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Enabling sustainable and reliable energy using locally manufactured micro-hydropower technology

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Enabling sustainable and reliable energy using locally manufactured micro-hydropower technology

Joe Butchers

A thesis submitted to the University of Bristol in accordance with the requirements of the degree of Doctor of Philosophy in Mechanical Engineering.

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December 2020

Abstract

The United Nation’s 7th Sustainable Development Goal (SDG7) is to *ensure access to affordable, reliable, sustainable and modern energy for all.* A key challenge in achieving SDG7 is providing access to the estimated 0.9 billion people living in rural areas without access to electricity. In Nepal, factors including political unrest, challenging geography, and a weak economy, have limited electricity access. However, micro-hydropower has been used to provide electricity in rural areas. The technology is mostly manufactured locally, with the Nepali government supporting communities with a subsidy that funds approximately 50% of the total project cost. Manufacturing companies fulfil the roles of designer, manufacturer, and installer with the local community providing labour during the construction phase. The combination of locally manufactured equipment that is subsequently owned and operated by the community provides a unique range of challenges. This thesis explores the opportunity to improve the reliability of the technology and the operational sustainability of projects. To do so, a new design methodology is proposed that allows an existing technology, the Turgo turbine, to be adapted for local manufacture and use in Nepal.

The proposed design methodology, known as ‘Design for Localisation’, frames the direction of the thesis. Firstly, an understanding of the local context is developed. A field-based methodology is developed and used at 24 micro-hydropower plants to consider factors affecting their operational sustainability. Findings from the site study are combined with a detailed evaluation of the project process, using available literature and interviews with stakeholders, resulting in an improved understanding of how strengths and weaknesses in the operational sustainability of plants develop.

Secondly, design solutions for local manufacture are developed. A survey of manufacturing companies is used to identify the local availability of materials and processes. These findings indicate determine the method for manufacture of the turbine blade. Subsequently, computational fluid dynamics is used to optimise the performance of the runner, increasing efficiency from 69.0 to 82.5%. In collaboration with a local manufacturing company, a locally appropriate design is developed and manufactured. CAD, the internet, and additive manufacturing are used to transfer and physically replicate the digital design as a mould for casting.

Thirdly, local testing and monitoring is used to evaluate the design. A hydrodynamic testing rig is developed at Kathmandu University. The locally manufactured Turgo turbine runner and an imported off-the-shelf Turgo turbine runner are tested under the same conditions, and the results compared. A site-based installation is used to understand the performance of the runner once integrated with ancillary sub-systems, and in environmental conditions.

Finally, the efficacy of the Design for Localisation process and its further application is considered. A scaling method, allowing the Turgo turbine design to be adapted for any site with appropriate geography, is presented. An open-source approach is proposed to improve the availability of the design, enable subsequent improvement and further local adaptation to other contexts.

Acknowledgements

I would like to thank my supervisors, Sam and Julian, for your guidance and support throughout. I have really valued your generosity with your time and the opportunity to talk anything through.

This research has depended on the efforts of many people. I would like to thank Prem, Biraj, Topaz, and the whole PEEDA family. Prem for making travelling in the field both possible and enjoyable, and for the countless other things I have asked for help with. Biraj for unwavering cooperation and good discussions. Topaz for help in keeping everything moving. To everyone at PEEDA, thank you for always making me feel welcome and at ease whilst staying in Kathmandu.

There are also many project partners and collaborators who have helped to shape the research. Suman and Bikram for many useful conversations about design and manufacturing in Nepal, and for allowing me to spend hours in the workshop! Jiwan and Muhan for emails and conversations, helping me to understand the national perspective. Aatmaram and all of the staff at the TTL for many hours of work in conducting the testing. Shaun Benzon for his efforts and commitment to our project. Jonathan Cox for sharing many experiences of Nepal and the development of micro-hydropower. Anh Tran for assistance in developing the field study and useful conversations that helped to direct the research.

I am also very grateful to all the people who were generous with their time for interviews and hospitality whilst I was moving around Nepal.

A very special thank you to Kiran and Sarita who made me feel at home every time I came to Nepal. Thanks to friends in Butwal - Subass, Bimal, and everyone at Oshin Power Services - for making life easy and enjoyable for me whilst visiting.

To friends in the EEMG for friendship, lunches, and interesting discussions about our work.

Finally, to friends, family, and of course, Esther for love and laughter along the way.

Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: [redacted] DATE: 09/12/20

Memorandum

The accompanying thesis “Enabling sustainable and reliable energy using locally manufactured micro-hydropower technology” is based on work carried out by the author.

The main contributions are:

1) Development and application of a field-based methodology for assessing the sustainability of micro-hydropower plants.
2) A detailed project process analysis using multiple sources to consider the connection between stakeholder actions and operational strengths and weaknesses.
3) Evaluation of manufacturing capability in the micro-hydropower industry in Nepal.
4) Development of a turbine runner design appropriate for local manufacture and use in Nepal.
5) Experimental and field-based testing of the turbine.
6) Formation of a design methodology for the adaption of an existing design for local manufacture, assembly, and use in a new geographic location.

Publications

Journal Articles

J. P. Butchers, J. V. Cox, S. J. Williamson, J. D. Booker, and B. Gautam. "Design for localisation: A case study in the development and implementation of a low head propeller turbine in Nepal." Development Engineering 5 (2020): 100051.

J. P. Butchers, S. J. Williamson, J. D. Booker, A. L. H. Tran, B. Gautam, and P. B. Karki. "Understanding sustainable operation of micro-hydropower: a field study in Nepal." Energy for Sustainable Development 57 (2020): 12-21.

S.J. Williamson, W. D. Lubitz, A. A. Williams, J. D. Booker and J.P. Butchers. “Challenges Facing the Implementation of Pico-Hydropower Technologies.” Journal of Sustainability Research 4 (2019).

Peer Reviewed Conference Proceedings

J. P. Butchers, S. J. Williamson, J. D. Booker. “The development of strengths and weaknesses in the sustainable operation of micro-hydropower plants in Nepal: a project process analysis.” In Sustainable Development of Energy, Water and Environment Systems, Cologne, 2020.

J. P. Butchers, S. J. Williamson, J. D. Booker, A. L. H. Tran, B. Gautam, and P. B. Karki. "A study of technical, economic and social factors affecting micro-hydropower plants in Nepal." In IEEE Global Humanitarian Technology Conference, San Jose, 2018.

J. P. Butchers, S. J. Williamson, J. D. Booker, A. L. H. Tran, B. Gautam, and P. B. Karki. "A study of micro-hydropower plants in Nepal: Sustainability from technical, economic and social perspectives." In International Conference on Developments in Renewable Energy Technology, Kathmandu, 2018.

Presentations

J. P. Butchers. “Reliability of micro-hydropower plants in Nepal from technical, economic and social perspectives.” In Resilience and Reliability of Energy Projects in Nepal, Smart Villages Webinar, Online, 2019.

J. P. Butchers. “Micro-hydropower: Providing reliable electricity to rural Nepal.” In Research Without Borders, Bristol, 2018.

Posters

J. P. Butchers, S. J. Williamson, J. D. Booker. “Methodology for improving the efficiency and manufacturability of locally manufactured micro-hydro turbines.” In Low Carbon Energy for Development Network Conference, Durham, 2017.

List of Abbreviations

AEPC	Alternative Energy Promotion Centre
AT	Appropriate technology
BEP	Best efficiency point
BTI	Butwal Technical Institute
BYS	Balaju Yantra Shala
CAD	Computer Aided Design
CC	Consulting companies
CFD	Computational fluid dynamics
CFL	Compact fluorescent light
DCS	Development Consultancy Services
DFL	Design for Localisation
DFM	Design for Manufacture
DFX	Design for X
DOE	Design of Experiments
ELC	Electronic load controller
HCD	Human Centred Design
HDPE	High-density polyethylene
HH	Household
IMAG	Induction motor as generator
KAPEG	Kathmandu Alternative Power and Energy Group
KMI	Kathmandu Metal Industries
KU	Kathmandu University
kW	Kilowatt
M/IC	Manufacturing or installation company
MCB	Miniature circuit breaker
MHFG/C	Micro-hydropower functional group or co-operative
MHP	Micro-hydropower plant
MS	Mild steel
MW	Megawatt
NGO	Non-governmental organisation
NHE	Nepal Hydro Electric
NMHDA	Nepal Micro Hydro Development Association
NPDP	Nepal Power Development Project
NPR	Nepali rupee
NYSE	Nepal Yantra Shala Energy
O&M	Operation and maintenance

OPS	Oshin Power Services
OSAT	Open-source appropriate technology
OSH	Open-source hardware
PCB	Printed circuit board
PCD	Pitch circle diameter
PEEDA	People, Energy and Environment Development Association
PEU	Productive end use
POV	Power output verification
PT	Propeller turbine
PVC	Polyvinyl chloride
QA	Quality assurance
QC	Quality control
REDP	Renewable Energy Development Project
RERL	Renewable Energy for Rural Livelihood
RHL	Remote Hydro Light
rpm	Revolutions per minute
RSC	Regional service centre
RSM	Response surface methodology
SDG	Sustainable Development Goal
SS	Stainless steel
TTL	Turbine Testing Laboratory
UC	University of Canterbury
UMN	United Mission to Nepal

List of Symbols

a	Scaling ratio	
C	Specific speed	
C_H	Head coefficient	
C_P	Power coefficient	
C_Q	Flow rate coefficient	
C_v	Nozzle discharge coefficient	
D	Diameter, pitch circle diameter	m
d_j	Diameter of jet	m
F	Force	N
f	Frequency	Hz
g	Gravitational constant	m/s^2
H	Head	m
n	Number of jets	
N	rotational speed	rpm
P	Power	W
Q	Flow rate	L/s, m^3/s
r	Moment arm length	m
T	Torque	Nm
α	Entry angle	°
β	Exit angle	°
δ	Uncertainty	
γ	Blade cut back angle	°
η	Efficiency	
ω	Rotational speed	rad/s

Table of Contents

Chapter 1

Introduction

1.1 Problem statement

The United Nation's 7th Sustainable Development Goal (SDG7) is to *ensure access to affordable, reliable, sustainable and modern energy for all* [1]. The importance of energy in relation to the other Sustainable Development Goals has been recognised with energy systems described as the "foundation of social and economic development" [2]. In particular, services delivered through electricity access drive improvements in education, health, and livelihoods [3-5]. Achieving SDG7 depends upon delivering energy services sustainably, in relation to the availability of the planet's natural resources and the impact of energy generation upon climate change. A particular challenge is providing access to the estimated 0.9 billion people living in rural areas without access to electricity [6]. In rural areas, the effects of improved energy access can provide a greater benefit than in the urban areas [7], encouraging a multiplier effect that leads to diverse improvements in quality of life and availability of opportunities [2, 8]. However, the process of electrifying rural areas often provides unique obstacles which require alternative approaches to those used in urban areas [9-11]. Rural communities tend to live in dispersed settlements in environments with challenging geography and weak infrastructure; these challenges often making the extension of national grids unsuitable and expensive [12, 13].

Research has shown that off-grid technologies that are owned and operated by the local community can be effective in providing electricity and delivering developmental benefits [14-16]. These technologies have a much smaller environmental impact than on-grid services, using available natural resources more sustainably than large-scale fossil fuel-based generation, and with less environmental and social impact than grid connected renewables such as large-scale hydropower [17, 18] or wind [19, 20]. Off-grid technologies also strengthen local independence through project ownership and can be used to drive greater economic change in the area local to the energy system [21, 22]. When such systems fail, communities are forced to revert to traditional energy forms, temporarily (or permanently) losing the developmental benefits of electricity access. Literature has indicated that the combination of technical, economic and social factors that lead to weak sustainability of community-owned systems is often poorly understood [23-26].

In Nepal, micro-hydropower is an off-grid technology that has been used to electrify rural communities. At the national level, factors including political unrest, challenging geography, and a weak economy, have limited electricity access across the country [27]. As recently as 2016, Nepalis faced blackouts of up to 12 hours day through regulated power cuts, known as load shedding, used to address the deficit between supply and demand [28, 29]. Whilst load shedding occurs less frequently [28] and Nepal's generation capacity is continuing to increase, the quality of power delivered by the national grid remains low with voltage droop and short power cuts remaining common [30]. In 2017, a study found that the national grid serves 72% of the population, whilst 23% have access to electricity through an off-grid supply, and 5% have no electricity access [31].

From the 1970s, micro-hydropower has been used in Nepal to electrify rural areas [32]. In Nepal, micro-hydropower refers to electricity generation of less than 100 kW using hydropower [33]. A typical micro-hydropower plant (MHP), shown in Figure 1.1, is run-of-the-river, diverting a small amount of water from a river, using it to drive a generator, before returning the water to the same river further downstream. Since its use began in Nepal, the technology has largely been manufactured locally, with the generator being the only major imported component [34]. Today, the Nepali government supports local communities with a subsidy to fund approximately 50% of the total project cost [35]. Local manufacturing companies fulfil the roles of designer, manufacturer, and installer with the local community providing labour during the construction phase [35]. The benefits of micro-hydropower in Nepal have been well reported and the adoption of the technology is generally regarded as a success [36].

Figure 1.1 - A micro-hydropower plant in Ilam, Nepal. Photo credit, Sam Williamson.

However, as with other forms of locally owned and operated technology, achieving sustainable operation of micro-hydropower plants is a significant challenge with studies and reports attributing this to either technical or socio-economic reasons. Technically, it has been suggested that the quality of manufactured equipment is low [37, 38] with a lack of quality assurance [35] throughout the manufacturing, construction, and installation phases. Meanwhile, a lack of productive end uses and poor tariff collection result in a failure to generate the required income to maintain the plant [16, 39]. Furthermore, maintenance is often not performed to the required standard leading to poor reliability [40, 41].

The combination of locally manufactured equipment that is subsequently owned and operated by the community provides a unique range of challenges. Frequently, whilst the successful installation of a project is noted, the sustainability of ongoing operation is not considered. Across a range of technologies, there are many challenges relating to the sustainable operation of electricity generating equipment, often interdisciplinary in their nature. Specifically, in micro-hydropower in Nepal, the actions (and interactions) of stakeholders throughout the project have not been considered. Particularly amongst manufacturing companies, their capability and their approach to project development is not well understood. There are opportunities to deliver more sustainable hydropower plants through the introduction of new designs, and new approaches to design and manufacturing, whilst considering what is possible within the local context. With a local manufacturing industry, government supplied subsidy, and willing communities, there is a need to ensure that all micro-hydropower plants are reliable and sustainable, delivering electricity services that benefit communities.

1.2 Sustainability and reliability

The terms *sustainable* and *reliable* both appear within the definition of SDG7. Given the centrality of the goal and these terms in this thesis, there is value in considering their definitions and how they will be used within the research. The term sustainable development - which describes the goals adopted by the United Nation Member States in 2015 - gained popularity in the Brundtland report in 1987. The definition from this report remains often quoted: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [42]. Specifically, for the energy sector, a later definition from [43] with similar wording to SDG7 is: “sustainable energy development will require electricity services that are reliable, available and affordable for all, on a sustainable basis, world-wide”. These definitions are focused on a broad picture, evaluating development concepts in relation to the world. When considering small-scale renewable energy projects (such as micro-hydropower) and comparing to alternative large-scale methods of energy provision, an intrinsic feature is that they extract fewer natural resources and inflict less environmental damage. An Oxford English dictionary definition of sustainable is “capable of being maintained or continued at a certain rate or level” [44]. Evaluating small-scale projects at a global level, they can be considered environmentally sustainable. However, the ability of an energy project to be “maintained or continued” at the local level is not exclusive to environmental impact. It depends upon a wide range of factors: environmental, technical, social, economic, political, and cultural. In this research, where sustainability is considered local to the plant, it is defined as: *the ability of the technology and its stakeholders to deliver electricity services that meet the expectations of consumers over a system’s expected lifespan.*

Alongside sustainability, reliability also has a range of definitions. In engineering, reliability can be defined as: “the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered” [45]. Often, numerical data is used to quantify this. For example, in energy systems the amount of power delivered, and the operational time lost due to failures [46]. For small-scale energy projects, such data is not necessarily available. Therefore, in this research, reliability will be considered more qualitatively, as such it is defined as: *the ability of the system to consistently deliver the expected electricity service whilst avoiding failures.* In exploring this, the resultant reliability depends on the installed technology and the operation & maintenance (O&M) practices that take place. Therefore, in the case of micro-hydropower in Nepal, the actions of the manufacturing company and the community are considered important in determining the reliability.

1.3 Research aim and objectives

The aim of this research is to **identify approaches to local manufacture and project implementation that ensure micro-hydropower plants in Nepal operate reliably and sustainably.** To address this aim, the research focuses on the introduction of a turbine type currently unused at the micro-hydropower scale in Nepal, using a design methodology to develop a locally appropriate version of the turbine.

To achieve this, there are five research objectives:

1. **To understand the factors that affect the sustainability of plants.**

To develop a detailed understanding of the local context where micro-hydropower plants operate allowing the identification of the individual and interconnected factors that affect the sustainable operation of plants.

2. **Identify opportunities to tackle threats to sustainability within the project process.**

To consider the complete project process and stakeholder roles in relation to sustainable operation allowing the initiation, development, and manifestation of threats to be identified and the suggestion of mitigation that includes ‘hard’ and ‘soft’ approaches.

3. **Evaluate the approach and capability of micro-hydropower manufacturers.**

To evaluate the typical capability and the responsibilities fulfilled by manufacturing companies during the design, manufacture, installation and operation phases of the project process, and to understand the opportunities to introduce new methods in design, manufacturing, and quality assurance that result in more reliable systems.

4. **Develop a new locally appropriate turbine runner design.**

To develop a locally appropriate turbine runner design in collaboration with a local manufacturer, that utilises recent technological developments to tackle identified technical issues; simultaneously, to explore the opportunity for new approaches in collaborative design and manufacture. In addition, to identify the next steps which could lead to further replication of the turbine design.

5. **Apply a design methodology that enables the development of locally appropriate design solutions.**

To propose a methodology that helps address the challenge of developing locally appropriate design solutions. Subsequently, to use this methodology in the development of the turbine runner design.

1.4 Thesis structure

Chapter 2 reviews the available literature to showing the typical turbine technology in Nepal, the development of a local hydropower industry in the country, and the range of problems relating to the operation of plants that have been identified. The chapter considers the history and present status of design approaches that are used to design or adapt technologies for new environments, leading to the identification of a current knowledge gap.

Chapter 3 proposes a new design methodology, called ‘Design for Localisation’, and uses it to derive the research methodology. The experiences of a case study are used to propose the design methodology with supporting examples used to validate it. The derived research methodology is presented. The research activities and their connection to the objectives are described, with individual research methods, collaborations, and ethical considerations explained.

Chapter 4 describes a field study used to understand the sustainability of operational micro-hydropower plants in Nepal. The study method is derived based on previous approaches within the literature. The results are presented in relation to three key areas: technical reliability, financial viability, and community engagement.

Chapter 5 considers the complete project process for micro-hydropower in Nepal and the role of stakeholders within it. Using examples from Chapter 4 and within the literature, specific strengths and weaknesses in the sustainable operation of plants are identified, their initiation and development is tracked throughout the project process.

Chapter 6 focuses on the development of a locally appropriate turbine runner design. The capability of manufacturers is explored using a survey. Computational fluid dynamics is used as a tool to improve the efficiency of the turbine runner design whilst maintaining a focus on its appropriateness for local manufacture. The resulting design is presented, and the experiences of local production are shared.

Chapter 7 presents the development of an testing rig, method and the experimental results. The results are used to compare the performance of a Chinese and Nepali manufactured Turgo turbine. Results and experiences from a field-based installation are also presented.

Chapter 8 considers the broader application of the Design for Localisation methodology and the opportunity to increase use of the Turgo turbine design through an ‘open-source’ approach. A method is presented that allows the scaling of the Turgo turbine design. Approaches that enable transfer of the relevant design information to Nepal and elsewhere are proposed.

Chapter 9 summarises the main findings of the work, discusses the applicability of the Design for Localisation methodology, and makes suggestions for further work.

Chapter 2

Literature review

2.1 Introduction

The literature review considers micro-hydropower and its typical sub-systems. It provides an overview of the specific types of turbines that are used in Nepal, including their key components. It introduces the Turgo turbine as a type that is not currently used in Nepal but identifies its potential region of operation and reasons that support its development. To understand the present status of micro-hydropower in Nepal, the history of its development is explored. Literature regarding studies of operational micro-hydropower plants provides an overview of the issues that affect their sustainability. Due to the interaction of social and technical elements that occurs at MHPs, a background is provided for a socio-technical systems approach. As a locally manufactured technology, approaches to technology transfer, both past and present, are explained. The chapter concludes by assimilating the diverse sources of literature.

2.2 Micro-hydropower

Hydropower turbines extract energy from a fluid, using the energy to drive a shaft [47]. Hydro-turbines exist at a range of sizes with their rated power commonly used to classify them. Around the world, the classifications vary. Table 2.1 lists the classifications of hydropower that will be used in this thesis [48, 49]. Although separated on the basis of power, the varying scales lead to other differences in the form of installations and their impact. Pico-, micro-, mini-, and many small hydropower plants are typically run-of the river schemes [17]. Usually they require only a weir (rather than a dam) and store only a small amount of water [17]. As little water is stored, it is quickly returned to its source river or stream, a short distance downstream from where it was extracted. Consequently, the environmental impact is small. Conversely, the larger scales of hydropower may require large dams that impact the local environment, affecting water access and the local ecology. Similarly, the human impact of larger hydropower schemes is much greater; they often force local people to move, and with a disproportionate impact upon indigenous populations [50].

Table 2.1 - Classifications of hydropower.

Classification	Power range
Pico	<5 kW
Micro	5 to 100 kW
Mini	100 kW to 1 MW
Small	1 MW to 10 MW
Large	>10 MW

In this research, the focus is on turbines within the pico- and micro- range. Across this range, the same sub-systems are usually required. Figure 2.1 shows the sub-systems of a pico- or micro-hydropower plant, whilst Table 2.2 describes the function of each of these sub-systems.

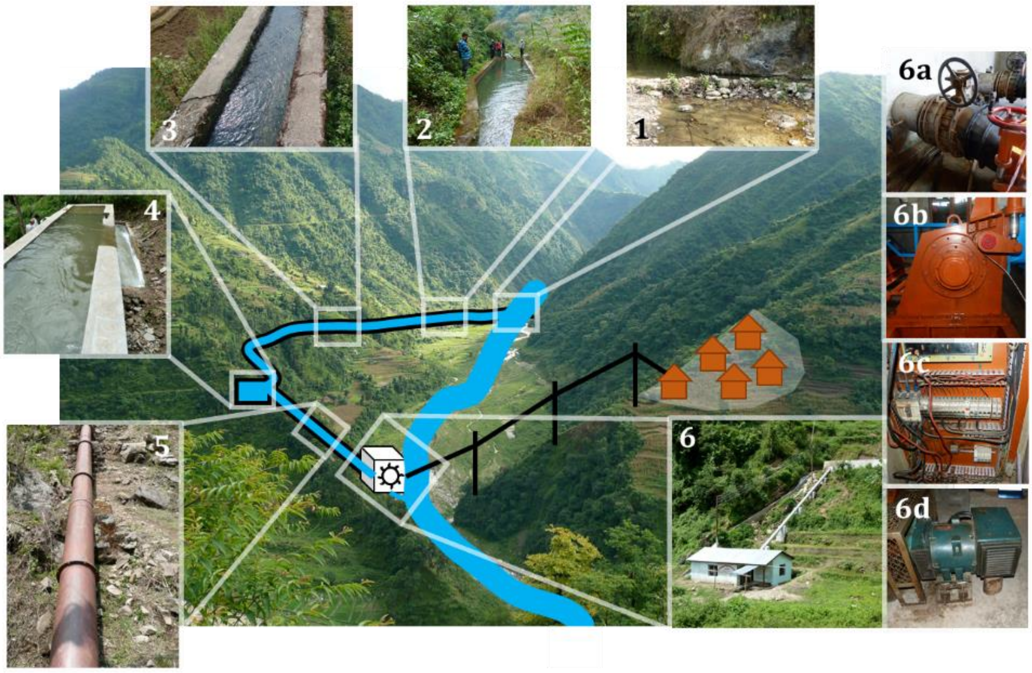


Figure 2.1 - Constituent sub-systems of a micro-hydropower plant. Labels indicate the following: 1. Intake, 2. De-silting bay, 3. Canal, 4. Forebay tank, 5. Penstock, 6. Powerhouse, 6a. Internal pipework, 6b. Turbine, 6c. Control panel, 6d. Generator. Adapted from [51].

Table 2.2 - Sub-systems of a micro-hydropower plant.

