharel N, Chitrakar S, Thapa BS, Thapa B. Opportunities and Challenges of introducing Francis Turbine in Nepalese Micro Hydropower Projects. Available from: https://iopscience.iop.org/article/10.1088/1742-6596/1266/1/012007/pdf. Accessed 2023 Nov 13.
29. Dutta S, Sing RP, Thakali H. Terminal Review Report, Rural Energy Development Programme, United Nations Development Programme, Nepal. Available from: https://www.undp.org/sites/g/files/zskgke326/files/migration/np/UNDP_NP_REDP-Terminal-Review-2007.pdf. Accessed 2023 Aug 26.
30. Schumacher O, Austegard A. RHL Cross Flow turbine. Available from: http://www.remotehydrolight.com/CrossFlow.php. Accessed 2023 Aug 26.
31. Williamson SJ, Stark BH, Booker JD. Performance of a low-head pico-hydro Turgo turbine. Appl Energy. 2013;102:1114-26.
32. Butchers J, Williamson S, Booker S, Tran A, Karki PB, Gautam B. Understanding sustainable operation of micro-hydropower: a field study in Nepal. Energy Sustain Dev. 2020;57:12-21.
33. EnergizeNepal. Available from: https://energizenepal.ku.edu.np. Accessed 2023 Aug 26.
34. Alternative Energy Promotion Centre. Reference Micro Hydro Power Standard. Available from: https://aepc.gov.np/uploads/docs/2018-06-19_Reference%20Micro%20Hydro%20Power%20Standard,%202014.pdf. Accessed 2023 Aug 26.
35. HPNET. Local capacity development through technology transfer: turgo turbine in Nepal. Available from: https://www.hpnet.org/blog/local-capacity-development-through-technology-transfer-turgo-turbine-in-nepal. Accessed 2023 Nov 13.
36. Butchers J, Benzon S, Williamson S, Booker J, Aggidis G. A rationalised CFD design methodology for Turgo turbines to enable local manufacture in the Global South. Energies. 2021;14(19):6250.
37. Thake J. The micro-hydro Pelton turbine manual: design, manufacture and installation for small-scale hydro-power. Rugby (UK): Practical Action Publishing; 2000.
38. Massey BS, Ward-Smith AJ. Mechanics of Fluids. 9th ed. London (UK): Spon Press; 2012.
39. X-Rates. Exchange rate average (Nepalese rupee to US dollar). Available from: https://www.x-rates.com/average/?from=NPR&to=USD&amount=1&year. Accessed 2023 Aug 26.
40. Yadoo A. Delivery models for decentralised rural electrification: case studies in Nepal, Peru and Kenya. London (UK): International Institute for Environment and Development; 2012.
41. Terrapon-Pfaff J, Dienst C, König J, Ortiz W. How effective are small-scale energy interventions in developing countries? Results from a post-evaluation on project-level. Appl Energy. 2014;135:809-14.
42. APLISENS. Smart pressure transmitter (APC-2000ALW). Available from: https://aplisens.com/apc-2000alw.html. Accessed 2023 Nov 13.

43. ISOIL Industria. Portable clamp-on flow meter (IFX-P200 ISOFLUX). Available from: https://www.isoil.it/en/product/isoflux-ifx-p200-portable-flow-meter-clamp-on. Accessed 2023 Nov 13.
44. AC/DC Clamp Meter (UT203–UNI-T). Available from: https://meters.uni-trend.com/download/ut203-ut204-user_manual/?wpdmdl=7233&refresh=6538dd48628181698225480. Accessed 2023 Nov 13.
45. IEC. IEC 60193:2019—Hydraulic turbines, storage pumps and pump-turbines—Model acceptance tests. Available from: https://standards.iteh.ai/catalog/standards/iec/e473e535-bcfb-45dc-8b0b-3e60bc13d4c4/iec-60193-2019. Accessed 2023 Nov 16.
46. Williams A, Simpson R. Pico hydro—reducing technical risks for rural electrification. Renew Energy. 2009;34(8):1986-91.
47. Khadka SS, Maskey RK. Performance study of Micro-hydropower system in Nepal. Available from: https://ieeexplore.ieee.org/abstract/document/6357409. Accessed 2023 Nov 13.
48. International Hydropower Association. Hydropower Sector Climate Resilience Guide. Available from: https://assets-global.website-files.com/5f749e4b9399c80b5e421384/5fa7e38ce92a9c6b44e63414_hydropower_sector_climate_resilience_guide.pdf. Accessed 2023 Nov 13.
49. Social Enterprise for Energy, Ecological and Economic Development. Module K: Turgo turbine—open source design. Available from: https://seeedlearning.org/courses/module-k. Accessed 2023 Aug 26.

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