No.	Sub-system	Description
1	Intake	A structure to divert water from the river into the canal. The intake may include a permanent weir or temporary structure, e.g. large stones arranged to divert the flow.
2	De-silting bay	A settling tank that is used to remove particles of silt and sand from the water. It usually has a gate which can be opened to flush the sediment away.
3	Canal	This is usually an open canal that takes water from the intake to the de-silting bay and from the de-silting bay to the forebay tank. Often made from stones lined with cement although it can be an earthen channel only.
4	Forebay tank	A settling tank which is used to remove silt and sand. A trash rack is used to prevent leaves and any other debris from entering the turbine.
5	Penstock	A closed pipe which transfers the water to the turbine from the forebay tank. Typically made from mild steel or high-density polyethylene (HDPE) pipe.
6	Powerhouse	The building or structure where the turbine and ancillary equipment is stored.
6a	Inlet pipework and valve	Pipework inside the powerhouse connecting the penstock to the turbine. Usually, this includes a butterfly or gate valve which can be used to stop the flow to the turbine.
6b	Turbine	Converts the power available as head and flow into mechanical shaft power. It is often necessary to use a belt drive to transmit the power to the generator.
6c	Generator	Converts the mechanical shaft power into electrical power.
6d	Control panel	Regulates the rotational speed of the generator using an electronic load controller which diverts excess power to a ballast load.
-	Tailrace	A civil structure that returns the water to the river. The environmental conditions determine the form of this sub-system.

2.3 Turbine types and their use in Nepal

The type of turbine and its power depends on the head and flow rate available at the site. The two main turbine types are impulse and reaction. For impulse turbines, the interaction between water and the turbine’s runner takes place at atmospheric pressure [17]. Typically, a jet (or jets) of water is used to drive the turbine’s runner. In reaction turbines, the runner is usually fully immersed with a pressure difference across the runner causing it to rotate [17]. This allows reaction turbines to use a draft tube below the runner, which slows the flow, reducing the static pressure, allowing more power to be generated [17]. Three common turbine types that are frequently mentioned within this thesis are introduced and their usage in Nepal discussed.

2.3.1 Pelton

Pelton turbines are impulse-type turbines. In the case of the Pelton, the jet of water is directed at buckets that are attached around the periphery of the runner. Figure 2.2 shows the interaction between the incoming jet and the Pelton bucket. The central splitter ridge separates the jet of water and the symmetrical buckets divert the flow of water away from the trailing bucket. The change in momentum of the water imparts a force on the bucket which generates torque [47]. Table 2.3 lists the typical components of a Pelton turbine whilst Figure 2.3 shows a Pelton turbine and identifies the location of these components.

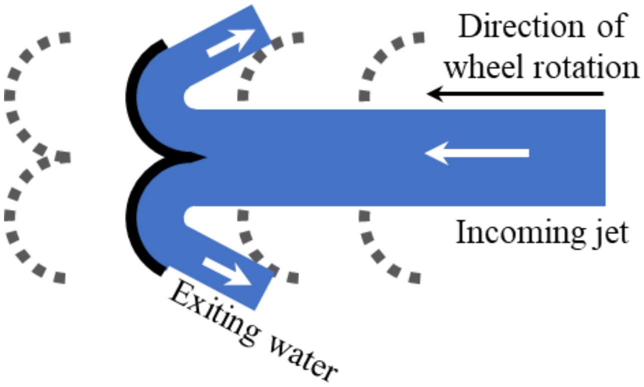


Figure 2.2 - Diagram showing the interaction between the jet and the Pelton bucket, adapted from [52].

Table 2.3 - Typical components of a Pelton turbine.

No.	Component	Function
1	Runner	To generate torque from the jet.
2	Nozzle	To direct the jet towards the runner.
3	Casing	To position the runner and nozzle correctly relative to one another and contain the water that is diverted from the runner.
4	Deflector	To prevent the water from impacting with the runner when the turbine is operating with no load (e.g., at runaway speed). Some Pelton turbines do not include a deflector.

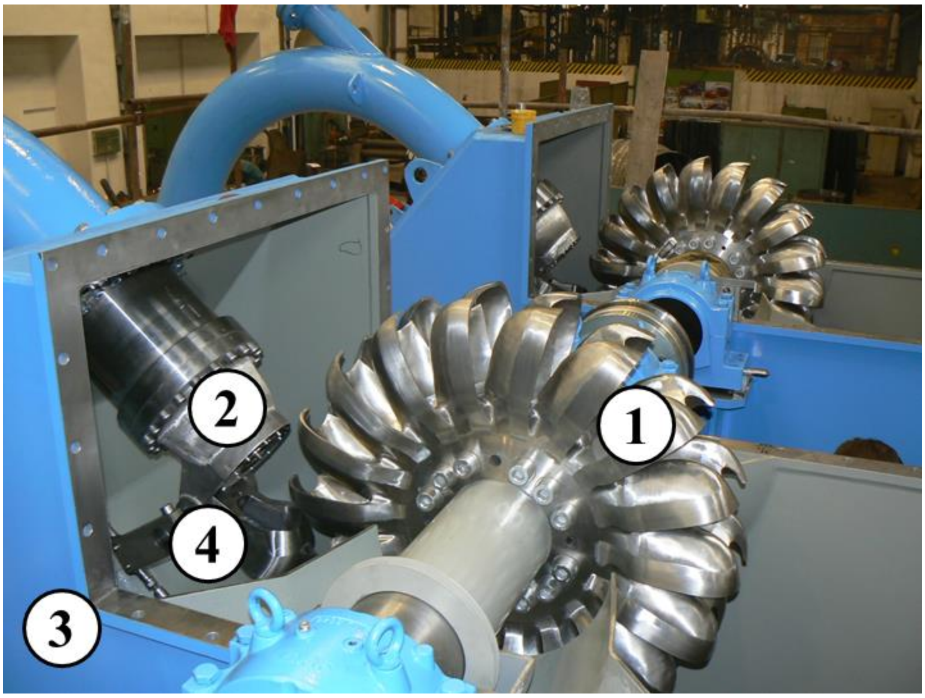


Figure 2.3 - Typical Pelton turbine [53] with the components numbered as follows: 1. runner, 2. nozzle, 3. casing and 4. deflector. The function of these components is described in Table 2.3.

Pelton turbines are common at all scales of hydropower. At the pico- and micro-scales, approximate minimum heads of 20 m and 50 m respectively are typical. High performance large-scale Pelton turbines are capable of hydro-mechanical efficiencies of above 90%; at the pico- and micro- scales, efficiencies between 75% and 85% are possible [54].

The Pelton turbine was invented in 1880 [55] and its widespread usage means that is produced by manufacturers for rated powers from 0.3 kW to 300 MW [56]. Most turbine manufacturing and design companies have exclusive designs; for large scale schemes, several extra percentage points of efficiency can result in a higher income. However, there are several designs openly available in the public domain. In 1957, Nechleba presented four commonly used designs for Pelton buckets [57] which could be scaled in relation to the diameter of the jet. Later, as part of international development efforts to widen the use of hydropower for off-grid generation, [54] and [58] published bucket designs that were intended for use in small workshops. These simple bucket designs were appropriate for use with basic casting and machining facilities, and they are commonly used in Nepal.

2.3.2 Crossflow

The Crossflow turbine, also known as the Banki-Mitchell or Ossberger turbine [59], is considered a part-reaction and part-impulse turbine [60]. The runner is only partially immersed but the interaction between the water and runner blades involves a change in hydrodynamic pressure, meaning draft tubes can be used [59]. Torque is generated by a flow of water passing through the curved blades of the runner. The flow passes through the centre of the runner and then interacts with it again on the other side, generating more torque [17]. Figure 2.4 shows the flow of water passing through the Crossflow runner. Crossflow turbines are typically used at sites with low and medium heads and have very good part flow efficiency [61]; compared to other turbines, there is only a small change in efficiency in response to changes in the flow rate. Table 2.4 lists the typical components of a Crossflow turbine whilst Figure 2.5 identifies the locations of these components.

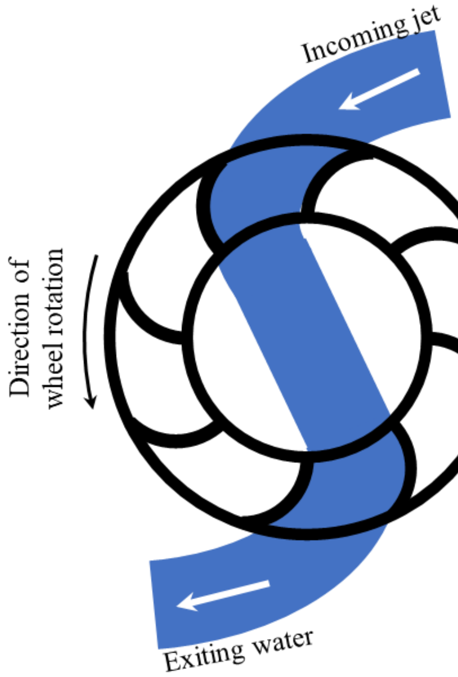


Figure 2.4 - Diagram of the flow of water through a Crossflow runner.

Table 2.4 - Typical components of a Crossflow turbine.

No.	Component	Function
1	Runner	To generate torque from the jet.
2	Diverter	To direct the jet towards the runner.
3	Casing	To position the runner and contain the water that is diverted from the runner.
4	Inlet	To direct the flow of water towards the diverter.

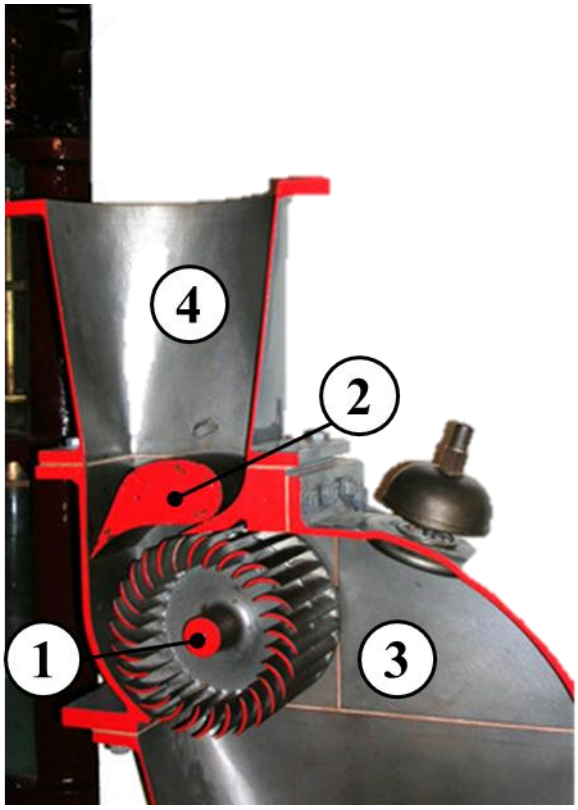


Figure 2.5 - A section view of a Crossflow turbine [62] with parts numbered as follows: 1. runner, 2. diverter, 3. casing and 4. inlet. The function of these components is described in Table 2.4.

The maximum experimental efficiency achieved for a Crossflow turbine is 90% [61] although manufacturers generally state lower expected efficiencies; an example is Ossberger who state an average efficiency between 84 and 87% [63]. Crossflow turbines are typically used for rated powers up to 5 MW [63]. For higher rated powers, other low and medium head turbine types, such as the Kaplan and Francis, are favoured due to their higher efficiencies [61]. At the micro-hydro scale, efficiencies between 70 and 80% are typical [17, 64, 65]. Regardless of the overall rated power, Crossflow turbines have excellent part flow efficiency [60] achieving efficiencies of 70% when operating with only 10% of the rated flow [17].

The Crossflow turbine was first invented by Anthony Mitchell in 1903 [66], and later developed further by Donat Banki between 1916 and 1918 [67], leading to its commonly used name – the Banki-Mitchell turbine. The turbine manufacturer Ossberger obtained a patent to the technology in 1933 and continues to have a strong association with the Crossflow turbine [63]. From the 1970s, the Crossflow design was adapted for use in simple workshops due to its robust nature and the ability to produce the turbine with limited machinery [64]. Later, a range of guidelines were produced and published by the Swiss Centre for Appropriate Technology (known as SKAT) [64] aiding more widespread use of the Crossflow turbine.

2.3.3 Turgo

Turgo turbines are typically used at sites with medium to high heads [68], however, research has suggested that they can be used at very low heads whilst maintaining high efficiencies [52]. Furthermore, they have also demonstrated very good part flow efficiency [68]. It is similar to the Pelton turbine in form and operation; the change in momentum of a jet interacting with a blade is used to generate torque. Figure 2.6 shows the interaction between a jet and a Turgo blade. Unlike the Pelton, the jet is inclined at an angle to the runner, usually between 20° and 22.5° , meaning that the water enters and exits on different sides of the runner [17]. A consequence is that the diameter of the runner is not limited by interaction with the jet. This means that for an equivalent power, the diameter of the Turgo runner can be smaller than for the Pelton.

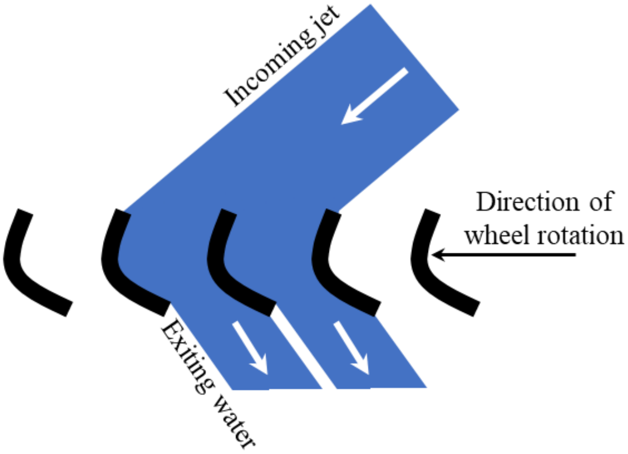


Figure 2.6 - Diagram showing the interaction between the jet and the Turgo blade, adapted from [52].

In Figure 2.7, a diagram is shown for the water passing through a single blade, with velocity triangles shown for the inlet and outlet. It is assumed that all of the jet impacts at the same radius and that the water enters and exits in the same vertical plane. Radial movement of the water is neglected. In the diagram, the following nomenclature is used: v is the absolute velocity of the water, w is the resultant velocity of the water, u is the peripheral velocity of the runner at the radius considered, α is the angle between the runner's plane of rotation and the jet, and β is the resultant velocity angle. Where relevant, the subscripts I and O are used to indicate inlet and outlet, respectively.

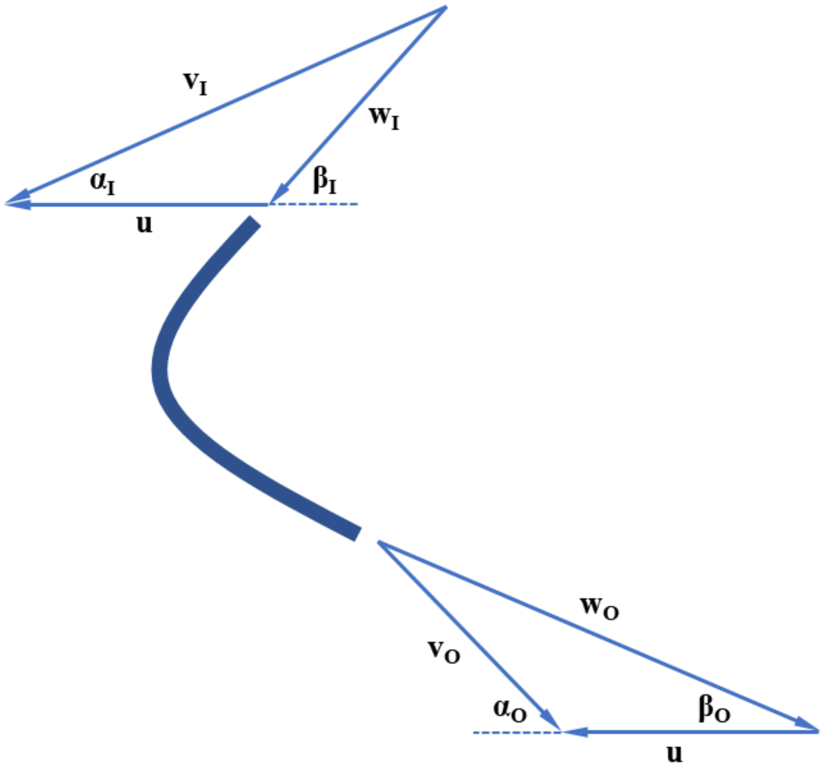


Figure 2.7 - Diagram showing the velocity triangles at the inlet and outlet of a Turgo blade.

At the point of impact, the blade has a peripheral velocity u, dependent on the rotational speed of the runner and the radius at which the jet impact is being considered. The water leaves the nozzle and impacts the blade at an absolute velocity, v_I. Due to the blade's movement relative to the jet, the water enters the blade with a relative velocity, w_I, with a relative velocity angle of β_I. The water passes through the blade and leaves at the outlet with an absolute velocity v_O. The rotational speed of the blade is assumed to be constant as the water travels through the blade, therefore, the peripheral velocity of the blade is also constant. At the outlet, the blade's movement causes the exiting water to leave with a relative velocity, w_O, and a relative velocity angle of β_O. The force exerted on the runner depends on the change in momentum of the water through the blade, in its direction of motion, and the mass flow rate of the fluid. Therefore, with reference to the diagram, the rate of change of momentum is the sum of the horizontal (i.e., perpendicular to u) components of v_I and v_O. From the diagram, it can be seen that the change of momentum will be greatest when the absolute velocity at outlet has no horizontal component, $\alpha_O = 90°$. The torque generated is the product of the force and the radius considered. Finally, the power generated is the product of the blade's rotational speed and the generated torque.

There are a number of key losses within the blade which are not represented in Figure 2.7. On impact, the jet will split and some flow will move 'up' the blade towards the inlet [52]. In relation to the blade's performance, this interferes with the incoming jet. In addition, some of this reflected flow will pass the outer diameter of the runner, however, the remaining portion of the flow (depending on the runner orientation) may pass back through the runner, doing no useful work, and causing further interference. Another loss is associated with velocity profile present across the jet's area. As a result of this, portions of the jet will interact with different areas of the blade surface profile. Another loss occurs following impact where the variable velocity within the fluid will, in practice, have a radial component (e.g., into or out of the page in relation to Figure 2.7). The resultant mixing that occurs leads to turbulent flow, reducing the relative velocity at outlet [69]. Losses also occur due to skin friction on the surface of the blade as the fluid film in contact with the blade's surface will lose speed [52]. It should also be considered that, in practice, the blades have a physical thickness. Depending on the physical geometry of the blade, and the velocity triangles at the outlet, it is possible that the flow leaving a blade can interfere with the trailing blade. This reduces the rate of change of momentum for the trailing blade and therefore, the overall torque generated.

The Turgo turbine was invented by Eric Crewdson in 1919 whilst working for the British turbine and pump manufacturer Gilkes [68]. Gilkes held a patent for the design until 1983, making the use of the Turgo less widespread than the Pelton [68]. After expiration of the patent, other manufacturers have begun to produce the Turgo turbine for mini-hydropower and larger projects. At the pico-hydropower scale, several off-the-shelf designs are available [70, 71]. At a large scale, turbines can achieve efficiencies up to 90% [68], whilst for smaller systems, efficiencies are typically around 85% [72]. Through academic research, there have been some developments in the design of Turgo turbines although much of this research has been focused on Gilkes' own turbines [73]. Some efforts have been made to explore approaches for designing Turgo turbines [74, 75] and the optimisation of market available and simplified Turgo designs [72, 76] although this has not resulted in widespread production. In Nepal, the turbine manufacturer Kathmandu Metal Industries constructed a single prototype [77], however this did not lead to widespread use. Figure 2.8 shows a typical Turgo turbine with the components labelled. The labels refer to the description of components provided in Table 2.3.

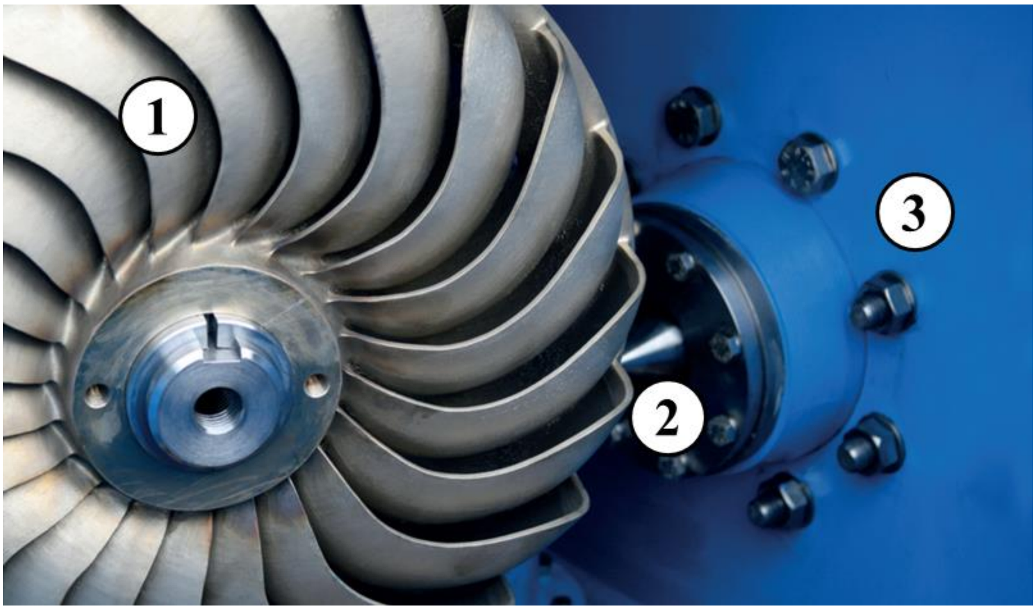


Figure 2.8 - A Turgo turbine [78] with parts labelled as follows: 1. runner, 2. nozzle, 3. casing. The description of parts provided in Table 2.3 for Pelton turbines is also valid for the Turgo turbine, in this case.

2.3.4 Turbines in Nepal

In Nepal, micro-hydropower manufacturers produce mainly Pelton and Crossflow turbines. The simple Pelton bucket design developed by Thake was initially developed in Nepal for use with basic casting and machining facilities [54]. Similarly, the development of a simplified Crossflow turbine took place at workshops in Nepal [64], and it has continued to be frequently manufactured. In [79], site information for MHPs installed under the Nepal Rural Development Programme up to 2007 is provided. Figure 2.9 plots the head and flow rate data for the Pelton and Crossflow sites described in this source. It should be noted that this list of sites is not exhaustive, providing only a selection of site data from a particular period. However, there is distinct trend of the Pelton turbine being used for sites with heads greater than 60 m, whilst the Crossflow is used for heads less than this. Similarly, the majority of Pelton sites have flow rates less than 0.05 m^3/s, whilst the Crossflow sites have higher flow rates. On the figure, a selection of sites are encircled in a red oval. These sites are the outliers of these approximate limits for head and flow rate. In this region, the mixture of Pelton and Crossflow sites suggest both types can feasibly be considered acceptable by designers. At this interface, Pelton turbines become large and expensive due to their slow rotational speed, whilst Crossflow turbines are likely to be narrow and less efficient [80].

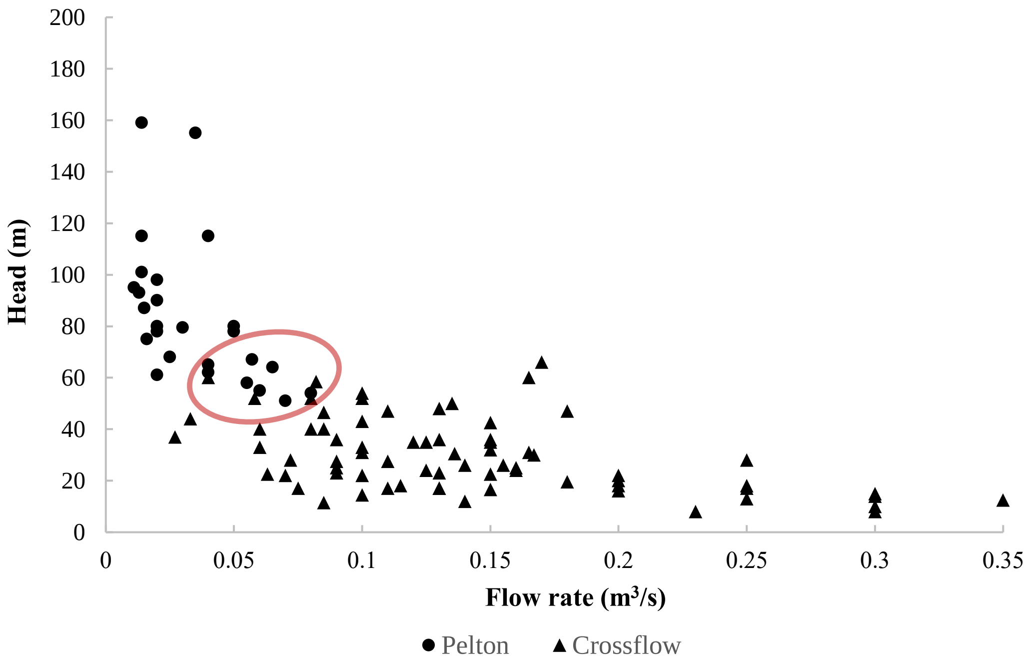


Figure 2.9 - Pelton and Crossflow sites installed under the Rural Development Programme before January 2007. Plotted using data from [79]. The red circle indicates a region where the choice between Pelton or Crossflow turbines is indistinct.

As this interface exists, it suggests that for certain site characteristics, when considering factors such as cost, reliability, and efficiency, there are regions where a turbine is more appropriate than others. Generally, the required head and flow rate for a Turgo turbine is intermediate to the requirements of the other two [17]. As such, the Turgo turbine could be applicable for sites, like those indicated in Figure 2.9, where the choice is indistinct. Other features of the Turgo (mentioned in Section 2.3.3) including its good part-flow efficiency, capacity to deal with silt, and smaller jet to PCD diameter ratio suggest potential benefits in efficiency, reliability, and cost respectively.

The viability of Turgo turbines for small-scale hydropower has been identified in existing research [52, 72, 76]. As an impulse type turbine, their design and construction is similar to Pelton turbines, but with several features which are encouraging for application at the micro-hydropower scale, particularly in Nepal. In available literature [34, 35], poor performance of civil structures and high silt content in rivers has been observed. A consequence is abrasion of turbine runners leading to frequent repair or early replacement. Compared to the Pelton turbine, the jet of a Turgo turbine is aimed at a larger surface resulting in more evenly distributed surface abrasion [68]. In Turgo turbines, water enters and leaves the runner on opposite sides. As such, the majority of the flow passes through the runner without danger of interference with the oncoming jet. Therefore, for similar rated conditions, a Turgo turbine can have a smaller diameter runner than a Pelton, which results in a lower cost. Furthermore, the smaller diameter of the runner results in a higher rotational speed meaning there is greater potential to operate in a direct drive arrangement [68]. For Pelton turbines in Nepal, transmission belts are often required [54, 81] to increase the rotational speed to the rated speed of the generator, most notably at the lower head range. Directly driven systems benefit from fewer parts leading to a reduction in cost, improvements in performance (through fewer transmission losses) and reliability (fewer rotating components). In Nepal and elsewhere, at the pico- and micro- scales, local workshops have typically manufactured Pelton and Crossflow turbines [17]. The typical ranges of head and flow rate for Turgo turbines fall between those of the Pelton (higher head and lower flow) and Crossflow (lower head and higher flow). The introduction of the Turgo turbine could offer a third choice which for some sites may be advantageous in cost and performance trade-offs.

2.4 Development of micro-hydropower in Nepal

In the hilly areas of Nepal, hydropower has been used for centuries using traditional water mills, known as *paani ghatta*, for agricultural processing [77, 82]. This practice has helped to foster a common local knowledge of hydropower in Nepal. Hydropower was first used for electrification in Nepal in 1911 [77]. A plant of 500 kW capacity was installed at Pharping, in the Kathmandu Valley, by the Government of Nepal [82]. In 1934, a second plant of 640 kW was installed at Sundarijal [82]. Later, in 1943, the 677 kW Sikarbas plant was installed at Chisang Khola [83]. The next plant was not installed until 1965, however, since then gradually more large-scale hydropower projects have been connected to the national grid, increasing electricity access but predominantly for urban populations.

In the 1960s, alongside the increasing incorporation of large-scale hydropower into national level planning, there was a new focus on locally manufactured small-scale hydropower. In 1962, the first turbine locally manufactured in Nepal was installed near to Kathmandu [32]. Throughout the 1960s and 70s, foreign aid initiatives aimed to improve capacity in hydropower manufacturing [36]. In 1960, a mechanical workshop, Balaju Yantra Shala (BYS), funded by the Swiss international development agency Helvetas, was founded in Kathmandu [84]. Later in 1963, the United Mission to Nepal (UMN), an international Christian aid organisation focused on poverty relief, established the Butwal Technical Institute (BTI) which focused on training apprentices at its mechanical workshop [85]. However, as technical capacity improved it helped to spawn a number of private companies. In 1972, UMN founded Development Consultancy Services (DCS) in Butwal to design technology for the purpose of poverty alleviation [54]. Separately, BYS and DCS worked on the development of Crossflow turbines that could be used to mechanically drive milling systems [77]. Later, electric generators were added and a simple control system, developed by the Intermediate Technology Development Group (now Practical Action), was used to regulate the supply of electricity [86]. Many of the purely agro-processing units were run as commercial services and found to be financially sustainable after installation [32]. In 1984, The Nepal government responded to these developments by removing the need for water licences for projects with rated power below 50 kW [36].

The Government of Nepal introduced renewable energy into national level planning in the 7th Development Plan (1985 – 1990) which promoted the use of off-grid renewable energy technologies [87]. From 1989, the Government of Nepal also made rural electrification projects eligible for a 50% capital cost subsidy from the Agricultural Development Bank [32]. In 1990, this subsidy was changed to cover the total capital costs and the funds made more widely available by increasing the number of participating banks. However, the impact of these initiatives was small due to ad-hoc delivery methods and the limited available funds [88]. The 8th Development Plan (1992-1997) continued to emphasise the importance of improving capacity within the renewable energy sector [87]. During this period, the 1992 Electricity Act, 1992 Water Resources Act, and 1992 Hydro Power Development Policy were introduced. Collectively, they aimed to promote small-scale hydropower (<1MW) through the delicensing of water rights and promotion of private sector investment into renewable energy [38]. In 1996, the Alternative Energy Promotion Centre (AEPC) was formed, ensuring that improvements in the availability of renewable energy technologies were driven by policy, aided by technical support and backed by international donor funding [89]. The 9th Development Plan (1997 – 2002) concentrated on improving rural livelihoods and reducing the costs of renewable energy technologies to increase its deployment. In this period, the Hydro Power Development Policy was twice updated. Ultimately, the purpose of these changes was to ensure that conditions that were favourable for local private sector engagement in the hydropower sector [87]. The 10th Development Plan (2002-2007) proposed a Rural Energy Fund to manage grants and loans for renewable energy technologies. The Rural Energy Policy and Subsidy for Renewable Energy formalised a subsidy process for all technology types including micro-hydropower, whilst the 2006 Subsidy Delivery Mechanism legislated the process for disbursing subsidies. Both the Subsidy Policy and the Delivery Mechanism were updated in 2010 and again, to their most recent form, in 2016. The most recent changes extended the subsidy availability to include private sector investors as well as community groups and cooperatives [89].

2.5 Operation of micro-hydropower plants in Nepal

Today, there are more than 3,300 micro-hydropower plants in Nepal, manufactured and installed by local small- and medium-size enterprises across the country [90]. The AEPC supports the development of projects by providing a subsidy of approximately 50% of the project cost [35]. The amount of the subsidy depends on how remote the location of the plant is [91]. Local government funding and contributions from the community make up the remainder of the project cost. The community also provides labour 'in kind' during the construction of the plant's civil works. Following installation, the operation and management of these plants becomes the responsibility of members of the local community.

In the literature, the benefits of micro-hydropower in rural Nepal are well documented. In the home, extended hours of evening light are used for education, socialising, and domestic tasks [16, 92]. The electricity is used for domestic appliances including televisions, radio, fridges, and rice cookers [92]. Consequently, for lighting and cooking, micro-hydropower decreases reliance on kerosene and firewood respectively [16], consequential effects of this are reduced health issues due to less smoke in the home and less time spent on firewood collection. Both of these changes tend to effect women and children more than men. Lighting increases the time available for education of children [92]. In addition, Legros et al. found a correlation between electrification using MHPs and women's education, and their access to information [92]. In communities connected to MHPs, income and agricultural output tend to be higher whilst expenditure on energy is usually lower [92]. In addition to agricultural production, electricity can lead to new income generating opportunities. In the case study considered by Bhandari et al., this included milling, poultry farms, carpentry, photocopying, tailoring, and electronic repair centres [93]. Other electricity uses mentioned in the literature include community services such as primary and secondary schools, health centres, and local government offices [16, 22].

The ability of an MHP to deliver these benefits depends on the operation, maintenance and management of the plant. Once commissioned and handed over to a community, operation and maintenance is typically carried out by a trained operator. Plant operator training takes place on a 22-day course, arranged and delivered by the Nepal Micro-Hydro Development Association, which covers maintenance of the mechanical, civil and electrical components [94]. Managers are expected to collect the required tariffs from the community. The collective action of the community during the development process helps to create a sense of ownership which is beneficial in collecting tariffs from the consumers [35]. Where tariff collection is effective, there have been examples of the managing committees providing loans to the community to establish productive end uses [22].

In discussing the issues that affect MHPs, it is worth defining two terms commonly used when evaluating the performance of power generating equipment. Capacity factor is the ratio of generated power to the maximum possible generated power, within a given time frame [95]. It provides an indication of a system's ability to deliver the expected amount of power. A low capacity factor may suggest that the generated power is reduced due to variation in the source (e.g. for hydropower, low river levels) or poor reliability of the generating equipment. Load factor is the ratio of average electrical load to peak electrical load, recorded within a specific time period [95]. The load factor shows the variation in system demand. When low, it indicates that there is a large variation, meaning there may be extended periods where the consumed electricity is significantly lower than at the peak. For MHPs, the data required to evaluate these factors numerically is often difficult to access. However, the terms remain useful in describing the performance of the plants.

Despite the positive effects of electrification, there is evidence in the literature of a range of issues that affect the capacity factor of MHPs. At the outset of a project, a feasibility study should indicate key site characteristics, most importantly the available head and flow rate. It has been suggested that in Nepal, these studies are often inadequate with poor estimations of flow rate resulting from limited hydrological surveys [35, 37, 39]. Incorrect estimation of site characteristics results in incorrect turbine design and an inability to deliver the expected power [96].

Khennas and Barnett examined the quality of turbines in Nepal for a study published in 2000 [37]. They identified that despite efforts to improve quality, the physical assets are still a "substantial cause of failure" [37]. An interview respondent in [38] described the quality of micro-hydro manufacturing in Nepal as of "moderate to low quality". Despite the number of manufacturing companies that now exist, there is a lack of research and development in the micro-hydro industry in Nepal. The manufacturing technology used remains basic with no use of four axis milling machines nor laser cutting [34]. Testing of turbines occurs only at the final stage, there are few quality assurance check during the production process [35]. Arter found that despite using high quality belts, pulleys were not built to specification resulting in faster wear of the belt and bearing [34]. Without standardisation, many components are built bespoke for every turbine.

The civil installation has frequently been mentioned as a cause of problems. Gill et al. identified a common issue that junior field workers who oversee civil works often lack experience and are over-accommodating to customer requests [40]. Both Khennas et al. and Gill et al. suggest that overly long and poorly designed canals are common [37, 40]. The World Bank recommends greater supervision over the construction of civil work, particularly for de-silting basins where poor design and construction results in increased turbine erosion [35]. During the installation of the turbine, weak foundations and the misalignment of pulleys can cause excessive vibrations leading to the premature failure of components [40]. As there is no requirement to demonstrate performance testing, a final machine efficiency is rarely known and generally assumed to be around 50% [40]. Khadka & Maskey carried out efficiency testing on 15 sites using a flow meter and a pressure gauge to accurately determine flow rate and head [97]. In their sample, they found that the efficiency was highly variable with a range of 45% to 75% at rated flow, with 3 of the 15 turbines failing to achieve an efficiency of 50% at any flow rate.

Whilst there is training delivered by the Nepal Micro-Hydro Development Association (NMHDA), the literature suggests the quality and regularity of maintenance is highly variable. Barr’s study of operation and maintenance at 6 MHPs is the most detailed qualitative analysis available [41]. The report demonstrates that whilst there are a range of technical problems that have affected these sites, they rarely occur for purely technical reasons. It was shown that at sites where the benefits of electricity were obvious to the community, the quality of maintenance was superior. At these sites, preventative tasks were carried out more diligently. Gill indicates that there is often a high turnover of staff due to low salaries or because plant operators find work elsewhere, typically abroad [40]. A study carried out by Multi Electrical Ltd. found that across 15 MHPs in Nepal, there was an average of 116 days per year of downtime [98]. Before entering service, there is inadequate education for consumers regarding the connection cost, tariff cost, when and how much electricity they can use [99]. Due to this lack of consumer knowledge, Barr found that at an MHP in Burtibang, a town in Western Nepal, all the circuit breakers had been removed meaning there was no protection for the system. Meanwhile, most of the consumers were unaware of this and continued to use the system in the same manner [41]. When maintenance is required, the remote nature of sites makes repairs slow as technicians must usually be sent from Kathmandu or Butwal where the majority of companies are based [39].

Once in operation, economic and managerial issues include low load factors due to a lack of productive end uses, low income to pay for repair, and mis-use by consumers [16, 39]. Lord states that the uncertainties associated with hydropower, such as the amount and regularity of available power should be better communicated to the community [100]. A further issue identified in several studies is that access to electricity is unevenly distributed within communities due to gender, caste, and ethnicity [101, 102].

2.6 Socio-technical systems

In [103], Trist claims that the term ‘socio-technical’ arose around 1949 in relation to a field research project undertaken by the Tavistock Institute and the British coal mining industry. The project focused on the diffusion of innovative working practices in the mining industry. Work organisations were considered as socio-technical systems where the social (the people) and technical systems (the equipment) were the “substantive factors”. Further development of the theory led Trist to argue that socio-technical studies require analysis at 3 levels. At the micro level, primary work systems where activities are carried out within a “bounded sub-system of a whole organisation”. Secondly, whole organisation systems which may be a plant, workplace, or corporation. Lastly, at the macro level, the macrosocial systems that exist within communities and industrial sectors.

The use of the term ‘socio-technical’ expanded into other areas and has often been used within the field of energy studies. In [104], Hughes presents the history of modern power systems and argues that large-scale technological changes cannot be understood without an appreciation of the social context, and the mutual socio-technical implications. Its use has been common at a macro-societal level with the term ‘socio-technical transition’ used to analyse the movement from one dominant ‘socio-technical system’ to another [105]. This has been used to consider how society-wide transitions can be made towards the use (and integration) of renewable energy technologies [106, 107]. Elsewhere, Sovacool has repeatedly used a socio-technical approach to analyse the barriers facing the development of renewable energy technologies in specific countries [38, 108, 109]. These studies, both the theoretical and the applied, have tended to be ‘top-down’, focused on the macro-level of governmental and societal actions, and their impact on transitions towards renewable energy use.

Recently, some research has taken a ‘bottom-up’ socio-technical approach to consider the development of individual small-scale renewable energy technologies. In [110], the construction of a mini-hydropower project in Tanzania is considered as a “dynamic process” where the creation of a socio-technical system results in new relationships between people, technology, institutions, and resources. Similar to the 3 levels of analysis discussed by Trist in [103], this work considers that there are multiple levels of socio-technical context that influence one another. The new socio-technical system that is formed, encompassing the technology and direct users, develops “in relation to” but also “constrained by” the local context and a broader national (or international) context. In [111], a socio-technical systems approach is used to consider the implementation and use of solar mini-grids in the Sunderban Islands in India. The approach is used to highlight that the technology and society influence and shape one another, and the dynamic nature of the system means that the changes that occur mutually affect the technical elements, local community, and actions of individuals. Consequently, technical and non-technical factors are considered indivisible in their influence upon the implementation and ongoing operation of the mini-grid. These factors occur at local and institutional levels demonstrating the importance of a holistic implementation approach. The bottom-up approach is reflected in the definition used in this work, where a socio-technical system is defined as a “configuration of heterogeneous technological and social elements, such as technical devices, organisational, involved actors and social practices in the implementation and use, as well as competences linked to the technologies”. The relationship between technology and people has been discussed directly in relation to sustainability. Whilst considering the sustainability of 23 small-scale renewable energy projects in [23] , Terrapon-Pfaff et al. observe that “technical sustainability did not only depend on the reliability of the technological innovation alone but the embedding of the technology in the socio-cultural, political and ecological context". In [112], the same authors further this concept with the observation that outcomes and sustainability depend upon "the changes in the socio-economic configurations."

2.7 Approaches to technology transfer

As described in Section 1.3, micro-hydro turbines are made locally by manufacturers based in Nepal. The benefits of locally manufactured (and community owned) renewable energy technology have also been well documented, particularly for hydropower and wind power. In comparison to importing foreign equipment, there are numerous benefits to this approach: local capacity in repair and maintenance, access to spare parts, shorter downtimes, and potential for local adaptions. Alongside the local manufacture, involvement of the community also has potential benefits such as: easier knowledge transfer to end users, community ownership of the technology, and additional opportunities to build capacity.

This approach of using community owned and locally manufactured technology to provide developmental benefits has its roots within the 'appropriate technology' movement. In the 1950s [113], the transfer of Western designed technologies was promoted as a methodology to develop countries (seen as less developed) by the more industrial Western economies. Nieusma suggests that a lack of understanding of the local context meant many early efforts failed [114]. Partially in response to this, the 'appropriate technology' movement, inspired by Mahatma Gandhi, but spearheaded by E.F. Schumacher [115], identified that the suitability or 'appropriateness' of a technology to the local context was vital in determining its success [113]. Initially named the 'intermediate technology' movement, it focused on technology more sophisticated than what was locally available, but smaller in scale than the technology used in industrialised countries [116]. Later, due to the perception that 'intermediate technology' indicated only a temporary solution, the term 'appropriate technology' gained wider popularity. In comparison to the technology transfer approach that had been used previously, appropriate technology made understanding of the local context the key focus and integrated this within the design approach [114]. The movement was influential in both developed and developing countries leading to projects focused on transport, agriculture, and energy.

The movement inspired development efforts in Nepal. Initially, the focus of international development agencies (Swiss, Norwegian, and British) was on agricultural technology [32, 36]. Hydropower was used for its ability to drive rotating machinery, only later being used to power generators [54]. Despite the 'appropriateness' of the technology - it could be manufactured in Nepal and used within the local context – its dissemination depended on the presence of foreign experts. A sustained input of aid money and foreign experts was required to build the capacity and create a micro-hydropower industry within Nepal. Whilst Nepal continues to remain dependent on large scale funding to support the micro-hydropower industry through subsidies for projects, the industry has reached some level of selfsufficiency. The experiences of the experts working on the ground in Nepal during the 1970s, 80s, and 90s have been well documented. Literature including [81] and [54], provide all of the information required to identify a site, design and manufacture a turbine, construct civil structures, and operate and maintain the plant.

As a movement, appropriate technology lost momentum in the West during the 1980s [117]. Whilst the term appropriate technology is still used, a number of design specific disciplines have emerged to occupy a similar space. Academics have proposed new fields and terminology to document efforts in design and engineering related to poverty alleviation. These include 'human-centred design' (HCD), 'design for development', and 'design for the developing world'. Although primarily focused on the design of digital interfaces, many of the key principles of HCD described by Maguire in [118] have parallels with those present in related fields. These include understanding the user, iteration of design solutions, and using multi-disciplinary teams. In [119], Mattson and Wood use the available literature that describes the design of products for the Global South to identify 9 key principles for 'design for the developing world'. The shortened versions of these 9 principles are:

- empathy through codesign
- importance of in-context testing
- risk in technology importation
- rural and urban opportunities
- effects on women and children
- project management strategy
- interdisciplinary teams
- cooperation with government
- using existing distribution strategies

Despite the usefulness of the guiding principles, the terminology reduces the developing world to a homogenous entity. The variations in local context across the Global South, and internal to individual countries, require acknowledgement.

Globally, design fields motivated by the proliferation of the internet and (more recently) additive manufacturing, have also developed. These innovations have supported the development of movements focused on making technological hardware 'open-source'. In the field of software development, an open-source approach has been present as long as the early 1970s (and the early development of Unix); now there are numerous examples of successful software applications for a wide range of uses [120]. A famous instance is the operating system Linux which was created in the early 1990s [120]. The principle of open-source software is that the source code is openly available, allowing collaborators to work freely on its improvement and adaption [121]. More recently, this approach has been transferred to physical technology or ‘hardware’. From 2009, the term ‘open-source appropriate technology’ (OSAT) has been regularly used in academia in the United States and Canada [122]. It describes appropriate technology that is designed collaboratively with the resulting design information and specifications made openly available [122]. There is evidence that a similar approach was developed at Thinkcycle at the Massachusetts Institute of Technology (from 2000) where ‘open collaborative design’ was proposed as an approach for developing ‘sustainable engineering solutions’ to “critical problems” [123]. In [122], the website Appropredia is highlighted as an example of OSAT in action. Appropedia is a website where collaborative solutions in sustainability, poverty reduction and international development can be shared [124]. As a wiki, anyone can add and edit content. Pearce states that such websites have significant potential in international development due to their ability to organise information such as project examples, best practices, and ‘how-tos’ [125]. In the paper, Pearce acknowledges the development of open-source manufacturing and discusses the potential of RepRap, an open-source 3D printer that can produce some of its own parts.

In [126], Reinaur & Hansen develop a framework to consider the key determinants in the use of ‘open-source hardware’ (OSH). Based on a comprehensive literature review of small wind turbines, they consider the problems being solved, the open-source community, the solutions, and the users. They suggest that the benefits of open-source hardware include its cost and adaptability to local context. However, they also suggest that its uptake depends on poor functionality of market-based solutions or barriers that prevent their use. The accessibility and detail of design information is found to be an important determinant in the use of the design, and the degree to which it can be used by different types of users. Depending on the user, the most appropriate form of knowledge transfer may vary. It is suggested that OSH solutions are “more likely to be diffused widely” if they address a productive need or resource scarcity rather than being for enjoyment, in the realm of hobbyists and enthusiasts.

Open-source technology is also central to an alternative method of international production proposed by Kostakis et al. in [127]. The model is called ‘design global-manufacture local’ and Kostakis et al. argue that “the emergence of commons-based peer production and desktop manufacturing technologies, may signal new alternative paths of social organisation”. In [128], two case studies are presented that demonstrate the concept of ‘design global, manufacture local’. For both case studies - robot hands and small scale off-grid renewable energy technology - evidence is presented for 3 key areas: design-embedded sustainability, on-demand production, and sharing of the design. Common to both of the case studies, design-embedded sustainability is achieved through active participation of users and a design approach that attempts to decrease the number of components. On-demand production is achieved through desktop manufacturing. Designs are shared globally online under a creative commons licence, whilst online resources and fora allow digital collaboration, with face-to-face collaborations also documented. Digital resources, including CAD files and tutorials, are made available to a (potentially) worldwide community who can use, modify, and adapt the design information.

2.8 Summary

In Nepal and similar countries, small-scale hydropower is an environmentally friendly technology that is capable of delivering sustainable and reliable electricity. The electricity services provided in the home and in communities provide improvements to health, education and income generating opportunities. In Nepal, through international development efforts and government support, an active micro-hydropower industry has developed. The government provides subsidies that allow rural communities to develop micro-hydropower plants. Local manufacturers produce the hydropower equipment, with the community providing labour during the construction phase, and later operating plants independently. The development process involves multiple actors with individual capabilities, roles and responsibilities. To understand this, a socio-technical approach can be used. Akin to the levels of a socio-technical system identified by Trist, the following three levels can be identified for a micro-hydropower plant:

1) Primary level – micro-hydropower technology and operational team
2) Community level – Interaction between the community, technology, and operational team
3) Macro level – National landscape including government, industry, and finance.

Within the literature, issues have been identified that affect the ability of the plants to operate reliably and sustainably. Typically, these sources have tended to focus on the operational stage, and on social or technical elements in isolation. In the Nepali context, a socio-technical approach could be useful in understanding that the sustainability and reliability of MHPs depends upon interactions between stakeholders and technology, that occur at multiple levels, and are dynamic throughout the project process.

Alongside a number of specific technical issues, the literature indicated that approaches to hydropower manufacture in Nepal are outdated, and there is a limited variety in the types of turbine constructed. Pelton and Crossflow turbines are locally manufactured by companies to serve sites with high and low heads respectively. There are sites where in terms of cost, efficiency, and reliability, other turbine types may provide a superior alternative. By examining the ranges of head and flow rate that led to a mixture of Pelton and Crossflow turbines, a range was found where the Turgo turbine could be applicable. Through a detailed understanding of the availability of materials and processes, it would be possible to identify opportunities to improve the quality of manufactured equipment and develop locally appropriate designs for turbines that are currently not available.

Inspired by the appropriate technology movement, a range of design methodologies have developed that attempt to address the challenges associated with designing technology for use in the Global South. Whilst disciplines such as ‘design for the developing world’ and ‘design for development’ have emphasised the importance of understanding local context, their design approach is often externally based, making non-specific recommendations for a homogenous ‘developing world’. Furthermore, as in the case of the Pelton and Crossflow turbines in Nepal, appropriate solutions often exist but require adaption to ensure they are locally appropriate, manufacturable, and repairable. A design methodology with this focus could be effective in developing locally appropriate hydro-turbine designs. Recent developments, particularly the internet and additive manufacturing, are being used to drive alternative approaches to design and manufacturing such as ‘open-source hardware’ and ‘design global-manufacture local’. These technologies (and the associated design approaches) provide new opportunities to create, share and adapt designs. However, such advantages have not been widely utilised in the context of the Global South, Nepal, or hydropower specifically.

Chapter 3

Design for Localisation and the research methodology

3.1 Introduction

From the literature review, the opportunity to use a different turbine type in Nepal was identified. To achieve this requires the translation of an existing design to a new local context. In the first section of this chapter, a methodology called 'Design for Localisation' is proposed to address this translational process. Initially, the methodology is derived based on the experiences of a case study. Using the proposed methodology as a framework, supporting examples from available literature are analysed to establish its validity. The second section of this chapter uses this *design* methodology to inform the *research* methodology for this thesis. The research methodology is shown visually and used to demonstrate how the research aim and objectives are addressed. Finally, the specific research methods, collaborations with partners, and ethical considerations of the research are discussed.

3.2 Design for Localisation

Engineering design can be defined as "a process of developing a system, component, or process to meet desired needs" [129]. Meanwhile, for a given system or component, the availability of tools, materials and capacity of personnel affect how they are manufactured. As such, a holistic design process should also consider these factors. In many instances, to solve a desired need, a viable design solution may exist. However, factors present in the local context may limit the applicability of the solution. For example, supply chains may make transportation of a product prohibitively expensive, or the availability of particular processes may prevent manufacture of a product locally. Under these circumstances, it may be advantageous to develop a locally appropriate version of a proven design solution.

In design theory, the term Design for X (or DFX) has been used to describe a design approach where ‘X’ is a particular desirable characteristic (e.g. quality, reliability, or safety) to be aimed for [130]. A common example is Design for Manufacture (DFM), where design goals and manufacturing constraints are considered simultaneously [129]. In this section, it is proposed that Design for Localisation (DFL) is a necessary and viable addition to the DFX paradigm. As a methodology, its objective is the adaption of an existing design for local manufacture, assembly, and use in a new geographic location. This major objective is considered as the summation of two criteria which must be fulfilled. A localised design must:

- Be manufacturable and repairable in the local geographical region of use considering the availability of skills, processes and materials.
- Be appropriate for the local geographical region based upon consideration of the technical, social, economic, and environmental context.

In this section, a case study is used to derive three key stages of the Design for Localisation methodology and several principles that support its application. The case study focuses on the development of a series of propeller turbines in Nepal that were designed to fulfil the above criteria. The supporting evidence is derived from the personal experiences of the researcher and several collaborators, and from available literature.

3.2.1 A case study – the propeller turbine series

From 1997, the hydropower manufacturer Nepal Hydro and Electric (NHE) began the process of developing several propeller turbine sets, known as the PT series [131]. Using information from papers published by the University of Canterbury (UC) in New Zealand, an initial laboratory prototype model was specified, built, and tested. This led to the development of 0.2 kW, 0.3 kW and 1 kW versions that were installed in the field. NHE were responsible for the design and manufacture of all hydro-mechanical and electrical sub-systems. In 2009, the rights to the technology were transferred to the People, Energy and Environment Development Association (PEEDA), an NGO focused on promoting economic development in Nepal. From then, PEEDA have been technically assisted by Oshin Power Services (OPS), a micro-hydropower manufacturer and installer, and Kathmandu Alternative Power and Energy Group (KAPEG), a research organisation focused on electrical engineering in renewable energy [132].

For the propeller turbine system, specific design requirements were derived through an understanding of the installation environment [131, 133]. Engineers working at NHE had identified that there was no locally manufactured technology to serve rural sites in Nepal where the available head was insufficient for Peltric sets (pico-hydro scale Pelton turbines) or Crossflow turbines [133]. Table 3.1 outlines considerations relating to the local context and their effect on the system requirements.

Table 3.1 - Considerations that affect the socio-technical system design specification for a Nepali context.

No.	Consideration	Design requirement
1	Many rural areas are located far from the industrial centres of Kathmandu and Butwal.	Reliability and simplicity of the design should be a key priority.
2	Sites could be located far from nearest road head.	Individual components should be portable on foot.
3	Agricultural canals for irrigation are common across Nepal.	Existing civil works can be used to divert water to the turbine.
4	Monsoon season in Nepal often leads to significant flooding.	Electrical components must be secure from water damage.
5	The rivers in Nepal carry a very high sediment content during the monsoon season.	The turbine must be resilient to a high sediment content in the flow.
6	Water flow may include vegetation and other debris.	Through filtration or alternative methods, the turbine should be resilient to vegetation and debris that are typical in the local area.
7	The technology is owned, managed and operated by a community.	• The system must be simple to operate even by someone with little technical expertise. • Electricity tariffs must be collected to pay for operation and maintenance of the technology.
8	Projects where consumers make no financial contribution are likely to fall into disrepair.	End users should make a financial contribution to the scheme prior to installation.
9	There are limited opportunities for income generation in rural areas of Nepal [16].	If possible, the technology should improve opportunities for income generation.
10	Income of consumers is typically low.	• The cost of the technology should be minimised. • Tariffs must be set at an appropriate level so that consumers can pay regularly.
11	Communities in Nepal often consist of multiple caste groups with more disadvantaged groups less able to access assets and make an income [134].	The provision of electricity should not discriminate consumers who have less ability to pay.
12	There is typically a good availability of unskilled labour in rural Nepali communities.	End users should provide labour in kind as a contribution during the construction works.
13	There may be water rights issues associated with using water to generate power.	Sites should be selected carefully to avoid creating conflict.
14	Communities may be unfamiliar with the concept of hydropower.	Communities should be educated to understand the technology.
15	Some communities have no access to a reliable supply of electricity. In 2016, an estimated 7 million people had no access to electricity whilst 20 million relied on biomass for cooking [6].	Consumers need to understand using electricity, electric lighting and electrical appliances.

16	Every community is socially and economically unique whilst environmental and technical features of each site will also vary.	The most effective process for implementation will vary from one site to the next.
17	Paying for energy services on a monthly basis may be unfamiliar to rural communities.	The payment process and its importance should be explained to consumers.

From 1981, the UC had been developing a set of cost-effective designs ready for installation at sites with appropriate geography in New Zealand [135]. As these sites were likely to be in remote areas, reliability and repairability were key drivers. The designs were all vertical shaft propeller turbines, standardised to minimise their cost and maximise simplicity. The sizes of turbine were considered in discrete steps to correspond to typical generator specifications. Alongside the turbine and generator, an electrical control system was developed. This electronic load controller (ELC) allowed turbines to run at a constant speed by maintaining a constant resistive mechanical load; using a dummy load that varied in response to changes in the consumer load [136]. Consequently, no moving guide vanes or blade actuation were required which reduced the number of parts, cost, and maintenance requirements. The high specific speed of a propeller turbine allowed it to be directly coupled with a generator. This avoided the need for a transmission system (such as a belt drive or gearbox) which also reduced the number of parts, cost and maintenance requirements. Reaction-type, propeller turbines are inherently good at dealing with silt which means complex and expensive de-silting civil structures were not required. Another advantage was that a draft tube could be used, allowing the generator and electrical components to be positioned safely above the flood plain. These features fulfilled many of the requirements in Table 3.1, and made the design a viable candidate to be adapted for local manufacture and use in Nepal.

Design and manufacture in the local context

Following the identification of the propeller turbine design, the ongoing research and development occurred in the country of use. During the initial development at NHE, Nepali engineers were encouraged to devise and conduct their own tests on the sub-systems of the turbine set. By encouraging an experimental approach, the engineers learnt to devise experiments that tested the equipment, even to the point of failure. For the individuals, this improved their understanding of the equipment and its weaknesses, allowing them to suggest and implement design changes. The technology benefited from robust testing of all sub-systems, with targeted experiments conducted by Nepali engineers who understood the installation environment. Over the course of its development, the local context posed challenges affecting both the function of the technology and its production. Table 3.2 describes three problems, and the solutions that were developed to overcome them.

Table 3.2 - Problems in the local context and their solutions.

Component	Problem in the local context	Solution	Outcome
Casing	The size of engine lathe typical at micro-hydropower manufacturers was too small to carry out machining operations on the runner housing and scroll casing. For one version, the machining operations on this part took over 70 hours and were sub-contracted to a machinist with a larger engine lathe, increasing the total cost.	The manufacturing process was changed to conduct machining operations on the runner housing prior to fabrication with the casing. An alignment jig was used to ensure concentricity between these two components during fabrication.	This change to the design allowed all the manufacturing processes to take place at OPS, and therefore the processes could be replicated by other micro-hydropower manufacturers with similar equipment. The method has been successfully used in the production of two 1 kW and one 3 kW turbines.
Electronic load controller	Many income generating activities or productive end uses such as grinding mills, sawmills and sewing machines require the use of motors. When powering a motor, a large inrush current occurs when a voltage is applied whilst the motor's shaft is stationary [137]. The inrush current can be several times greater than the rated load current and the resulting droop in voltage prevents the motor from starting.	A variable capacitor bank connected across the generator poles could be used to vary the capacitance across the generator phases. Using a testing rig, it was possible to identify a selection of capacitors that would allow the IMAG to drive an inductive load. A printed circuit board electronic load controller could be used to limit the voltage drop.	The capacitor arrangement allowed the 0.3 kW rated turbine-generator set to drive a hand drill. The new ELC limited the droop in voltage to 190V and ensured recovery to the design point voltage of 230V in 0.5s. A method for the manufacture of PCBs was developed by KAPEG.
Trash rack	For the reliability of hydro-turbines, it is important to prevent debris from passing through the turbine. In many parts of the world, small- scale hydropower schemes often use Coanda screens to effectively filter small particles whilst self-cleaning. Coanda screens were not available in Nepal's local market and the existing alternatives for Pelton and Crossflow systems allowed debris of up to 10 mm to pass through the system. Stones of	NHE used a laboratory rig to test using perforated steel sheet as a self-cleaning screen. The performance of locally available perforated 0.8 and 2 mm thick sheet, both with 3 mm diameter holes, was compared. The sheets were tested in straight and right-angled configurations.	The final form of the trash rack was a simple welded fabrication using the 2 mm sheet. The rack was installed into sites with upright threaded bar allowing adjustment of the angle depending on the quantity and type of debris to be filtered. This allowed the rack to be optimised on site for specific operating conditions.

	this size could easily block or damage the blades of the propeller turbine.	

These problems all occurred due to the local context. For the casing and trash rack, cost and the ability to complete production processes locally motivated the design changes. Whilst it would have been possible to import components from elsewhere (e.g., a Coanda screen) or pay another company to do machining work, these actions would have increased cost and reduced the number of components that could be manufactured by local companies. For the electronic load controller, the original motivation was to improve the functionality of the product by increasing the range of feasible electrical loads. Similar to the other two problems, the solution that was developed allowed the production of the component to take place locally.

Monitoring and testing

During the initial development, the laboratory developed at NHE was crucial in testing individual components and their integration. The testing rig consisted of an open flume which was fed by a pump. For the early versions of the turbine, this allowed testing to closely replicate the conditions found on site. Engineers at NHE were encouraged to develop their own tests to improve the reliability, performance and safety of all components. The method and results for all these tests were recorded so that the product development path could be easily understood. Over a 10-year period more than 50 tests were carried out, these included testing of new and existing designs, and failure analysis of parts returned from the field.

For field-based testing, the BTI was responsible for conducting a monitoring programme of 3 PT turbines [138]. NHE were a partner in the programme and provided all the equipment, training and technical support to the engineers responsible for monitoring. As well as supporting the three field sites, NHE made a series of design changes based on reports from the field. At each installation, practical training was delivered regarding operation, maintenance, and repair procedures to the selected operator. An O&M guidebook, written in Nepali with clear supporting images, was also provided to operators. In addition, training for consumers explained electricity use and the importance of tariff payment. Over the course of the field monitoring, a number of problems were identified relating to the different sub-systems. The identification of these problems and the feedback to NHE meant they could be individually resolved at the time and targeted for remediation in future designs. Examples included changing the quality of bolts used and adapting a stub pin design due to repeated failure.

Alongside technical issues, monitoring indicated problems relating to installation and operation. For example, it was found that the distribution cable was fragile and would often tear during installation. Subsequently, greater care was taken with both handling and routing the cables. At some sites, to increase the available load, the community tampered with miniature circuit breakers (MCBs). Operators were advised that regular checking of these MCBs should form an important part of their O&M responsibilities. The actions of the community had a significant impact on the technical performance of the plant. The communities learnt that their behaviour could damage the plant or reduce the quality of service for themselves or others. When compact fluorescent light (CFL) bulbs broke, the usual response by the community was to replace them with cheaper incandescent bulbs. The higher power rating of these bulbs led to overloading of the system. Similarly, at another site, wealthier members of the community began using televisions. At one site, these problems were resolved when NHE staff instructed households to reduce their individual loads and continue to use CFL bulbs. At another site, the community independently introduced their own informal system which allowed only one television to be used each evening.

A later version of the turbine, manufactured at OPS, was used to test the efficiency of the complete set and configure the ELC for the 1 kW unit. Testing was conducted at the Turbine Testing Laboratory (TTL) at Kathmandu University (KU). The best efficiency of 54.3% occurred at a rotational speed of 1557 rpm with a head and flow rate of 3.8 m and 50.3 L/s respectively. The testing did not investigate the efficiency of the generator therefore the exact efficiency of separate components was not known. In [34], a motor of equal size to the one tested had an efficiency of 76% when operating as a generator at full load, hence the hydraulic efficiency of the turbine can be assumed to be approximately 71%. The performance of the ELC was tested to ensure that the output voltage and frequency could be maintained at acceptable levels whilst the main load was changed. The ELC ensures that there is sufficient ballast load to maintain a constant rotational speed of the runner. The test began with no main load whilst the ELC ensured that there was sufficient ballast load. As the main load increased, less load was diverted to the ballast load. The ELC ensured that the voltage and frequency were maintained close to their design points of 230 V and 50 Hz respectively. The fluctuation in the values of voltage remained inside the ± 10% suggested by Nepal’s national guidelines on power output from small-scale hydropower projects [36].

Testing and monitoring were used throughout the development process. Initially, laboratory-based tests were important in understanding performance but also in exploring failure modes affecting the suitability of local solutions. During field-based monitoring, lessons from the field could be used to understand sub-systems that needed greater consideration in the laboratory or specific redesigns. Alongside technical findings, the monitoring programme indicated appropriate methods for familiarising communities with the technology. Subsequently, prolonged use by the community demonstrated strengths and weaknesses in the product. The performance testing was important in evaluating the efficiency, with the results allowing the turbine to be quantitatively compared with others and promoted.

Discussion

The development process of the low head propeller turbine led to a solution which satisfies the two criteria described above. In this case study, there were three key stages that enabled these criteria to be satisfied. Firstly, understanding the local environment in establishing the design requirements was key to developing a robust system. The operating environment in Nepal is different to New Zealand (where the design originated), with the market, operating conditions, and a lack of skilled labour identified as some of the key differences. The specific requirements for Nepal influenced the solution choice, design changes and methods for its implementation. Secondly, technical capabilities in Nepal affected how the product's sub-systems could be manufactured. Design changes were required in response to material and process availability for the casing and trash rack. Finally, the laboratory and field testing of the product was able to provide strong and robust feedback that resulted in a more reliable and suitable system. The product was delivered as a complete system with tested interfaces between sub-systems.

Based on the experiences of the case study, it is proposed that the DFL methodology is applied in three stages:

1. Understand local context for solution, deriving product requirements/specification

A requirement capture process needs to be undertaken, based upon the requirements of the solution and the technical, social, economic, political and natural environment that it will be implemented in. This derivation of local requirements can be used to inform a revised product specification for the adaption of the existing solution.

2. Develop design solutions for local manufacturing

The capabilities of the local manufacturing industry must be understood. A full assessment of the material, processes and skills available, including maximum size of work for the machinery, achievable tolerances and number of facilities and operators. Using this information, the design can be reviewed, any design changes identified, and a manufacturing plan can be developed.

3. Conduct local research and field-testing phases to ensure the product is suitable for the application

Once the product has been designed and manufactured, a comprehensive laboratory- and field- testing programme should take place. This will ensure the localisation modifications to the design work together as a whole, and the product system is able to operate as required to solve the initial problem whilst meeting the local requirements. This is a critical component of the process; without this, any bugs from the localisation process may cause the product to underperform, become unreliable or be unsuitable for local integration.

Alongside these three stages, the case study suggested three further principles are relevant throughout the process. Firstly, the DFL process may be non-linear. Lessons learnt during field testing phases improved understanding of the local context and led to further design changes. Secondly, the process of localisation should take place in the country of use. Nepali communities, engineers and implementors working in the field provided relevant input to the design based on an understanding of the rural context, the availability of materials and processes for manufacture. The short feedback loop between these stakeholders allowed changes to be implemented quickly. Thirdly, fulfilling the local requirements may require a range of supporting activities alongside the technology. Education and training were important in ensuring that communities were equipped to operate systems sustainably.

3.2.2 Supporting examples

In academic literature, the use of case studies as a research methodology has been advocated as a means for generating theory [139]. This process is aided by using a variety of data forms such as literature, observation, experiences, and the insight of the researcher [139]. Subsequently, validation of a theory can be reinforced by the identification of similar patterns within other case studies [139]. The propeller turbine case study – which was rich in multiple sources of information and relied on experiences that spanned 20 years – motivated the proposal of the DFL methodology. However, validation and progression of the theory is dependent upon corroboration elsewhere.

Within small-scale hydropower, there are a number of turbine designs that have been adapted for use in local workshops. In comparison to the PT case study, the researcher is unable to draw directly on personal experiences when analysing these case studies. However, there are examples that are well documented in academic and grey literature. Furthermore, as they are recent, personal communication can be used to provide further insight. Consequently, whilst the breadth of available information is narrower than for the PT case study, there is sufficient information to cross examine several case studies in relation to the DFL methodology. To determine the validity of a theory requires “identification of similar patterns” [139]. Therefore, the objective of the analysis was to determine whether (within these case studies) there was evidence of the three stages and supporting principles that were proposed. Table 3.3 presents three case studies of local micro-hydropower development, their key characteristics and evidence for the three stages of the DFL methodology.

Table 3.3 - Case studies of local micro-hydropower development.

Name of turbine/series	**Peltric set**	**Remote Hydrolight (RHL)**	**Entec/SKAT T-series**
Developer/s	Akal Man Nakarmi from Kathmandu Metal Industries (KMI).	Owen Schumacher and Anders Austegard from International Assistance Mission.	Entec, SKAT, Balaju Yantra Shala.
When did it happen?	c. 1980	1998 - 2008	c. 1970 - 2005
Type of turbine	Pelton	Crossflow	Crossflow
Power range	0 – 5 kW	0 – 120 kW	10 – 500 kW
Models	N/A	Traditional Mill Turbine, Hindu Kush Turbine, Pamir Turbine	T-1 to T-15
Description	An induction motor as a generator directly driven by a Pelton turbine.	A family of Crossflow turbines intended to span the range of 5 to 120 kW. Larger turbine sizes were designed to be increasingly robust.	A series of Crossflow turbines developed collaboratively between local industry, foreign industrial consultants, and international development consultants.
Country of origin	Nepal.	Afghanistan.	Nepal, Thailand, Argentina, and Indonesia.
Estimated installations	At least 1000.	In Afghanistan, over 1300. It is suspected that the design has been replicated elsewhere.	Unknown.
Evidence of *understand local context for solution, deriving product requirements/specification*	• Cheap enough to be affordable for rural Nepali communities. • Could be carried by a person alone. • Integration of turbine, generator, and controller for simplicity.	• Must be transportable by person or by animal. • Identified that workshops will need to be taught how to fabricate the turbine.	• Initially intended to be used only for agricultural processing. • Production of electricity added subsequently based on local demand. • Multiple progressions of the design with a different focus. • Education was identified as an important and necessary element of the approach.

Name of turbine/series	**Peltric set**	**Remote Hydrolight (RHL)**	**Entec/SKAT T-series**
Evidence of *develop design solutions for local manufacturing*	• Similar approach in manufacturing as with larger scale Pelton turbines. • Use casting to produce individual buckets. • PVC rather than penstock pipe to reduce production costs.	• Design is intended to be manufactured by an automotive workshop. • Can be manufactured on a Pakistani 8ft lathe that is typical in Afghanistan. • Dimensions driven by availability of materials in the local market. • Significant effort to standardise, including through use of available bought out components.	• Key aim was that no casting was required, only machining and welding. • Production of drawings that can be easily adapted to a range of sizes by local workshops.
Evidence of *conduct local research and field-testing phases to ensure the product is suitable for the application*	• Developed at a Nepali micro-hydropower manufacturer (KMI). • Field testing conducted in Nepal.	• Designs have been refined over a number of years in operation. • Tested in Norway in an experimental lab. • Multiple workshops were taught how to manufacture the turbines.	• Long term partnership with a local Nepali workshop. • Iterative nature of the series demonstrated a willingness to revise and improve. • Long term presence of foreign experts. • Multiple phases of experimental testing.
Sources	[77, 96, 140]	[80, 141, 142]	[32, 143]

Table 3.3 shows that in these case studies, there is evidence for each of the stages within the DFL methodology. An understanding of the local context was demonstrated in all of the case studies. Akal Man Nakarmi, former managing director of KMI, identified an opportunity to develop a turbine 'set' that would be easier for users to install and operate themselves [77]. For the Remote Hydrolight and T-series cases, the presence of foreign experts was significant. However, they worked in country and on the ground over extended periods of time. The design solutions all showed some adaption to the availability of manufacturing processes. Nakarmi's own experiences with larger scale Pelton turbines meant he was aware of what was achievable within the KMI workshop. In Afghanistan, Remote Hydrolight identified that there were existing automotive workshops with the ability to produce hydro-turbines [142, 144] . The initial development of the T-series in Nepal took place alongside the creation of engineering workshops in Nepal by foreign aid organisations [64]. Design solutions were developed on the ground within these workshops. There is evidence that in all of the case studies, the designs developed and improved as a result of installations in the field. For the T-series in particular, each new design iteration was renamed, leading to 15 versions. Changes were made due to both engineering requirements (e.g. reduction in vibration) and social requirements (e.g. a strong local demand for electricity) [64]. In Afghanistan, the Remote Hydrolight design was manufactured at multiple workshops. The collective experiences of the workshops lead to a best design which has been tested experimentally. For the Peltric set, there is some evidence of specific design progression; the 'Pico Power Pack' was a further development of the Peltric set but with the generator oriented horizontally rather than vertically [145]. The uptake of the Peltric set amongst manufacturers in Nepal is a useful indication that it was considered suitable for the local environment.

Within the PT case study, 3 further principles were identified as important: non-linear design progression, development in the country of use, and the need for supporting activities alongside the installation of technology. In all the examples in Table 3.3, the development took place in the country of use where a local understanding of manufacturing capability and product requirements were consistently important. There is specific evidence of non-linear progression in the RHL and T-series where a number of design changes were made based on experiences in the field. For the Peltric set, such changes were not described in the literature. In addition, specific activities to support the installation were not mentioned. Conversely, for the RHL, extensive community education is described and for the T-series, education in the field was maintained as a key feature of the implementation approach.

For these case studies, the local adaption of the design followed similar stages of development to the propeller turbine case study. Furthermore, there was evidence that the suggested principles were also relevant. The findings are supportive to the proposed DFL methodology; suggesting that following the 3 stages and the supporting principles are appropriate measures to adopt when adapting an existing technology to a new local environment.

3.3 Research methodology

Currently, a DFL methodology has been proposed (based on the PT case study) and used as a framework to consider the development histories of several different turbines. In this thesis, the methodology is applied. The literature review established an opportunity to expand the range of turbines available in Nepal, with the Turgo turbine a relevant and viable choice. Consequently, this work will follow the stages and principles of the Design for Localisation methodology (outlined in Section 3.2.1) and use it to develop a locally appropriate Turgo turbine runner design.

In this thesis, the research methodology is guided by the stages of the Design for Localisation process. Individual research activities address research objectives whilst also contributing to the progression of the DFL process. Figure 3.1 is a diagrammatic representation of the research methodology. The summarised version of the research aim is shown in a box on the right of the diagram. Individual research activities are shown in the blue circles, with the relevant chapter for each of the activities indicated.

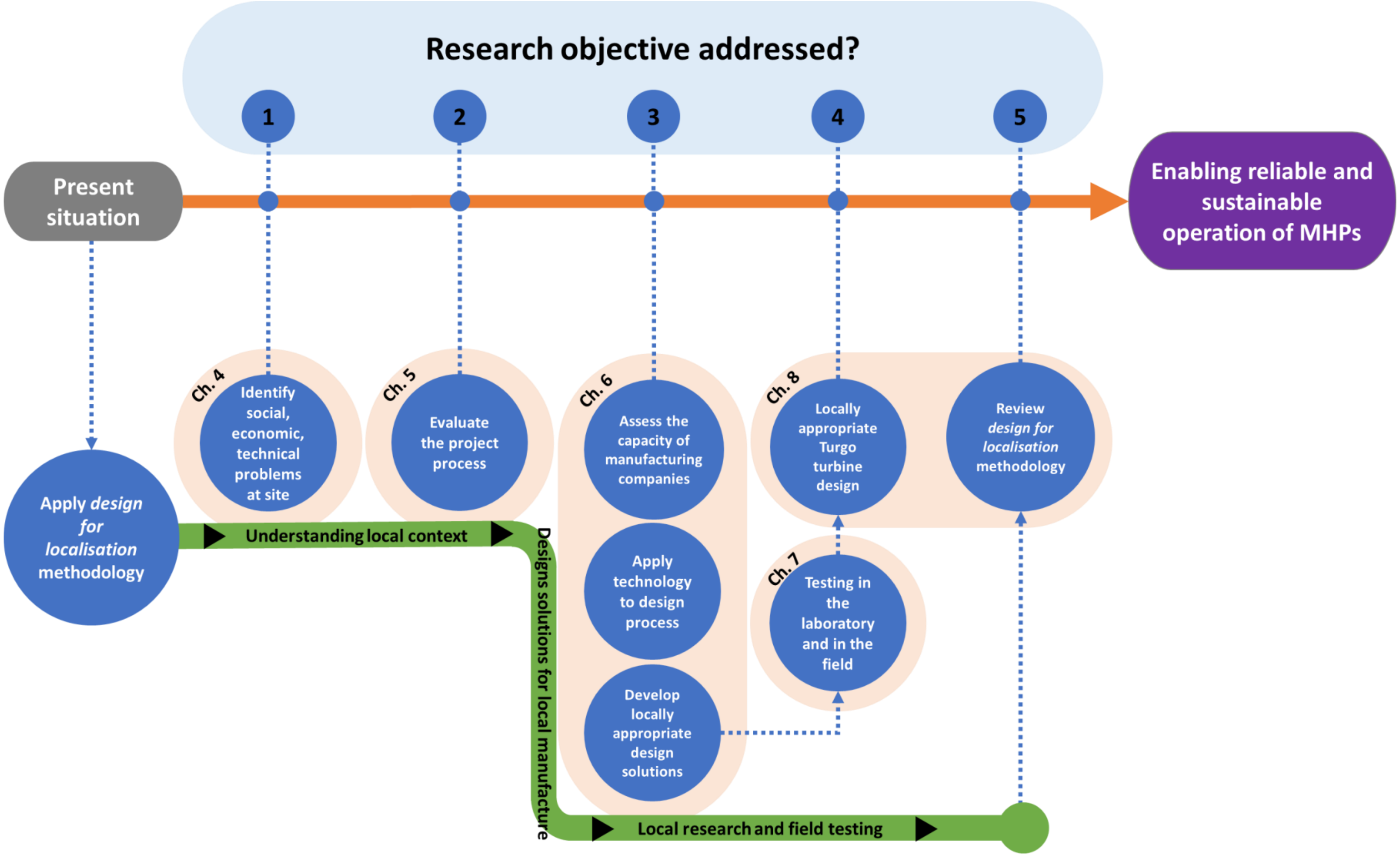


Figure 3.1 - A diagram to represent the research methodology.

From the starting point (present situation), the Design for Localisation methodology (represented by the green line) provides the framework for the research methodology. The research activities are derived from this; however, each activity is also pertinent to a particular research objective. In addressing research objectives one to four, the findings can be directly applied to the research aim. The fifth research objective concerns the application of the Design for Localisation methodology. As an unproven methodology, there is value in assessing its relevance, efficacy, and potential for future use. Whilst not limited to the hydropower field, future applications of the Design for Localisation methodology with other turbine designs could also be supportive to the research aim.

3.3.1 Research methods

Throughout the research, a mixed-methods approach was used to develop a more complete understanding of the key problems [146]. The complex and interdisciplinary nature of the research meant using both ‘numbers’ and ‘words’ was found to be effective in analysis [147]. During the research, the selection of methods frequently progressed non-linearly; the interrelation between research objectives resulted in new findings influencing the chosen research methods.

Literature review

A review of the available literature was used to summarise the basis of knowledge in relation to the micro-hydropower industry in Nepal and its development, the operational status of micro-hydropower plants in Nepal, and design approaches for local manufacture. The conclusions drawn from these diverse sources of literature were used to identify gaps and opportunities to address [148].

Case study

A case study approach was used in the consideration of the propeller turbine development. The case study included personal experiences of the researcher and collaborators, and a range of qualitative and quantitative data. Analysis of a case study can be used to develop a theory [139], in this case the DFL methodology. To establish the validity of the theory, additional cases were also analysed [149].

Field study

Early in the research, field visits were used to improve understanding of the local context where MHPs are installed. During visits, other specific research methods were used. Whilst these methods were both qualitative and quantitative, several characteristics of the field study approach were typical of a qualitative research design [150, 151]:

- Collecting data in a natural setting – Data was collected at the MHPs where technology could be observed in person and interactions could take place face-to-face.
- The researcher collecting the data in person – Most of the collection of data was carried out by the researcher themselves, rather than relying on others.
- Using multiple sources of data – The data collected included interviews, observations, and a numerical site assessment. Therefore, data analysis could rely on themes that were emergent from all of these sources.
- Aiming to develop a holistic account – The complex nature of the investigated problem required an appreciation of a broad range of influential factors.

Data collection was carried out by the researcher and a Nepali colleague (a rural development officer at PEEDA) experienced at working in rural areas. During the field studies, informal discussions with this colleague improved understanding of the local area and helped to contextualise the experience in relation to the author's personal knowledge of Nepal. When travelling to remote areas, local accommodation and public transport were predominantly used. These choices aided the cultural 'richness' of exposure for the researcher.

Site assessment

During the field studies, the site assessment used a combination of quantitative and qualitative assessment to consider the reliability of MHPs. The collection of qualitative data allowed the identification of common themes, whilst the quantitative data enabled comparison between the sites.

Interview

Interviews were used throughout the research to (initially) improve understanding, and subsequently focus on the collection of specific information. Depending on the purpose, the style of interviews was either semi-structured or structured. The 'semi-structured' questions were useful in understanding thoughts, values, and opinions [146]. When the desired data was quantitative, structured interviews with specific closed questions were used allowing the aggregation of interviewees' responses [152].

Document analysis

Document analysis was conducted on government documentation and specific project reports from Nepal. The documentation was used alongside other qualitative information as a means of ‘triangulation’ [153] to understand the project process and its relation to project sustainability.

CFD based simulation

To quickly explore design changes that could drive an improvement in efficiency, computational fluid dynamics was used as a tool. CFD simulations have been shown to provide a reliable agreement with experimental testing results [154].

Experimental testing

Experimental hydraulic testing was used to evaluate the performance of the Turgo turbine design. The key quantitative data generated was the turbine efficiency allowing comparison with other turbines.

Field testing

For this research, testing at a pilot site was used to evaluate the performance of the turbine in conditions that resemble its expected use case. As the local environmental, social and cultural complexities cannot be recreated in a laboratory [155], field testing is significant in the product development process [119].

3.3.2 Collaboration with partners

Collaboration with local (Nepali) and international partners was integral to the research methodology. The researcher was aware of the limitations of their own knowledge in relation to the culture and context of Nepal. Collaboration provided multiple opportunities to improve the quality of research. As a foreign researcher working in a different context, local partners were able to facilitate research activities, help establish connections, and provide their own personal and professional reflections on the research direction. Alongside local partners, the use of computational fluid dynamics was not a skillset the researcher possessed nor one that can be learned and applied quickly. Consequently, a collaboration was established that enabled the use of CFD, without consuming a significant amount of time. In addition to the work of the supervisors, the key partners and their role in the research are described below:

People, Energy and Environment Development Association

The People, Energy and Environment Development Association (PEEDA) is a non-governmental organisation (NGO) that was founded in Nepal in 1997 [156]. Their goal is to “mobilize both local and external resources to harness Nepal’s indigenous resources, thereby promoting activities for economic development and poverty alleviation” [156]. The researcher has been working with PEEDA on a variety of projects since 2014. In this research, responsibilities fulfilled by PEEDA included:

- Co-ordination of site visits.
- Translation of interview material and conduction of interviews.
- Management of partners involved in experimental testing.
- Identification of a field-testing site and community mobilisation.

Nepal Yantra Shala Energy

Nepal Yantra Shala Energy is a micro-hydropower manufacturing company based in Kathmandu which has been trading since 1976 [157]. Services provided include turbine design and manufacture, production of electrical control systems, and installation and commissioning. The company is one of the oldest micro-hydropower companies in Nepal and a member of the Nepal Micro-Hydro Development Association. In this research, responsibilities fulfilled by NYSE included:

- Collaborative design of the Turgo turbine.
- Manufacturing of the Turgo turbine.
- Manufacturing of testing rig components.
- Field-based installation and commissioning.

Turbine Testing Laboratory

The Turbine Testing Laboratory (TTL) at Kathmandu University is a hydropower testing facility established in 2011 [158]. It is equipped with two 250 kW centrifugal pumps capable of producing flow rates up to 0.25 m^3/s with a maximum head of 75 m [158]. In this research, responsibilities fulfilled by the TTL included:

- Co-design of testing rig.
- Procurement of testing equipment.
- Installation of the resting rig.
- Conducting experimental testing.

Shaun Benzon

Shaun Benzon is the Head of Tidal Project Development at Liverpool City Region Combined Authority. In August 2016, Shaun completed a thesis at Lancaster University titled “The Turgo impulse turbine; a CFD based approach to the design improvement with experimental validation” [154]. He is experienced in the fields of CFD simulation and turbine design. In this research, responsibilities fulfilled by Shaun included:

- Set-up and simulation of CFD models of the Turgo turbine.
- Collaborative discussions regarding results and design progression.
- Advisory role during experimental testing.

Jonathan Cox

Jonathan Cox is a consultant Mechanical Engineer. He worked at Nepal Hydro Electric between 1997 and 2005 as a secondee from the United Mission to Nepal. He has extensive experience in hydropower in Nepal and the UK. In this research, responsibilities fulfilled by Jonathan included:

- Provision of materials regarding the development of the propeller turbine series.
- Sharing experiences of the propeller turbine development, the requirements of locally manufactured equipment and the hydropower industry in Nepal.

Anh Tran

Anh Tran is the Humanitarian International Liaison Manager for the Modern Energy Cooking Services Programme at Loughborough University. In this research, responsibilities fulfilled by Anh included:

- Review of site assessment materials for the field study.
- Assisted in evaluation of results from the field.

3.3.3 Ethical considerations

Taking an ethical approach to research means avoiding or minimising “doing long-term or systemic harm … to individuals, communities and environments” [159]. This is particularly important when working in foreign contexts that are socially and culturally different to the researcher. Prior to undertaking this study, the researcher lived in Nepal for 9 months. This experience helped to develop an understanding of the local culture, and a basic knowledge of the Nepali language. Whilst this experience is not extensive, it provided a foundation of local understanding that was useful when planning research activities. To achieve the overall research aim, there were a number of general considerations.

Firstly, when conducting research activities, actions should be taken to minimise impact. For research activities involving human participants, this is particularly important. Ethical approval was sought from the University of Bristol and interviewees were informed that the interviews or surveys were conducted only for the purpose of research. With the permission of the interviewee, the interviews were recorded (so that they could be transcribed and checked after the interview), and photos were taken to document the process. All interviewees were informed that they could end an interview at any time. Whilst working in rural areas where foreign visitors are less common, it was important to be aware of local customs. For this, the researcher took guidance from PEEDA colleagues.

Secondly, as a field of research, micro-hydropower has received a reasonable amount of attention with journal articles published by Nepali and international authors. Alongside the body of academic literature, there have also been numerous reports and studies published by Nepali and international NGOs. These organisations, many that have been working in this field for a long time, have a wealth of on the ground knowledge. Consequently, the work of local practitioners (both historic and current) should be evaluated. Furthermore, efforts should be made to converse and collaborate with local practitioners to improve the quality of research and maximise impact.

Finally, high unemployment in Nepal means large numbers of engineers seek employment abroad. As a foreign researcher working in Nepal, it was important to be mindful of how to make the research useful in this context. It should not (deliberately or accidentally) reduce the availability of work for Nepali engineers, rather it should focus attention on a local industry that could provide greater employment opportunities.

3.4 Summary

Based on the findings of the literature review, this chapter proposed a design methodology that enables the transfer of a design to a new geographic location, considering its local manufacture and use. The methodology was devised based on the experiences of a case study, with additional supporting examples identified in the available literature. The principles of the design methodology provided a framework that informed the research methodology. The motivation behind this approach and its applicability in addressing the research objectives was explained. Finally, the specific methods, collaborations and ethical considerations in the research were described.

In summary:

- Design for Localisation was proposed as a design methodology focused on developing solutions appropriate for a local context in terms of use and manufacture.
- Three key stages of this methodology were proposed based on the experiences of a detailed case study and supported by evidence from literature.
- The design methodology was used to inform a research methodology to address all of the research objectives.

Chapter 4

Understanding sustainable operation of micro-hydropower plants: a field study

4.1 Introduction

The literature review indicated that research into micro-hydropower tended to focus on either the technical or the socio-economic elements separately. A range of literature has established that for community owned and operated renewable energy technologies, the inter-relation of these factors determines the sustainability or ‘success’ of a project. An approach was required that considered individual technical, social, and economic elements and their interconnection. To achieve this, a field study was devised with two main objectives:

- To understand the local context where hydropower technology resides.
- To understand the factors that determine the operational sustainability of MHPs.

The field study was conducted at 24 MHPs located in 2 districts in Nepal. The sites selected included those with Crossflow and Pelton turbines and a range in rated power, number of connected households, and remoteness of the electrified communities.

4.2 Methodology

To develop an appropriate methodology, the existing literature relating to site assessment of MHPs in Nepal was considered. Often there has been a focus on technical issues identified in the field [34, 35, 37]. Several studies have indicated that the quality of turbines can be low; poorly fabricated and installed pulleys have led to premature wear in belts and bearings [34, 35]. The construction of civil structures is often described as problematic due to overly long and poorly designed canals [37, 40]. A lack of supervision from installation companies during the civil works, particularly for the de-silting bay, can result in increased turbine erosion [35]. These studies have demonstrated technical issues that occur at MHPs, but rarely have they considered the interaction of the operational team, the community, and the technology once a project goes into operation. An exception is Barr’s [41] study of 6 sites which documented technical problems that occurred once plants were operational and showed that operators’ approaches to maintenance were affected by the economic opportunities in the local area. More recent research has focused on the sustainability or ‘success’ of MHPs. Bhandari et al. [93] developed a detailed sustainability assessment model which used interviews with households, management, an operator and micro-hydro experts to develop a list of 54 indicators. These indicators are carefully selected and allow specific dimensions of sustainability to be compared. In a similar study that considered MHPs in Nepal alongside those in Bolivia, Cambodia and the Philippines, a framework for assessing the ‘success’ of projects was developed [160]. The methodology used qualitative data from interviews with a range of stakeholders to provide numerical scores to several criteria. In both studies, the quantitative information allowed for comparison between criteria and projects, however, greater insight regarding specific issues could be derived from interviews. The literature focused on Nepal has demonstrated that there is evidence of technical problems, with a relationship to the local context and the economic performance of MHPs. However, aside from Barr’s study on maintenance practices, there is little evidence regarding the role of the community and operational team once a plant is functional. Furthermore, the relationship between these roles and a plant’s operational sustainability has not been evaluated in detail. Consequently, the wider literature regarding assessment of mini-grid projects was considered to learn alternative approaches that have been used to understand the relationship between socio-economic and technical factors, in relation to project sustainability.

4.2.1 Approaches to assessment of mini-grid projects

In the available literature, methods for assessment of mini-grid projects vary considerably. As mentioned above, ‘success’ and ‘sustainability’ are often the stated measurands, however, these terms are often uniquely defined within each study. Consequently, the purpose and approach of assessments also vary. By analysing a range of existing approaches to assessment, factors considered important that are common throughout the literature could be identified, and methods for their assessment devised. As these factors could be non-technical, it was considered important to analyse literature covering a range of renewable energy technologies.

Terrapon-Pfaff et al. [112] argue that there have been few studies that have specifically addressed the impact and post-installation sustainability of community-based projects. These authors use a combination of surveys and supporting empirical data to assess the sustainability of 23 projects located in 17 countries [23]. The results demonstrated that the technical sustainability of projects did not depend on the reliability of the implemented technology alone. It also depended on how the technology was embedded into the socio-cultural, political, and ecological context. Across all 23 projects, knowledge, maintenance capability, user satisfaction and community ownership were identified as key factors in enabling sustainability. Schnitzer et al. [26] considered best practices in the development of 17 mini-grid projects across several countries. They identified that to be sustainable, a threshold of reliability and financial viability should be maintained over a project's lifetime. They found that the connection of technical, economic and social factors in the operation of mini-grids would tend to drive projects into either "vicious" or "virtuous" cycles. An example of a "virtuous" cycle was when effective tariff collection led to a high standard of O&M, resulting in a reliable energy service. Conversely, a "vicious" cycle could develop when poor tariff collection led to insufficient funds for maintenance, which in turn resulted in a poor quality of service.

In a comparative study of 3 wind projects in Peru, Ferrer-Marti et al. [25] were able to contrast the successes and failures that occurred with different technologies and management methods. Similar to the cycles identified by Schnitzer et al., it was observed that shortages of energy affected the satisfaction of beneficiaries and consequently their engagement with the project. Hong and Abe [24] focussed on the social challenges and impacts of implementing an off-grid solar plant in the Philippines. They used interviews with a range of stakeholders and a survey of members of the project's co-operative. They found that despite providing reliable power at a reasonable cost, the obligation of a monthly payment was too much for some consumers. As a consequence, the tariff was reduced, broken parts could not be replaced, and the quality of service suffered. They identified capacity development and promoting productive end uses of electricity as key factors in improving the sustainability of the project.

The previous research on assessment of mini-grid projects has established that sustainability or project 'success' depends on multiple drivers. Project assessments used a mixture of qualitative and quantitative approaches. Typically, quantitative results were useful in making comparisons whilst qualitative approaches were able to provide greater insight into specific challenges. Despite variations in approach and the assessment criteria, broadly, the existing research indicates that to be sustainable (or successful), a project must operate reliably, providing the community with household and commercial benefits that ensure their financial and social engagement. In this thesis, as outlined in Section 1.2, the sustainability of a micro-hydropower plant is defined as the ability of the technology and its stakeholders to deliver electricity services that meet the expectations of consumers over a system's expected lifespan. To understand this, the site study methodology needed to evaluate: the specific threats to reliability, the capability and typical behaviour of the operators and management team, the types of load and the income they generate, and the factors that lead to successful engagement of the community. Combining this information enables an understanding of the three key areas (that have been identified as influential) in the sustainable operation of plants: technical reliability, financial viability, and community engagement.

4.2.2 Data collection

Through the review of literature related to project assessments, it was shown that qualitative and quantitative data is useful for contextual insight and comparison respectively. Due to the importance of the community in operating the plant, it was important that data collected included the actions and perspectives of key stakeholders. This was deemed essential in understanding the local context and the role that stakeholders have in determining the sustainability of MHPs. To collect the opinions of stakeholders, interviews were considered the most effective method [146]. Alongside the interview, a technical assessment was used to evaluate the quality of the installed sub-systems and attempt to quantify the reliability of the plant. Table 4.1 provides an overview of the methods used for data collection that resulted in a combination of qualitative and quantitative data. The mixed-methods approach was important in evaluating the interdisciplinary nature of plant sustainability [147].

Table 4.1 - Methods for data collection.

		Qualitative	**Quantitative**
Technical assessment		A visual evaluation was used to record a description of the quality of installed or constructed sub-systems.	Numerical assessment of the quality of maintenance based on pre-defined criteria.
Interviews	*Operator*	Open questions regarding their role, actions, and perspectives.	Closed questions focused on the frequency of maintenance activities.
	Manager	Open questions regarding their role, actions, and perspectives.	Closed questions regarding specific numerical quantities relevant to the MHP.
	Consumer	Open questions regarding their role, actions, and perspective.	Closed questions regarding their use of electricity.

Site selection

Due to its terrain and infrastructure, travelling to remote areas of Nepal is expensive and time consuming. As there are MHPs located in at least 45 of Nepal's 75 districts [161], a study representative of the whole country would need to visit sites in a large number of districts. Unfortunately, the budget for the study dictated a choice between visiting a small number of sites (< 5) in several different districts or a larger number (> 20) in a single district or neighbouring districts. It was decided that visiting a larger number of sites would be advantageous for several reasons. There was likely to be less variation in the socio-economic landscape than across multiple districts making it possible to develop a greater understanding of the local context. Proximity to turbine manufacturers – who are located mostly in Butwal and Kathmandu - and suppliers of parts was deemed an important factor in a plant's reliability. Within a smaller geographical area, the difference in travel times from these cities to each site was in the order of hours rather than days. Figure 4.1 is a map of Nepal with major cities marked, Kathmandu and Butwal (underlined in red) are both shown.

Figure 4.1 - Map of Nepal showing major cities. Image adapted from [162].

To visit at least 20 sites within a small geographical area, the neighbouring districts of Baglung and Gulmi, located in Gandaki Pradesh and Province No. 5 respectively, were identified as a region with a high density of MHPs. In Figure 4.1, the city of Baglung (the capital of Baglung district) is underlined in red. Most of Baglung district is west of the city, with Gulmi district to the south west. A list of 30 potential plants was considered, where the contact details were known, and the sites could be reached within a single day from the main road, the Mid Hill Highway. The approximate area where these sites were located is indicated on Figure 4.1 by the blue dashed oval. From these 30 sites, a total of 24 sites were visited. Table 4.2 outlines the ranges in the site characteristics. There was variation in the size, ages, and types of turbine, distance from a main road, and the number of households connected to the MHP.

Table 4.2 - Characteristics of the 24 visited sites.

Characteristic	Range
Number of connected households	94 to 1765
Rated power (kW)	18 to 135
Types of turbine	18 Crossflow, 6 Pelton
Time to powerhouse from main road (hours)[1]	0 to 6
Year since commissioning	1 to 18

[1] Journeys were made by vehicle, on foot or a combination.

The majority of the sites (22 of the 24) were located in Baglung district where historically many MHPs have been constructed. In 2009, Baglung was the only district in Nepal where more than 1 MW of mini- & micro-hydropower had been installed [163]. The topology of the visited districts is more favourable to Crossflow than Pelton turbines which accounted for the larger proportion of turbines of this type. Generally, Crossflow turbines are used at sites with lower heads and higher flow rates, whilst Pelton turbines are used for sites with higher heads and lower flow rates [17]. Their distinct designs can result in different issues relating to reliability and performance.

Interviews

Individual questionnaires were written for interviews with the plant operator, plant manager, and a consumer at each site. The questionnaires were developed based on the findings of Section 4.2.1 and the experience of the researcher, supervisors and Dr Anh Tran (see Section 3.3.2). They were reviewed by PEEDA staff, adapted to improve their applicability to the local context, and translated into Nepali. Figure 4.2 shows a PEEDA employee interviewing a plant operator. Interviewees were made aware that it was an independent study for research, and it would have no financial impact on the individual nor the plant. Due to the focussed sample size, the responses gathered from consumers were used to understand their perspectives rather than draw specific conclusions about the individual projects. A total of 50 interviews were conducted in Nepali and subsequently translated into English. To comply with the University of Bristol's ethical standards (as outlined in Section 3.3.3), participants were read a participant information sheet, and asked for permission to record the interview and take photos.

Figure 4.2 - PEEDA employee interviewing a plant operator during an interview. The photograph was taken by the author, with permission given by both of the subjects.

The semi-structured interview with the plant operator documented their responsibilities, actions, and opinions. To gain alternative perspectives on the plant's reliability and an understanding of the financial viability and community engagement, semi-structured interviews were conducted with a plant manager and a consumer at each site. With the manager, the interview also explored the current economic status of the hydropower plant, its organisational structure and the actions performed by the management team. Interviews with consumers used predominantly open questions to understand their opinion of the hydropower plant and their personal electricity use. The interview questions are provided in Appendix A.

Technical assessment

To support the data collected from interviews with the plant operator, a technical assessment was devised. The method of assessment was intended to give an indication of the reliability in a limited time and whilst many of the turbines were still in operation. Typically, numerical information regarding a system's performance over time is used to consider reliability; data such as the average time between failures allow a probability to be calculated. For power supply systems of all sizes, reliability can be considered in two parts: the amount of energy delivered over a certain period of time, and the system's ability to respond to disturbances [46, 164, 165]. Usually, numerical data is used to quantify these two parts; for example, using the amount of power delivered, and the operational time lost due to failures [164]. In this case, it was not possible to access such data due to a lack of recorded information. Consequently, within this study, reliability is defined as the ability of the system to consistently deliver the expected electricity service whilst avoiding failures. To operate reliably, each of the sub-systems of the MHP should be maintained to avoid failure and function as designed, allowing the required power output to be delivered. To assess reliability, a two-part evaluation was conducted at the following 10 sub-systems: intake, de-silting bay, canal, forebay tank, penstock, powerhouse, internal pipework, turbine, control panel, and generator.

At each sub-system, the evaluation consisted of a qualitative inspection and a quantitative assessment of the quality of maintenance. The purpose of the qualitative inspection was to visually identify threats that could reduce power output or lead to failure. The observations were recorded on site and documented using photography. The purpose of the quantitative assessment was to rate the quality of maintenance at each sub-system. A marking scheme was used that had been developed based on available literature [41, 81, 166]. Table 1 shows an example of the marking scheme used to assess the de-silting bay. In the marking process, scores were assigned as discrete values (e.g., 1, 2, 3, 4 or 5). The site assessment procedure and complete marking scheme for all sub-systems is shown in Appendix B.

Table 4.3 - Marking scheme for the de-silting bay.

	Description	Score
De-silting bay	**Very well maintained. Good evidence of regular preventative maintenance.** De-silting bay is clean, free from erosion with no obvious cracks visible. Minimal silt build up.	5
	Evidence of effort to maintain the sub-system but without following a schedule closely. Some dirt, debris and a small amount of erosion is visible. Cracks may be present, but they are small. Any obvious leaking is minor. Some silt is obvious in the bottom of the bay.	3
	Poorly maintained. Preventative maintenance is rare. Intake is heavily contaminated with obvious signs of erosion. Cracks are significant and/or leakage is obvious. Significant build-up of silt in the bottom of the bay.	1

4.2.3 Limitations

With many of the turbines in operation, the mixed-methods assessment was deemed an appropriate methodology to provide an indication of reliability. The nature of the assessment meant that it was only possible to assess the maintenance and identify threats at the time of inspection. Whilst this approach could not provide a value for the overall reliability, it allowed comparison between the sub-systems and plants. The location of the sites visited should be considered when analysing the results. In relation to reliability, all the sites in the study could be reached in less than a day from Butwal, where many turbine manufacturers are based. This means spare parts can be delivered and maintenance carried out a lot more quickly than in remote districts in the far East and West of Nepal. These factors suggest that the technical reliability of the sites is likely to be better than those located in more remote areas; the findings should be considered in this context. From a socio-economic perspective, both districts are below the national average in terms of per capita income and human development index [167].

There were several limitations to the interview methodology. Typically for each site, there was a single point of contact, usually an operator or member of the managing committee. These individuals usually suggested who the other interviewees should be. Their selection was likely to be biased, particularly in the case of the consumer. To mitigate this, effort was made to conduct the interviews in isolation though due to cultural conventions, this was not always possible. Through a participant information sheet, interviewees were told the purpose of the study. For many of the responses of interviewees, it was not possible to verify the claims made. It is possible that, particularly amongst the managerial staff, there may have been a desire to exaggerate the degree to which the plant was performing well.

In assessment of sustainability, it is common to consider the impact on the natural environment. Due to the skillset of the study team, a comprehensive method for this was not possible. Instead, the assessment of individual sub-systems included consideration of environmental risks, e.g., landslide or flood damage. As such, environmental risks were considered as a constituent part of the technical reliability. The assessment and interviews were usually conducted on a single day, occasionally over the course of two. The literature on site assessments had indicated the transient nature of plant sustainability. Consequently, assessment on a single day does not successfully capture these changes. Interviews with the stakeholders provided some information about past events but this did not necessarily lead to a detailed understanding of an MHP’s local history.

4.3 Results

4.3.1 Reliability

From the numerical assessment of maintenance, a notable outcome was the difference in the quality of maintenance delivered by trained and untrained operators. Most operators receive 22 days of technical training from the NMHDA or an accredited training company [94]. The training includes sessions that teach operators preventative maintenance tasks and the function of all of the sub-systems assessed during the study [168]. Following the training, the expectation is that operators will be able to operate the plant, carry out preventative maintenance tasks, identify basic faults and replace a number of components, e.g. bearings, fuses and transmission belts [41]. When a significant problem occurs, representatives of a manufacturing company will visit the MHP to carry out repairs. At all the sites visited, operators were paid for their work with their monthly salaries ranging between NPR 4,500 ($44, at the time of the study) and NPR 15,000 ($147). However, at 9 sites operators had left their job, typically moving abroad for employment. The operators who replaced them had not received any formal training. Figure 4.3 shows the mean scores of sub-system assessments by site for trained and untrained operators. The vertical dashed line is the mean ($\bar{x} = 3.16$) of all the sites suggesting (as per the marking scheme) that on average there was evidence of maintenance effort but without following a schedule closely. There were 9 sites with mean scores below 3, and 7 of these had untrained operators.

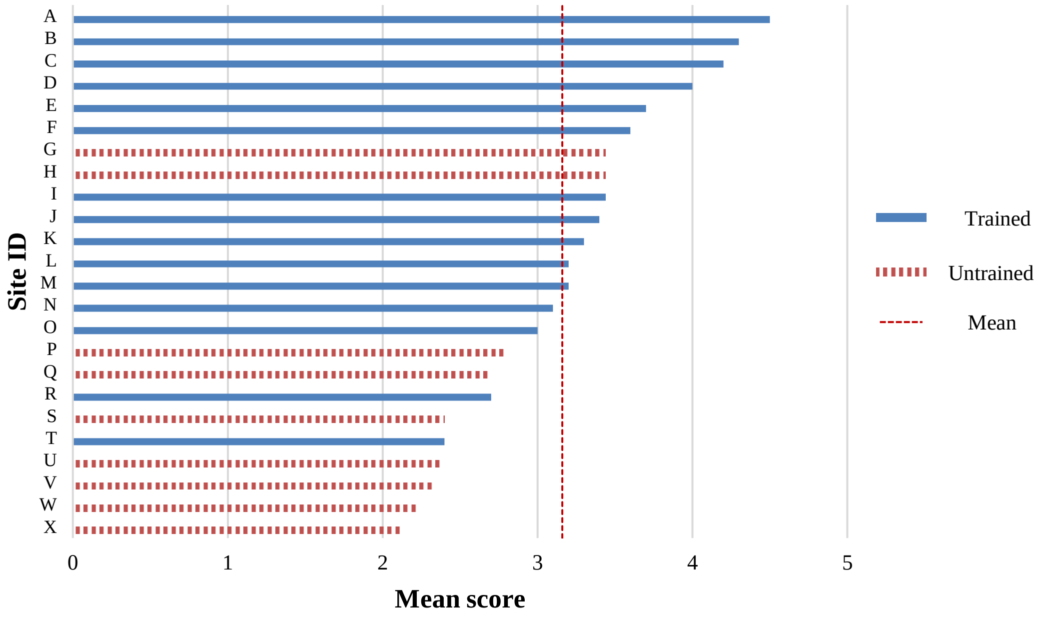


Figure 4.3 - Average maintenance scores by site.

An independent samples t-test was used to look for significant differences between the mean scores of trained and untrained operators. Table 4.4 shows the results that have been accepted as significantly different at the 1% and 5% confidence interval levels. It found that there were statistically significant differences in the overall mean and for the control panel, internal pipework, and turbine sub-systems. In the table, *M* and *SD* represent the sample mean and standard deviation respectively. Meanwhile, *t* (t-value) represents the size of the difference relative to the sample data which is used to give a corresponding *p* (p-value) which is the significance of the result. The significance of the results suggests that overall and for the 3 particular sub-systems, there is a very high probability that the same trend of worse maintenance by untrained operators would apply for the whole population. However, several factors are important in analysing these results. Firstly, the assessment was a one-off. Maintenance scores were given based on an instant assessment without knowledge of an operator's typical routine. Secondly, the assessment was made without stopping the turbine. It was not possible to evaluate some performance critical components, particularly the turbine runner. Thirdly, some of the sites visited were easier to maintain than others. For example, it is much less time consuming to maintain a short canal than a long canal. Finally, even amongst operators who had attended training, each training course was different and their attainment within the course unknown. These factors should be considered when analysing the statistical results. On a simplistic level, there is evidence that trained operators delivered a higher standard of maintenance. However, the factors noted above should be considered when discussing the results in relation to the whole population.

Table 4.4 – Significant t-test results for trained and untrained operators.

Type	Trained		Untrained		t	p	Significance level
	M	*SD*	*M*	*SD*			
Overall	3.47	0.59	2.62	0.49	3.49	0.002	1%
Control panel and other electrical	3.93	0.80	2.72	1.03	3.22	0.004	1%
Internal pipework	3.80	1.15	2.44	0.88	3.04	0.006	1%
Turbine	3.47	0.99	2.44	1.13	2.32	0.030	5%

N (sample size) =24

For the 3 sub-systems listed in Table 4.4, there were common problems observed which reduced the maintenance score attained by untrained operators. The electrical components were often poorly maintained; inside control panels, there were loose cable clamps and wires pulled from their conduit. For both turbines and the internal pipework, leakage (as shown in Figure 4.4), rust and loose bolts were common. For hydropower systems, leakage can reduce the overall turbine efficiency due to a loss in pressure and flow rate.

Figure 4.4 - Leakage from a turbine casing. Photo credit, author.

Amongst all the operators, the maintenance of civil structures was a weakness. The walls of canals were often cracked due to plant growth which resulted in leakage. The growth of moss reduced the safety of access as typically the walls of the canal are used to reach other civil structures. Alongside the maintenance issues, problems were identified with the original construction of some civil structures. A commonly observed problem was poorly shaped forebay tanks and de-silting bays. Typically, these sub-systems are located before the main canal section and further downstream before the penstock. Their critical function is to reduce the quantity of silt flowing through the system; small particles of material suspended in the flow of water can be abrasive to the turbine runner [81]. The shape of the tank slows the speed of the flow using a symmetrical divergent section (see Figure 4.5(a)), the particles settle on the floor of the tank allowing them to be flushed away. When these tanks are incorrectly shaped, they fail to decelerate the flow and are ineffective in settling silt. An example is shown in Figure 4.5(b), the divergent section of the tank is asymmetrical allowing the flow to continue quickly along one wall. The consequence of more silt passing through the turbine is faster abrasion of the runner. Figure 4.6 shows abrasion, scoring and dents on the blades of a Crossflow runner.


(a) (b)

Figure 4.5 – Examples of (a) effective and (b) ineffective forms of de-silting bay. Photo credit, author.

Figure 4.6 - Abrasion on a Crossflow turbine runner. Photo credit, author.

Mechanical issues were also identified that can manifest at a number of stages in the project process. Large vibrations in transmission belts were commonly observed. As a mechanical system, vibrations cause movement which alters alignment and changes the belt tension. During operation, the plant operator is responsible for correcting this issue, but it is possible that poor design and low quality in manufacture contributed to the problem initially. Plant operators were asked about the frequency with which they performed various tasks. For activities in the powerhouse, the practice of operators was mostly in line with expectation. Of the 24 operators, 19 said that they checked the noise and temperature of bearings daily. Usually bearings should be greased every 500 hours although smaller bearings will likely require less frequent greasing [54]. Depending on the daily time in operation, this suggests that greasing approximately every 2-4 weeks is a reasonable frequency. Of the operators, 14 gave a response that was within that time period, 8 said they did it more frequently and 2 less. At several sites, there was evidence of over-greasing as shown in Figure 4.7, suggesting bearings were greased too frequently or too much was applied each time. Over-greasing causes bearings to overheat as grease is churned away from rotating elements [81], it can also harden due to the heat and later prevent the ingress of new grease [169].

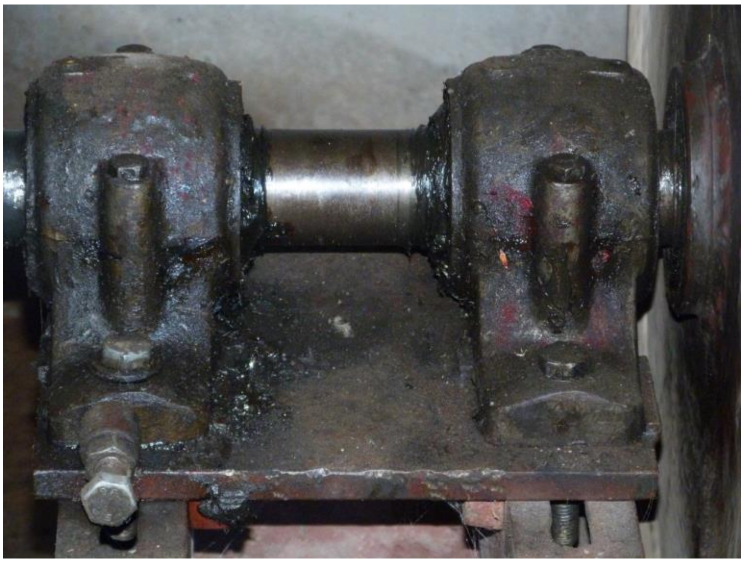


Figure 4.7 - Over-greasing of bearings in the transmission shaft. Photo credit, author.

Outside of the powerhouse, there was a lot more variation in what operators considered to be the correct frequency for various maintenance activities. Draining the de-silting bay and forebay tank is important to ensure that the build-up of collected silt does not pass through the turbine. In the monsoon season, heavy rains bring large amounts of silt and debris into micro-hydro systems. In this period, it is important to flush out the civil structures more frequently; half of the operators acknowledged the need to do this. A simple task that should be performed at least every other day is cleaning the trash rack [81]. Amongst the operators, 11 of the 24 did it with this frequency. The variation in responses between operators indicates a potential threat to plant sustainability. To maximise reliability of the system, there is a minimum frequency with which maintenance activities should be carried out. It is the responsibility of the plant operator to carry out these tasks; however, only 1 of the 24 sites had a maintenance schedule that the operator followed. Without a schedule, there is no means for the plant managers to check whether maintenance has been completed at the right time. Typically, this resulted in a maintenance approach that was more often corrective than preventative.

Operators were asked to list all the components that had broken in the previous year and the parts that were kept as spares in the powerhouse. Figure 4.8 shows the frequency of reported component failures and the frequency with which the same parts were kept as spares. Across all the sites, the stocked spare parts demonstrated there was an awareness of what was most needed. Turbine bearings were kept as spares at over 70% of sites ensuring many were ready to deal with the high proportion of bearing failures that were mentioned. Similarly, 25% of sites kept belts as spare parts whilst 29% mentioned a belt failure in the preceding year. In the figure, it can be seen that the ELC board was the second most frequently failing component. During the study, it was observed that the ELCs at all of the sites were based on electronic ‘breadboards’; these designs have been used since the 1980s [17]. Using modern power electronics manufacturing and devices, e.g., printed circuit boards, could improve the reliability of electrical components.

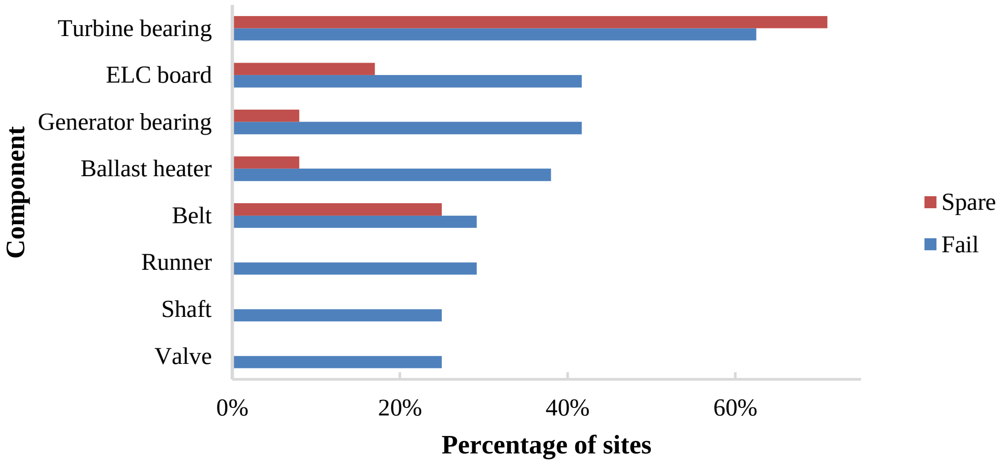


Figure 4.8 - Percentage of sites with component specific failures and spare parts kept.

The results of the study suggested that trained operators could deliver a higher quality of maintenance than untrained operators. Their superior expertise was most obvious inside the powerhouse where there was evidence of preventative maintenance. Across the sites, there was evidence of operators and managers responding to the common failures in bearings and belts by keeping spare parts ready for replacement. The qualitative inspection of sub-systems found threats to reliability that originated at the design, manufacture and installation stages.

4.3.2 Financial viability

During interviews, 3 forms of management structure were encountered: there were 2 private, 2 co-operatives and 20 community owned sites. Privately owned MHPs were run as a business with the proprietor(s) taking responsibility for management including tariff setting and financial bookkeeping. In both co-operatives and community owned sites, periodic meetings allow beneficiaries to have input into decisions made regarding the

MHPs and beneficiaries are often expected to provide labour when repairs are required. In the co-operative structure, consumers' initial labour and financial contribution give them a share in the MHP [170]. For community owned plants, the relationship is not formalised. In all cases, plant managers are responsible for collecting tariffs from consumers. The management structure was not found to have a significant impact on the financial viability of the sites.

In total, 23 of the 24 sites charged consumers based on electricity meters fitted in their homes. The one exception was a site where the electricity meters were not working, and a flat rate of NPR 200 ($2) per month was charged. At the other sites, tariffs were charged using a basic rate which permitted the use of a defined number of kilowatt-hours (kWh) with additional consumption beyond this limit charged on a per unit kWh basis. Figure 4.9 shows the variation in basic tariff costs for each site. The height of the individual blue boxes indicates the per unit charge whilst the number of boxes shows the permitted number of units that can be used. Beyond this, the additional charge is applied which is shown by a red box. Site T was the plant where the flat NPR 200 was charged. In the figure, the sites with a higher density of boxes represent those where the per unit electricity cost were lowest. The most expensive was site G, where each unit cost NPR 25. The least expensive was site F, where each unit cost NPR 5. Some sites used multiple tariffs structures to charge more for a higher current connection, meaning households with basic electricity needs (e.g., lighting and charging only) had a cheaper basic rate than those using higher current appliances. Using the tariffs charged by the national distributor, the Nepal Electricity Authority (NEA), the cost of electricity from the MHPs can be compared with the national grid. At the time of the field study, the lowest rate charged by the NEA for a 5 A connection was NPR 20 service charge and 3 NPR/kWh for up to 20 kWh [171]. Using this rate, the equivalent cost for grid-based electricity can be calculated. In all but one case, the cost of electricity from the MHP was more expensive than from the grid. On average across all the sites, the cost of electricity from the grid is 33% cheaper.

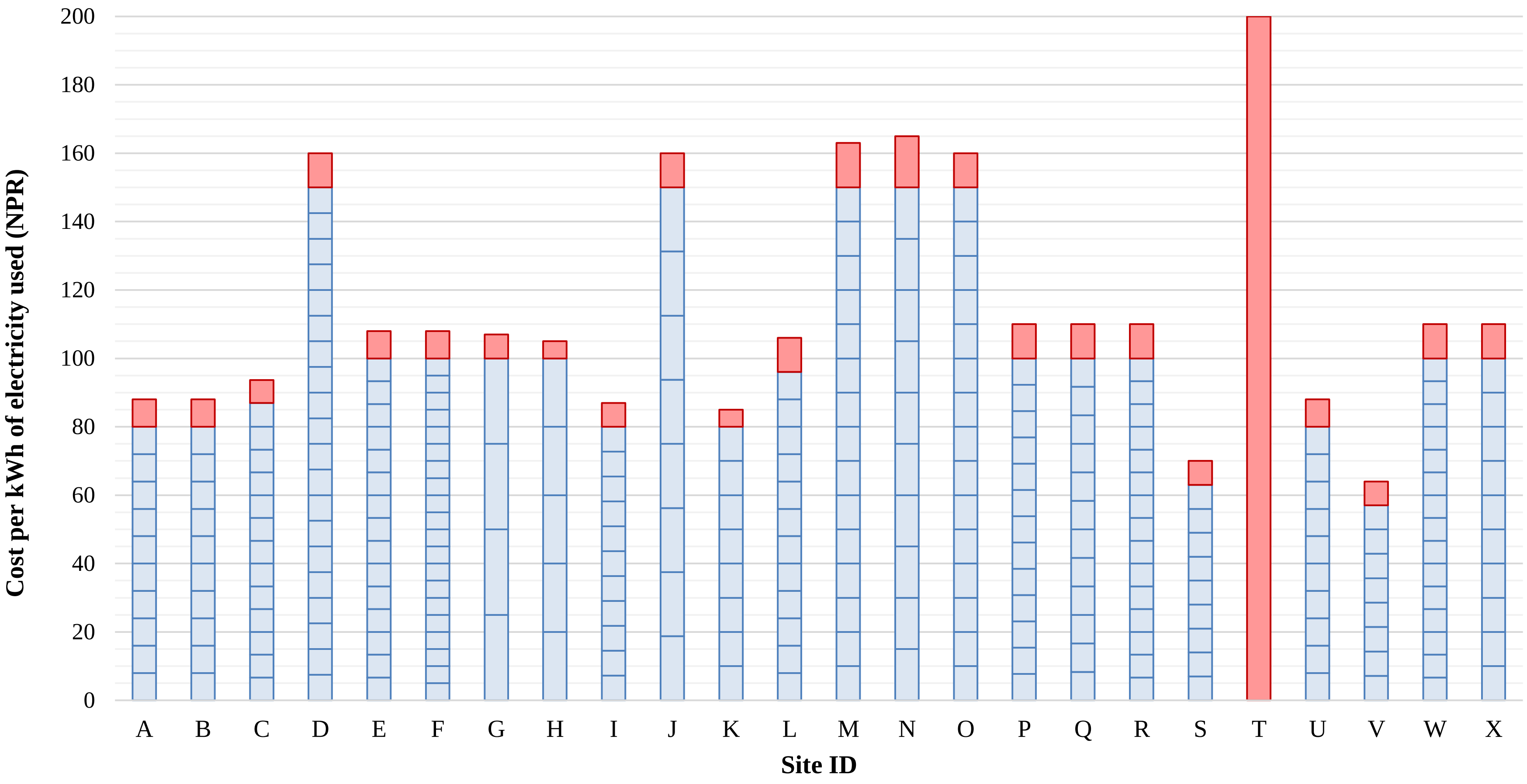


Figure 4.9 – Variation in basic tariff costs for the visited sites. The height of blue boxes indicates the per unit (kWh) charge whilst the number of boxes is the number of permitted units for the base rate. The height of red boxes indicates the charge for use of additional units.

At the sites visited, several methods were used to collect the tariffs. Some sites located in more densely populated villages instructed consumers to make the payment at the plant's office within a certain period in each month. At others, management employees would collect money from consumers' homes. At some sites with more dispersed houses, the tariffs were collected by beneficiary groups who were responsible for bringing it to the managing committee. One management representative highlighted this as a problem describing their beneficiary zone as "scattered". Another manager explained that amongst the 26 beneficiary groups, there were some that had not paid their bills for 15 months. With some of these groups more than 6 hours walk away, collecting tariffs was very time consuming.

Alongside household connections, MHPs are also used to power commercial services or productive end uses. The term productive end use is used to describe a use of electricity that can increase income or productivity [172]. Historically, hydropower has been used to drive machinery for agro-processing, however, electricity generation allows greater diversity in the types of productive end use. In this study, the end uses of electricity across all of the sites were highly varied. Table 4.5 groups the end uses into 3 categories: industrial services, commercial services, and community services. Industrial services included traditional agro-processing such as flour and grain milling, but also a range of less conventional industries including a factory for processing cotton and another for making noodles. Commercial services were dominated by shops, however, other uses included mobile phone masts and radio towers. Many community services were powered by hydropower plants including 84 schools, 40 hospital/health clinics and 9 community centres. The different types of end uses consume electricity during different times in the day. Whilst households use most of their electricity in the early morning and evenings, industrial services will often use electricity during daylight hours. Other connections such as telecom towers and hospitals may use electricity for 24 hours a day. These end uses that consume electricity continuously demonstrate the broader impact that MHPs have in rural areas. Significant tangential benefits are delivered through these services to the wider community, and not only to paying customers of a hydropower plant. For example, anyone in the local area might benefit from improved communication via a telecom tower, or the improved service offered by an electrified hospital or health post. In this way, MHPs contribute to the general development of an area.

Table 4.5 - Types of productive end use at the 24 sites.

Commercial services	Total	Industrial services	Total	Community services	Total
Grocery shop	353	Flour/grain mill	85	School	84
Tea shop	164	Poultry Farm	58	Hospital/health clinic	40
Bank/Co-operative	28	Furniture making	37	Local government office	35
Clothing shop	31	Welding workshop	19	Post office	7
Hotel/Lodge	16	Bakery	10	Community centre	9
Barber shop	9	Dairy shop/factory	4	Temple	2
Meat shop	8	Cotton factory	1		
Telecom tower	9	Stone thresher	1		
Radio tower	5	Noodle factory	1		
Computer training centre	3				
Stationary shop	3				
Irrigation pump	3				
Movie hall	1				
Petrol pump	1				
TV cable office	1				
Workshop/Garage	1				

Diversity in the types of end use is an important feature in achieving financial viability. Having a range of end uses can maximise the hours in the day when electricity is consumed (i.e., increasing the load factor) and the plant is generating an income. To understand this diversity, Figure 4.10 plots the number of different types of productive end use at each site against the number of connected households. The number of different types of end use gives an impression of the diversity of commercial, industrial and community services at that site. As the number of connected households increases, the trend is that the diversity in end uses does as well. However, for those sites with the highest number of connected households, the number of end uses appears to tend towards an upper limit. This is logical given that there was a lot of repetition in the types of businesses found and a likely limit to the different types of business that are found in rural areas. The figure indicates that the larger settlements in the study had greater variety in the types of end use, making those MHPs more likely to generate income throughout the day.

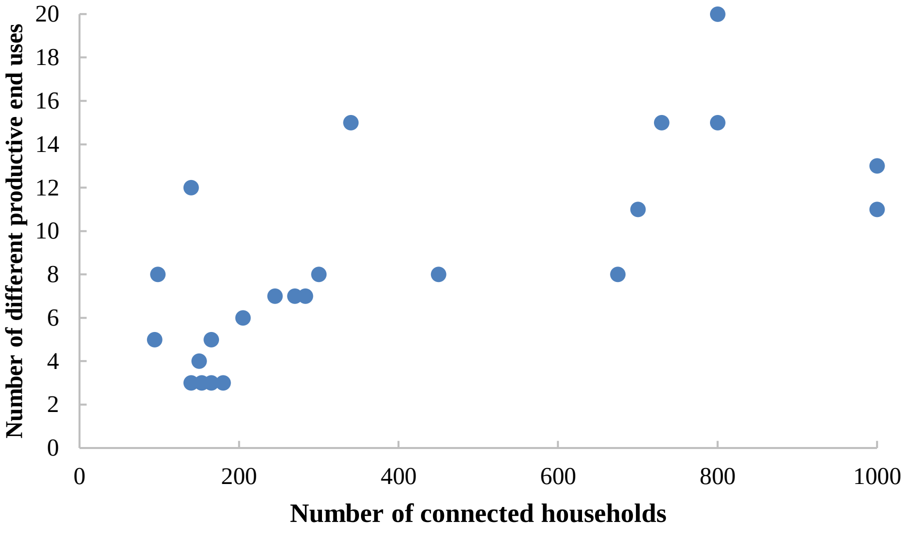


Figure 4.10 - Number of different productive end uses against the number of connected households.

Income is generated from both household and commercial connections. Figure 4.11 shows the number of connected households and connected end uses against rated power. The area of a marker represents the number of end uses that are connected to that MHP. The markers are coloured according to the manager's response to the following question: *"When there have been technical problems, has there been enough money to pay for repairs?"* Responses to this question were coded as "mostly yes", "sometimes yes/no" and "mostly no" and they can give an indication of the financial viability of the plant. The site with the highest rated power has been removed as its connection to a stone thresher with a typical load of 100 kW skewed the results in relation to the number of connected end uses (n=81).

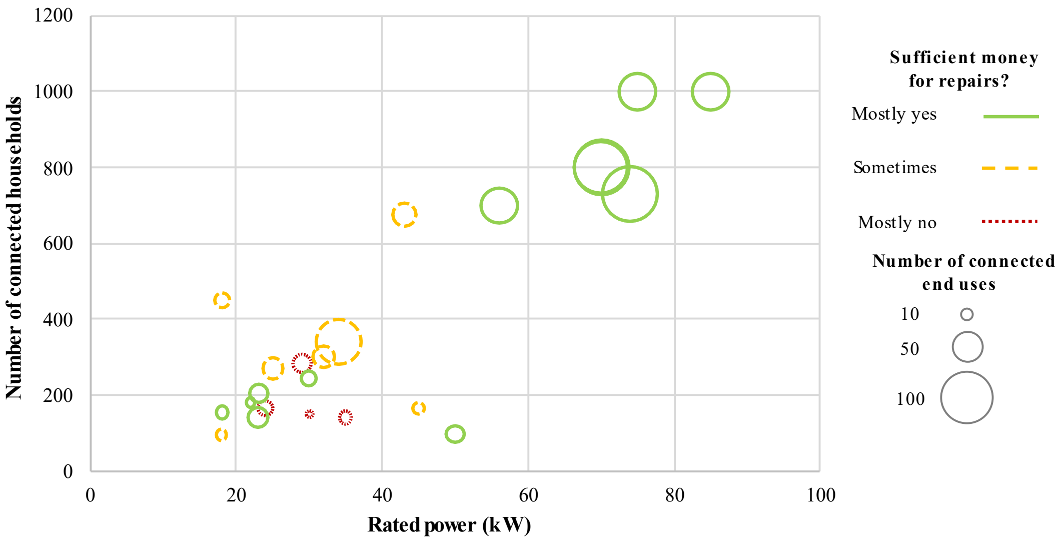


Figure 4.11 - Number of connected households and number of end uses against rated power.

The obvious trend is that the number of households is positively correlated to the rated power of the site. There is also a weaker positive correlation between the rated power and the number of connected end uses; mostly, the size of markers increases for higher rated power although there are some exceptions. Both relationships are assumed to be linearly correlated to site rated power with correlation coefficient *r* values of 0.86 (strong) and 0.68 (moderate) for households and end uses respectively.

One would expect that at the sites with a number of connected households less than the average, it may struggle to pay for repairs unless it has sufficient connected end uses to generate income. This assumption is corroborated by the 2 red markers at 30 kW and 35 kW, and the orange marker at 45 kW. However, the green marker at 50 kW is an exception. For this site, there are both a small number of household and commercial connections, yet it has always been able to pay for repairs. The end uses connected to this site included 2 flour mills, 2 furniture makers, 2 mobile phone masts and a poultry farm. These end uses are all high load applications and are likely to be reliable customers due to a high demand for their services. For consumers at this site, the tariff structure had the lowest minimum allowance of any site (NPR 100 for 4 kWh), meaning many consumers may exceed the lower limit. Technically, this plant was very well maintained and was the only site where a professional service took place every 6 months. This combination of factors suggest that good management of the plant has put it in a financially stable position.

For the sites where there had been problems paying for repairs, 3 managers explained that additional funding was collected from beneficiaries. One of these respondents explained that for the collection of additional funding, “people are categorised into 3 groups depending upon [their] economic condition”. This approach, also documented in [35], is unreliable and can lead to prolonged downtime whilst funds are collected. The results suggest that plants with higher rated power can connect both a larger number of connected households and end uses. Within the study, responses from managers indicated that the income of sites with rated power above 50 kW was usually sufficient to pay for repairs. With a higher number of connections, these plants are likely to benefit from a superior load factor, improving their financial viability [35, 37].

At the sites in the study, the use of electricity meters was almost universal allowing the plants to charge consumers accurately based on the amount of power used. There was variation in tariff structures and in the methods used for collecting income; sites in more densely populated settlements usually benefited from easier tariff collection. These also tended be sites with higher rated power (above 50 kW) that were able to connect more households and a large number of diverse end uses. Consequently, these sites were the most financially viable.

4.3.3 Community engagement

An aspect of community engagement is consumers’ satisfaction with the service provided by the MHP. Table 4.6 shows the percentage of responses given to 3 questions that focused on the quality of service provided. For both the quality of service and its cost, consumers were largely positive. No consumer interviewed was unhappy with either the price they paid for electricity or considered the service to be unreliable. When asked about the impact that connection to the MHP had upon their lives, responses from consumers were wholly positive and included social, economic and health benefits. It was often mentioned that children could study at night and village social events were improved. Many mentioned their reduced expenditure; one respondent explained that their spending on lighting had reduced from NPR 500 ($5) to NPR 100 ($1) per month. Several chose to mention the benefit of reduced smoke in the home in comparison to using kerosene or candles. The consumer satisfaction largely translated into regular payment by consumers. At 92% of sites, managers answered “Yes” or “Yes, mostly” when asked if consumers paid regularly.

When consumers were asked about the effect of late payment, several referenced the potential social, economic, or technical consequences. One respondent explained that “society shouts if [the bill is] not paid” whilst another said that “salaries will not be paid; maintenance repairs will not be on time”.

Table 4.6 - A selection of consumer responses.

“Are you happy with the price that you pay for electricity?”	
Yes	87.5% (21 of 24)
OK	12.5% (3 of 24)
No	0
“Is the supply reliable?”	
Yes	79.2% (19 of 24)
OK	20.8% (5 of 24)
No	0
“Would you prefer to be connected to the national grid?”	
Yes	29.2% (7 of 24)
Undecided	25% (6 of 24)
No	45.8% (11 of 24)

At community owned MHPs, beyond simply making payments, committee members expect that consumers take part in meetings and assist with the maintenance of the civil works. Responses from managers suggested there was more variation in the level of community engagement between the sites. Some felt that there was a lack of interest from the community as “the beneficiaries do not try to understand” when problems occur. Another manager said that despite beneficiaries considering the MHP essential in their lives, there was “low interest and ownership from the community”. It was noted by some that the economic condition of beneficiaries affected their ability to pay but they remained interested. Several other managers identified that there had been a change with time; the decreasing power of the MHP, an increase in the total load, and the encroachment of the national grid were all mentioned as factors that lead to a reduction in community interest.

The prospect of the national grid is regularly discussed in rural areas; it is often used by local politicians to solicit votes in elections. Consumers were asked whether they would prefer to receive electricity from the national grid, Table 4.6 shows that there was a mixed response. For those who stated that they would prefer electricity from the grid, several referred to the ‘temporary’ nature of the civil structures of the MHP. Damage from landslides and the monsoon often lead to consumers needing to help in repairs and maintenance. Several consumers said that they would connect to the grid but felt that the decision should be made collectively. This was also true of 2 interviewees who were uncertain about connecting to the grid. For them, the decision needed to be made by the entire community; one respondent said that they did not want to be “left alone and behind”. Amongst the 46% who had no interest in connecting to the grid, 3 more consumers chose to describe the MHP as ‘local’. Another interviewee went further by emphasising the collective effort that had been exerted; they did not want to be connected to the national grid as “much hard work had been done for the local level MHP plant”.

In most cases, the benefits and quality of service ensured that consumers paid regularly. The consumers were largely happy with the amount that they paid for electricity, with several mentioning that the cost of alternative sources was greater. Managers recognised that consumers paid regularly but that it did not always translate into a sense of ownership. Many managers felt that the level of ownership had changed with time. However, there were consumers that still identified strongly with the ‘localness’ of the plant.

4.4 Discussion

In all 3 areas (technical reliability, financial viability, and community engagement), factors present before plant operation began were influential. Plants that were located in larger villages, which were also located close to the main road, tended to have fewer problems in paying for repairs, due to a higher number and greater diversity of end uses. Figure 4.12 is an aerial photograph of one of the MHPs visited during the study. Homes, businesses, and a road are all visible in the image. This MHP lies on the outskirts of a town with an estimated population of 30,000 [173]. At sites like this, the proximity to a main road increases business opportunity but also enables easier access for the repair or replacement of failed components. Financial management in these larger settlements is aided by easier tariff collection, consumers come to pay at local offices rather than managers needing to walk long distances to collect payments. Figure 4.13 shows one of the visited plants located more remotely. The nearest houses and road were more than a one hour walk from the powerhouse.

Figure 4.12 – Micro-hydropower plant from the study located on the outskirts of a town. Photograph still taken from [174].

Figure 4.13 - Micro-hydropower plant from the study in a remote location. Photo credit, author.

At all MHPs, the actions of the operator should maintain the reliability at a certain level. However, there were problems identified that had initiated before the operational stage. An example was poorly shaped de-silting bays and forebay tanks, as also identified in [35]. The eventual outcome is that a greater amount of silt passes through the turbine which increases the wear rate of the runner, leading to the need to repair or replace parts sooner. Similarly, other identified issues like leakage and frequent failure of bearings could result from the actions of manufacturers rather than operators. Table 4.7 lists major issues identified at each sub-system and highlights the project phases which may have been important in their development. These results suggest that the original socio-economic, environmental, and technical features of an MHP affect the probability, positively or negatively, of heading into either ‘virtuous’ or ‘vicious’ cycles.

Table 4.7 - Issues identified at each sub-system and the project phases affected.

Subsystem	Major issue (s)	Design	Manufacture	Construction	Installation	Maintenance
Intake and weir	Temporary structures require repair or reconstruction after each monsoon	●		●		●
De-silting bay	Poor shape limits settling of silt	●		●		●
Canal	Landslides make regular repair necessary			●		●
Forebay tank	Poor shape limits settling of silt	●		●		●
Penstock	Ineffective drainage away from penstock foundations			●		●
Powerhouse	Dirty and cluttered spaces					●
Internal pipework and valves	Water leakage	●	●		●	●
Turbine	Water leakage	●	●		●	●
	Shaft and transmission belt misalignment	●	●		●	●
Control panel, cabling and ballast load	Dangerous cable routing				●	●
Generator	Transmission belt misalignment	●	●		●	●

Whilst a micro-hydropower site will have certain inherent features, the socio-technical system comprised of community, management, and technology is dynamic [175]. Furthermore, the system resides in a broader socio-economic environment [176]. During the field study, there were numerous examples of changes, both internal and external, that affected the resilience of the socio-technical system. Internal events that were witnessed or described by interviewees included the failure of components, insufficient collection of tariffs or the departure of a trained operator. It is common for young Nepali men and women to seek work in urban areas or abroad. For MHPs, this can often lead to the departure of the skilled trained operators. These internal shock events result in an instantaneous or quick effect on the system, leading to a decrease in the financial viability or reliability of the plant. Changes that were external were more variable in their timespan. Development in rural Nepal, perhaps even due to an MHP itself, has resulted in changes in the socio-economic landscape where they reside. Rural settlements have grown; income and electricity consumption have increased [41]. For MHPs, the consequences of these long-term changes can be both negative and positive. For some plants, this may reinforce the inherent benefits of being located in a larger settlement. An increasingly diverse range of end use connections and the higher electricity consumption of households will increase their financial viability. However, as the consumers at these sites may depend on running a business rather than agriculture; they may not be willing to give time to assist with the MHP. Furthermore, as rural settlements grow, it becomes more difficult to mobilise a community en masse.

The results of the study should also be considered within a wider context. In comparison to more remote districts that rely on micro-hydropower, the sites visited were largely accessible by road. The proliferation of MHPs within the study area means that there is a familiarity with hydropower; typically, communities have a good awareness of the project development process. Road access contributes to greater technical reliability but also greater access to markets, supporting the diversity of end uses found in the study. For sites in more remote, less accessible and less developed regions; the technical reliability and financial viability of MHPs is likely to be weaker. In addition, in more mountainous districts where distances between communities are greater, local knowledge regarding hydropower may be less concentrated. Even within the context of Baglung and Gulmi districts, threats to reliability, poor financial management and a lack of community engagement were witnessed. Therefore, despite the focussed geographical coverage of the study, one can expect that in more remote districts without a high density of MHPs, similar issues will occur. Furthermore, in these places with more challenging inherent features, the sustainability of plants is likely to be even more vulnerable.

4.5 Summary

In this chapter, a field-based study was used to understand the local contexts where micro-hydropower technology resides, and to evaluate the factors that determine the operational sustainability of MHPs. To do so, existing approaches for the assessment of mini-grids were considered and informed the development of a methodology focused on assessing three key areas relating to sustainability: technical reliability, financial viability, and community engagement. The methodology was used at 24 sites located in 2 districts in Nepal. The findings demonstrated that at the operational stage, the interaction between community and technology makes achieving sustainability complex. There was strong evidence that inherent features of each MHP can make a site more or less likely to be sustainable. It was also found that amongst the MHP sub-systems, there were problems affecting reliability that can initiate in earlier project phases before operation begins. These findings suggested that an improved understanding of the project process could be useful in preventing their occurrence.

In summary:

- A field-based methodology was devised and used to evaluate sustainability by considering reliability, financial viability, and community engagement.
- Inherent features of a site make some MHPs more likely to be sustainable.
- The socio-technical system comprised of community, management, and technology is dynamic, and this system resides in a broader dynamic landscape.
- The common occurrence of some technical issues suggests that particular actions within the project process may lead to their initiation.

Chapter 5

Evaluating the project process

5.1 Introduction

The findings of Chapter 4 indicated that threats to the sustainability of a plant develop at multiple points in the project process. Furthermore, the landscape that dictates project development is also influential in relation to sustainability. In this chapter, the project process and actions of the stakeholders are considered. Using government literature and other sources, the key stages of the project process and action of stakeholders are examined. Evidence from Chapter 4 and available literature are used to identify strengths and weakness that affect a plant's ability to operate sustainably. These strengths and weaknesses are mapped to the project process, and the critical actions of the stakeholders identified.

5.2 Background

Within available literature, the success of national level renewable energy interventions is often considered. Programmes within multiple countries are often compared with the strengths and weaknesses of different approaches evaluated [21, 177, 178]. Elsewhere, in-depth case studies focus on a particular country [179-181]. Both comparative and individual studies typically lead to the identification of factors that are deemed to affect the success of renewable energy interventions. Several studies have focused on the renewable energy landscape in Nepal. In [182], the funding mechanism of renewable energy projects in Nepal is analysed, with particular focus on the subsidy policy. It is found that within the micro-hydro industry, companies were dissatisfied with the centrally administered and "cumbersome" delivery process. Whilst in the financial sector, there is a reluctance for financial institutions to get involved due to a perceived high level of risk. In [179] and [183], the success of two different (but similarly administered) national level programs are considered: the Nepal Power Development Project (NPDP) and the Renewable Energy Development Project (REDP). Both programs provided funding for renewable energy and increased the number of MHPs in Nepal. The success of the programmes is attributed to their promotion of community involvement, the diversity of institutions involved (national and local government, and community-based), the focus placed on maintenance and after sales, and the flexibility of the overall programs. It should be noted that the subsidy process and many of today's practices are a legacy of the REDP programme. The findings of these high-level analyses of Nepal's renewable energy landscape are primarily focused on success at the national level (e.g., the number of installed MHPs) but still provide insight at the project level regarding crucial factors for success, e.g. community involvement and maintenance. However, the identification of these factors does not explain why they may occur in some projects and not others. In addition, the focus at the high level is of limited use in understanding the particular sustainability issues that can arise in individual projects.

Elsewhere in the literature, it is common to consider the success or sustainability of projects quantitatively at the operational stage [184, 185]. Typically, these assessments consider sustainability as a composite of multiple factors. Areas of focus are identified using numerical indicators, e.g., significant distribution losses suggest that the technical sustainability of a project may be poor. However, such one-off assessments are unable to identify what sequence of events have resulted in poor sustainability. Yadoo makes this argument in [22], stating that whilst there is a large body of research focused on assessment and technology selection, the project implementation process is rarely considered. By conducting interviews with governmental and industrial actors working within the renewable energy sector, Yadoo's analysis of 3 projects provides greater insight into the how the project process can help or hinder individual projects. Similarly in [186], a comparative study considers the challenges and success factors throughout the project process for 3 rural electrification projects in different countries in Central America. The study highlights that the capabilities of the community, project design, and presence of an enabling environment determine whether the project is sustainable. The authors found that stable and long-lasting social structures were supportive during implementation and the ongoing operation. Whilst assistance from outside the community is necessary for technical elements, sustainable operation was most achievable when an element of local capacity building was integrated.

Some literature focuses more directly on conditions within the project process that influence the outcome of a project. In [187], 4 capacity buildings projects are used as case studies to explore the conditions that result in successful (international development) projects in one setting but not in others. They identify initial and emergent success conditions at the structural, institutional, and managerial levels. Further, they suggest that project success depends on multi-stakeholder commitment, collaboration, alignment, and adaption. Ikejemba et al., take a similar approach by considering both the project process and the linkages between multiple actors in the implementation of renewable energy-based projects in Sub-Saharan Africa [188]. They find that within these projects the following factors are key to success: the political agenda of government, the process through which projects are awarded, planning activities, maintenance & management of completed projects, and the inclusion of beneficiaries. They find that issues develop when the designation of responsibilities between stakeholders is unclear. The authors suggest that checks on responsibility should be multi-directional, allowing beneficiaries to hold higher-level officials responsible. In comparison to micro-hydropower in Nepal, a key difference is that these papers consider projects that are not community owned-and-operated; therefore, less focus is given to the role of the community, and their relationship to the technology.

In literature focused on the Global North, stakeholder relationships have often been analysed in relation to community electrification projects. In [189], structured interviews with local people involved in community electrification initiatives in 7 countries in Western Europe are used to identify stakeholder influence at 3 levels: macro, intercommunity and intracommunity. The study demonstrates that projects can be considered in 2 phases; the ‘process’ where actors are involved in implementation, and the ‘outcome’ where actors are influenced by results. It is found that key stakeholders can support or hinder the project depending on their perception of benefit or harm from the project. In addition, during the project all stakeholders may take on multiple roles and these roles may change from process to outcome. These analyses of stakeholder influence are comprehensive but in the context of the Global North - where the community already has some form of energy access - the responsibilities of the community and resulting relationship with technology are very different to community electrification projects in the Global South. An example where stakeholder roles are considered for community electrification in the Global South is found in [190]. In this paper, a 3-phase methodology is proposed that considers the community as a ‘socio-ecological’ system that is affected by a technological intervention. Applying the methodology to a case study where a micro-grid is installed in a rural community in Chile, the importance of learning processes between stakeholders is highlighted. Furthermore, the paper finds that whilst technology adoption and adaption are unique to each community, they can both be enhanced by participation throughout the project process.

The existing literature is useful in understanding the ways in which renewable energy projects develop within a political and institutional landscape. Methods for the assessment of sustainability are well developed but often do not consider the preceding project process and the roles that have been fulfilled by stakeholders. Research in project management is useful in understanding that particular success factors are supportive to a project's development. However, often the completion of a project is considered as a success, failing to consider that sustainability depends upon ongoing actions from stakeholders, especially in community owned projects. A 'socio-technical systems' approach (presented in Section 2.6) is effective in documenting relationships between technology and communities during project implementation and demonstrates that systems continue to be dynamic at the operational stage. It has been shown that within the literature, the following are often considered, but usually separately: the institutional landscape which influences project development, the sustainability of operational projects, the roles of stakeholders during the project process, and the 'socio-technical system' that develops during a community electrification project. Within this chapter, a methodology is used to concurrently evaluate these areas.

5.3 Methodology

In Chapter 4, the field study attempted to understand sustainability by considering technical reliability, financial viability, and community engagement. The study revealed evidence of factors that were both supportive and restrictive in relation to these 3 areas, and more broadly to the operational sustainability of plants. To consider the development of these factors during the project process, it was deemed effective to consider them as strengths and weaknesses. As such, they can be defined as factors that either enhance or threaten sustainability. Whilst complex and often interrelated, the identification of individual factors and their categorisation was considered an effective approach when trying to understand the events that may lead to their occurrence.

Figure 5.1 is a process diagram for the methodology. The results of field study were used to identify strengths and weaknesses, with additional literature sources and interviews with representatives from manufacturing companies used to corroborate the identified factors and derive additional ones. To understand the development of these strengths and weaknesses, the objective was to analyse the project process and roles of stakeholders in detail. To do so, evidence was collected from the field study, interviews with manufacturers, an interview with a government official, policy and supporting government documentation, and available literature. In this context, stakeholders were considered to be groups or individuals that had a direct influence on project development and its outcomes. To reduce the complexity of the analysis, the stakeholders were categorised into 3 groups:

- **Institutional:** The stakeholders that create and manage the regulative or policy environment [103].
- **Community:** The collection of individuals located close to the micro-hydropower plant who participate in its development.
- **Industrial:** The stakeholders with financial involvement in the project, broadly, engineering and financial services.

Within the project process, each stakeholder takes a series of actions. The collective sum of these actions should ideally be an operationally sustainable MHP. Using the sources mentioned above, the actions of stakeholders could be mapped to the project process to understand the sequence of events and dependencies between them. The final stage of the methodology was to use the mapping of the project process (inclusive of stakeholder actions) to consider the series of events (and landscape) that result in particular strengths and weaknesses occurring at the operational stage. Subsequently, these results could be used to identify opportunities within the project process to tackle weaknesses and reinforce strengths.

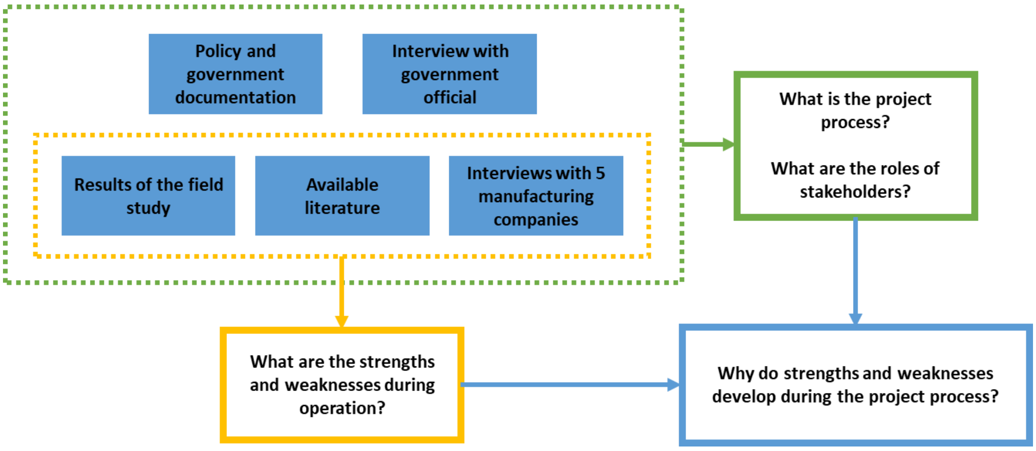


Figure 5.1 - Methodology for understanding the development of strengths and weaknesses.

The following sections discuss the data sources used in the methodology:

5.3.1 Results of the site study

The field study used a combination of interview and observation to understand the factors that affect the sustainable operation of plants at 24 sites. The results of this study were used to identify operational strengths and weaknesses in the sustainability of plants. Whilst each plant was different, common operational issues were observed. In addition, the interviews conducted with plant managers, operators, and consumers could be used to understand stakeholder experiences of the project process including roles fulfilled and actions taken.

5.3.2 Interviews with manufacturers

Semi-structured interviews were conducted with representatives of 5 micro-hydropower companies. The companies were all members of the Nepal Micro Hydro Development Association and have been trading for at least 20 years. The companies, as is typical in Nepal, fulfil roles as civil surveyors, equipment manufacturers and installers. In most cases, these interviews were conducted with senior employees who were responsible for managing the production of hydro-mechanical equipment. The questions were intended to explore their actions during the design, manufacture and construction phases, and their response to issues that occur in the field. The interviews were conducted in English and recorded. Table 5.1 lists the questions asked.

Table 5.1 - Interview questions for representatives of micro-hydropower companies.

No.	Question	
1	Do you think plant operators are well trained?	
2	What is the most common turbine fault once a turbine is in operation? Why do you think this problem occurs?	
3	If you are told of a problem with a turbine in the field, what is the process that leads to its repair?	
4	After a feasibility study is complete, what happens before manufacture begins? e.g., turbine selection, design, production drawings	
5	Is there a baseline design that you use? How is this adapted?	
6	How are the following made? e.g., process, material including grade (if known), finish, coating?	Pelton runner
		Crossflow runner
		Nozzle
		Spear
		Penstock
7	Have you experienced problems with communities building civil works? How do you mitigate against these problems?	
8	When ordering material and components from India and China, do you consult with other manufacturers in the local area to order in bulk to reduce costs?	

5.3.3 Interview with a government official

A semi-structured interview was conducted with an employee of Renewable Energy for Rural Livelihood (RERL), a United Nations Development Programme funded subsidiary of the AEPC. The interview focused on understanding institutional actions throughout the project process, changes that are taking place within the renewable energy landscape in Nepal and their impact upon the sustainable operation of plants. The interview was conducted in English and recorded.

Table 5.2 - Interview questions for the government representative.

No.	Question
1	What are the differences between community owned and co-operative structure for micro-hydro in Nepal?
2	Is the use of energy meters typical?
3	Who provides the specification included in bidding documentation?
4	Who is responsible for monitoring the construction of civil works?
5	Do manufacturers provide operation and maintenance guidelines?
6	Does the AEPC provide drawings of standard turbine designs?
7	Are the banks involved in micro-hydropower sector in Nepal?
8	What are the prospects for grid-connection of micro-hydropower?

5.3.4 Policy and government documentation

Table 5.3 lists the policy documentation and guidelines that are openly available from the AEPC. These documents are considered to be broadly of two types. First, those that are legal, e.g., the *Rural Energy Policy* and *Renewable Energy Subsidy Policy*. Second, those that are supportive to the policy or provide information to other stakeholders. These guidelines are predominantly advisory documents that advise on good practice.

Table 5.3 - Policy documentation and guidelines from the AEPC.

Year	Title	Overview
2006	Rural Energy Policy	Ensures the participation of local government and creates a Rural Energy Fund for subsidy delivery.
2008	Micro-Mini Hydro Power Output and Household Verification Guideline	Advises inspectors on how to verify the power output of MHPs at the plant and household level.
2013	Terms of reference for pre-qualification of consulting companies for survey and design of micro-hydropower projects	Provides the criteria that companies must fulfil to be eligible for subsidy.
2013	Guideline for cooperative model of mini-micro hydro projects	Provides background and instructions for the formation of a mini/micro-hydro-cooperative.
2013	Micro Hydro Project Construction & Installation Guideline	Provides detailed instructions for construction of civil structures.
2014	Reference Micro Hydro Power Standard	Provides the expected standard for hydroelectric-generating sets, associated civil works, and electrical transmission and distribution lines with capacities up to 100 kW.
2016	Renewable Energy Subsidy Policy	Provides the subsidy quantities for several renewable energy technologies.
2016	Subsidy Delivery Mechanism Policy	Outlines the process for administering subsidy to renewable energy projects.
2018	Guideline for Detail Feasibility studies of MHPs	Advises consultants on the standard approach for conducting and reporting on the detailed feasibility study of MHPs.

Alongside the freely available government documentation, the AEPC and a manufacturing company provided, in total, 4 tendering documents. These describe the details of a subsidy eligible project and provide the specification of sub-systems to be quoted for.

5.4 Key stakeholders

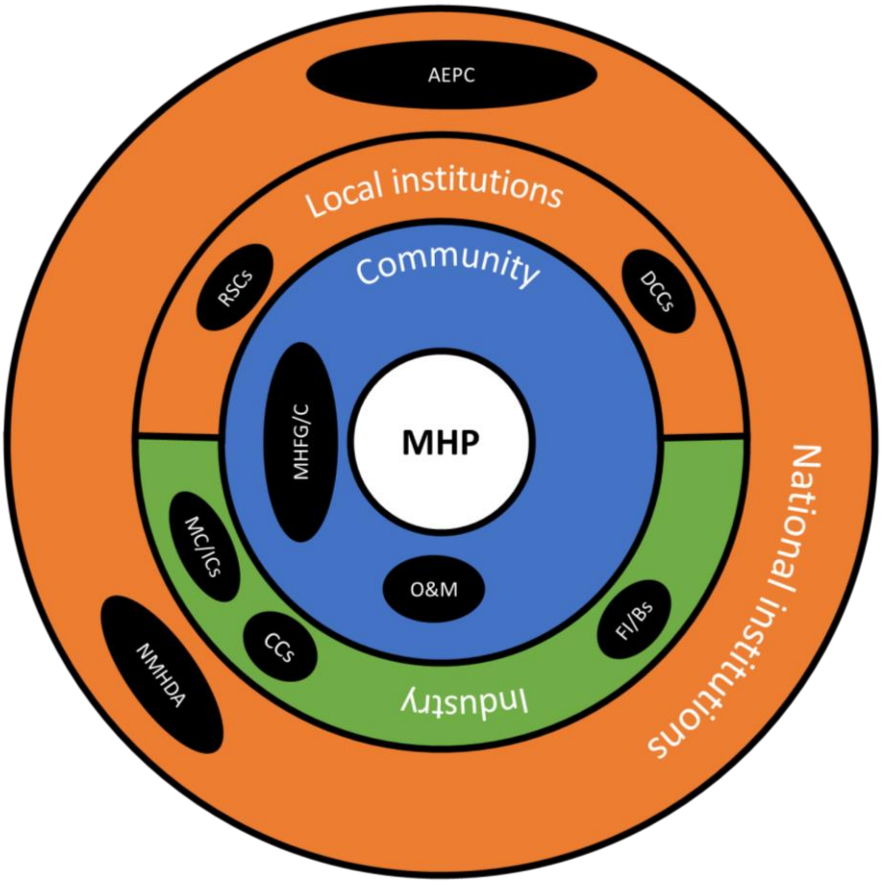
Within the project process, the details of the stakeholder groups are as follows:

Institutional: In Nepal, there are multiple institutional stakeholders acting at the national and local levels. Nationally, the AEPC is the government agency that supports renewable energy technology in Nepal. They administer subsidies, provide technical support to individual communities and to regional government offices. Working alongside the AEPC, the Nepal Micro-Hydro Development Association represents 60 of the micro-hydropower companies based in Nepal [191]. They advocate for the interest of these companies and regulate the training that is delivered to plant operators and managers. At the local level, District Coordination Committees (DCCs) are the government bodies that represent the interest of local communities within a single district. They usually provide financial support to renewable energy projects that occur within the district. Specifically working to improve access to renewable energy technologies, Regional Service Centres (RSCs) provide an on-the-ground presence to advise and support communities. There are 9 RSCs that cover the 77 districts of Nepal [35].

Community: The community may comprise multiple villages interested in developing an MHP together. The interests of the wider community are usually represented through a Micro-Hydro Functional Group (MHFG) or a cooperative. From the community, several plant operators and a plant manager are chosen, and are responsible for the operation and maintenance of the MHP once the installation is complete. It should be considered that individual members of the community are heterogenous which affects their perception of, and their actions in relation to, the MHP. In addition, there are existing social structures and local dynamics that affect the process of MHP development and its outcomes.

Industry: In this study, industrial stakeholders are considered to be those with financial interest in the project, broadly, engineering and financial services. Consulting companies (CCs) are responsible for conducting feasibility studies, sizing the overall scheme, specifying key components and designing the civil structures. Manufacturing and installer companies (M/ICs) produce or procure the hydro-mechanical and electrical equipment required to develop the project. In Nepal, it is common for companies to perform all three of the technical services of consultation, manufacturing, and installation. Private finance institutions and banks provide credit to local communities to pay for project costs that are not covered by the subsidy.

A stakeholder ‘onion’ diagram can be used to represent the relationships between stakeholders and a particular goal [192]. Figure 5.2 shows the onion diagram with stakeholder groups, sub-groups and (at the centre) their shared goal. The first level outside of the MHP is the community, the stakeholder group who will directly interact with the MHP upon project completion. The next level is shared between local institutional and industrial stakeholders. These stakeholders design, develop, and facilitate the installation and integration of the MHP within the community. The outer level comprises national institutional stakeholders who administer financial and technical support. For the purposes of this research, the boundary is drawn at this level. However, it should be considered that beyond this, the Ministry of Energy, Water Resources and Irrigation and international donors have significant influence over the AEPC’s direction and approach. Their effect cascades down to other stakeholders so may remain influential on a project basis.



Key

Institutional	**AEPC**	Alternative Energy Promotion Center
	NMHDA	Nepal Micro-Hydro Development Association
	RSCs	Regional Service Centers
	DCCs	District Coordination Committees
Industry	**MC/ICs**	Manufacturing and installation companies
	CCs	Consulting companies
	FI/Bs	Financial institutions and banks
Community	**MHFG/C**	Micro-hydro Functional Group/Cooperative
	O&M	Operation and maintenance team

Figure 5.2 - 'Onion' diagram showing the relationships between stakeholders.

5.5 Subsidy delivery and the project timeline

The subsidy policy is determined by 2 documents written by the AEPC: *Subsidy Policy* and the *Subsidy Policy Mechanism*. These documents were updated in 2016 with the aim of moving towards a market driven approach through the injection of credit, provision of subsidy based on energy consumption and the introduction of private sector eligibility [89]. Within this chapter, the focus remains on projects which are community owned and operated. Typically, in these cases the subsidy is still delivered based on the number of households and the overall rated power of the scheme. Table 5.4 shows the subsidy amounts that are made available for hydropower projects with rated power between 10 and 1000 kW. The total amount is capped at different levels depending on the district that the scheme is located in.

Table 5.4 – Subsidy amounts made available by the AEPC through the Subsidy Delivery, adapted from [193]. HH refers to household.

Subsidy category	Very remote districts where goods transport is only possible by air	Very remote districts	Remote districts	Accessible districts
Distribution (NPR per HH)	35,500	32,000	30,000	28,000
Generation – Equipment (NPR per kW)	125,000	95,000	85,000	80,000
Generation – Civil (NPR per kW)	80,000	30,000	25,000	20,000

During the project, the subsidy is paid at 4 stages. Table 5.5 shows the milestones required to release the instalments of the subsidy.

Table 5.5 - Subsidy delivery milestones throughout the project process adapted from [91].

No.	Milestones	Instalment
1	Advance on receipt of bank guarantee	30%
2	Delivery of equipment to site	45%
3	Approval of power output testing report	15%
4	Approval of one-year guarantee check report	10%

The first milestone is reached when the M/IC submits a bank guarantee. This guarantee effectively ensures that the company will underwrite a certain amount of the project cost in the event that they fail to deliver. The second milestone is confirmed through a report which demonstrates the equipment has been delivered to site. The third milestone is administered when the company can demonstrate that the MHP delivers the expected amount of power. The final instalment is paid after one year, when the company demonstrates that the MHP continues to deliver the expected amount of power.

Using the information from the subsidy documentation and supporting literature, it is possible to map the typical actions of the stakeholders. Table 5.6 shows the key actions required by the stakeholder groups throughout the project process. The actions listed are given approximately in sequential order but may occur concurrently. The project process is segregated into 5 distinct phases: project initiation, design and manufacture, construction, installation and commissioning, and operation.

Table 5.6 - Actions and responsibilities of stakeholder groups throughout the project process.

Project phase	Institutional	Industry	Community
Project initiation			Community makes an application to an RSC or the AEPC directly
	RSC carries out pre-feasibility study		
	RSC recommends to AEPC that a detailed feasibility study (DFS) takes place		
	RSC assists in selection of pre-qualified CC		MHFG/C selects pre-qualified company to conduct DFS
		CC conducts DFS and submits report to RSC	MHFG/C submit business plan for the MHP
	RSC and AEPC decide to accept DFS, business plan and approve subsidy		
			MHFG/C begin to collect funds and deposits in a community account
	RSC calls for bids from pre-qualified companies	M/ICs submit bids based on tender documentation	
			MHFG/C select M/IC
	Milestone: payment of 30% instalment	M/IC submit bank guarantee	
			Selection of operators and managers
Design & manufacture		Design by M/IC	
		Manufacture of electro-mechanical equipment by M/IC	
	Milestone: payment of 45% instalment	Equipment delivered to site	
Construction	RSC support civil works and may report to AEPC	M/IC supervises civil works	Civil works by MHFG/C supervised by MC
Installation & commissioning		Installation by M/IC	
	Power output verified by RSC	Power output testing by M/IC	
	Milestone: payment of 15% instalment	Submittal of power output report	
	Power output verification conducted by a 3rd party		
	NMHDA/CC train operator		Operator receives training
	NMHDA/CC train manager		Manager receives training
Operation & maintenance		M/IC provides assistance in repair and maintenance	Operation and maintenance of system
	Milestone: payment of 10% instalment - Final test of power output after one year		

5.6 Development of strengths and weaknesses

At the operational stage, strengths and weaknesses in the operation of plants either support or threaten the sustainability of MHPs. Table 5.7 lists operational strengths and weaknesses that were identified from the available sources. Within each list, some of the identified strengths and weaknesses may be directly contradictory. In such cases, there is evidence that both can occur. Furthermore, given the transient nature of the socio-technical system, they could potentially occur at the same plant at different times. Elsewhere, relationships may exist between the identified strengths and weaknesses, e.g., the factor ‘income insufficient to pay for repairs’ is connected to ‘beneficiaries not paying regularly’. However, as each strength and weakness may develop for a range of reasons and have multiple causal effects, all are deemed worthy of consideration.

Table 5.7 - Strengths and weaknesses of sustainable operation.

	Observation	**Evidence**
Strengths	Effective collection of tariffs	*Field study, [101]*
	Consumers pay regularly	*Field study, [194]*
	Plants deliver benefits to community	*Field study, [16, 34, 93, 195]*
	Use of electricity meters	*Field study, [34]*
	Good sense of ownership amongst community	*Field study, [93, 101]*
	Trained operator	*Field study, [34, 35]*
	Trained plant manager	*Field study, [194]*
	Installed equipment delivers expected rate of power	*Field study, [97]*
	Supportive community attitude	*Field study, [101]*
	Good relationship with M/ICs	*Interviews with M/ICs*
	Plant funds are correctly managed	*Field study*
	MHFG is institutionally strong	*Field study, [22, 34, 93, 179]*
	Community willing to assist with repairs	*Field study*
	High load factor	*Field study, [194]*
	Range of productive end uses	*Field study, [194]*
Weaknesses	Civil structures require repair due to landslides and monsoon	*[34, 101, 196]*
	Poor standard of civil construction	*Field study, [34, 35, 196]*
	Misalignment of rotating components	*Field study, [196]*
	Poor standard of maintenance	*Field study, [41, 196]*
	Insufficient income to pay for repairs	*Field study*
	Uneven distribution of benefits	*Field study, [101, 102, 195]*
	Conflict within the community – water/land/political	*[196]*
	Community not supportive in repair work	*Field study, [41, 196]*
	Reduced power output	*Field study, [97]*
	Low load factor	*[34, 35, 194, 197]*
	Problems with tariff collection	*Field study, [34, 101, 194, 196]*
	Beneficiaries not paying regularly	*Field study, [41, 196]*
	Untrained operator	*Field study, [93, 196]*
	Alternative energy sources are available (including grid encroachment)	*Field study, [35, 101]*
	Poor functioning of MHFG/C	*Field study, [34]*
	Insufficient flow rate	*[34]*
	Misuse by consumers	*Field study*
	Hydro-mechanical equipment failure	*Field study, [34, 41]*
	Low tariff setting	*[35, 101]*
	Distance to repair centres	*Field study, [41, 194]*
	Lack of proper accounting	*[194, 197]*

In the following five sections, each of the project phases identified in Table 5.6 is considered in detail. The key actions of the stakeholders, and relationships between them are discussed for each of these phases. Connections are identified between stakeholder actions (or inactions) and the strengths and weaknesses identified in Table 5.7. The strength and weaknesses are often mentioned in multiple phases to demonstrate the various points when they may begin, develop, and change.

5.6.1 Project initiation

The project process begins when a community applies to its local RSC or the AEPC to indicate an interest in constructing an MHP [35]. The community may have been advised by the RSC or a M/IC. When working in a local area, engineers often scope out potential sites. Nearby communities that have had MHPs installed provide a good advertisement and may recommend a particular company if they have had a positive experience. These recommendations allow companies to develop trust within a local area; one of the interviewed M/ICs had completed 8 projects within a small region of the Annapurna conservation area.

The RSC or a CC carries out a pre-feasibility study to determine a project’s viability. If it is found to be viable, the RSC recommends to the AEPC that a detailed feasibility study (DFS) takes place. Consultants that are pre-qualified by the AEPC are invited to submit proposals to conduct the DFS. The AEPC accredits companies as pre-qualified if they can demonstrate that they employ human resource with sufficient experience, and they own the equipment required to conduct site surveys [198]. From the proposals, the community and the RSC select a consultant to conduct the DFS. The total cost of the DFS is paid by the AEPC [91]. The pre-qualification process helps to ensure that the CC is competent to conduct the DFS.

In *Guideline for Detail Feasibility studies of MHPs*, the AEPC provides guidelines on the approach to conducting a DFS [199]. The document outlines the requirements, expected process, key considerations of the technical design, and the expected format of the report. During the DFS, the CC measures the flow rate of the river or stream that water will be extracted from and take measurements using an Abney level or a similar alternative to identify the location of key sub-systems. Within a year, flow rates in rivers in Nepal vary considerably due to the monsoon season. A hydrological mapping method allows estimation of the flow rate in a river in any month based on recording the flow rate and its geographical location [200]. Ideally, the flow rate in the river will be measured more than once (a few months apart) enabling a more accurate prediction of the flow rate throughout the year. Otherwise, the uncertainty in a single measurement could result in insufficient flow for the plant to generate its rated power throughout the year. The submitted DFS report includes detailed drawings of the overall scheme and sub-systems: intake, de-silting bay, canal route, forebay tank, penstock route, powerhouse and the proposed transmission and distribution network. The decisions made during the DFS have a significant influence over the sustainability of the scheme. Technically, the design of sub-systems affects their performance and reliability. Particularly important decisions include the placement and design of the intake and powerhouse. A poorly designed intake will result in regular repair work due to damage by the source river, especially during the monsoon season [35]. Powerhouses are often located close to the banks of a river and if sited in a dangerous location can be swept away during a flood. For system reliability, the de-silting bay and forebay tank should be designed correctly to perform their function. Socially, the design of transmission and distribution lines may determine who is and is not connected to the MHP.

The CC must also survey the community to understand the present energy situation in the area, proposed number of households to be electrified, the expected electricity usage and any potential productive end uses of electricity. These socio-economic considerations are important in understanding the financial viability of the plant. Without PEUs, the plant load factor may be low, limiting the plant’s potential to generate income. Understanding the availability of other energy sources is also important; encroachment of the grid or the introduction of solar home systems may reduce community interest in the MHP. Within the expected format of the DFS report, attention is also drawn to a range of environmental, economic, and social considerations. Surveyors are asked to consider the likely impact in the following areas: conservation and management of natural resources; impact on human rights; capacity building; impact on labour and working conditions; impacts on community health and safety; impacts on land acquisition and involuntary resettlement; and resource efficiency and pollution prevention. Consideration of these areas is useful in identifying operational risks early within the project process.

Depending on the rated power that is available, the proposed area for transmission may include multiple villages. The selection of settlements, and more locally households, may not depend purely on proximity and technical feasibility. Within a single or multiple communities, certain individuals or families carry more influence than others [101, 195]. From the outset of a project, individuals from a lower caste may not have their interests properly represented [195]. Amongst more powerful castes, there may also be competition due to political allegiances. When multiple villages are electrified by a single plant, the potential for conflict and marginalisation increases. Later, these conflicts can impact upon multiple project phases. For example, transmission line routes may be more favourable to particular groups of people; and at the operational phase, high caste beneficiaries may avoid providing labour for repair and reconstruction.

The DFS is submitted to the RSC and if approved is sent on to the AEPC for consideration by a technical review committee (TRC). Table 5.8 outlines the expected composition of the TRC. The Productive Energy Use Component and the Poverty Alleviation Fund are internationally funded organisations focused on the improvement of living standards in rural Nepal.

Table 5.8 - Composition of the TRC, adapted from [91].

Institution/body	Representation
AEPC Manager	Coordinator
Productive Energy Use Component	One representative, Member
Poverty Alleviation Fund	One representative, Member
Mini/Micro hydropower expert (private sector)	One representative, Member
Mini/Micro hydro expert (civil Society)	One representative, Member
Partner bank (financial institutions)	One representative, Member
AEPC personnel	One representative, Member Secretary

The composition of the TRC indicates a holistic consideration of the project to decide on its eligibility to receive funding. In particular, the presence of representatives from a finance institution and the Poverty Alleviation Fund indicates a consideration of the economic and social aspects of a project. At the same time that the DFS is submitted, a business plan is prepared by the MHFG/C [35]. Its preparation ensures that the members of the MHFG/C are aware of the importance of the financial operation of the plant. This business plan is also considered by the TRC, their evaluation can indicate potential weaknesses such as a lack of productive end uses. The TRC decide whether a project should be granted conditional approval for subsidy. If successful, the AEPC calls for bids from pre-qualified manufacturing and installation companies.

When a project is given approval, the community registers as a user's group such as a micro-hydro functional group, cooperative or private company [35]. In Nepal, the Cooperative Act 1992 helped to motivate the formation of cooperatives for a variety of purposes [170]. Consequently, in rural areas, community groups and cooperatives are well understood; community forestry and women’s groups are common examples [201]. The cooperative structure formalises individual financial contributions by providing shares, thus cooperative members receive a return on any profits generated [170]. In the case of the MHFG/C, the cash contribution of beneficiaries is acknowledged but not formally recognised in shares. In both cases, the formation of a representative body for the community is an important element in fostering ownership over the project and developing local capacity. It should also ensure representation of marginalised groups and provide a mechanism for conflict resolution [170]. At this stage, the community must also begin collecting the remaining funds for the project [35]. Typically, the subsidy covers 50% of the total project costs [35]. For the community, collection of funds is another stage which helps to develop ownership of the project. Regardless of financial status, beneficiaries are expected to contribute. In some instances, the community organisation may not be able to collect sufficient income themselves and must seek additional finance from banks or finance institutions. Later, the ongoing payment of bank loans from the plant’s operational income may limit the funds available for maintenance.

When a project is put out to tender, pre-qualified companies have the opportunity to prepare proposals. The bidding document provides a detailed specification of the sub-systems to be quoted for, based on the information collected during the DFS. Table 5.9 is an example of the specification provided for the turbine, generator, and civil structures.

Table 5.9 - Example of the specification within a bidding document, adapted from [202].

Item	Specification
Turbine: T15 model Crossflow Turbine (15 kW shaft power) Efficiency:70%	The turbine should be in standard of AEPC (mild steel casing should be of 10 mm thick), rated to continuously deliver adequate shaft output at 780 rpm at the operating condition of site: 52.0 L/s design flow and 40.0 m gross head to generate 11 kW from generator. The set should be complete with any inlet adapter pipe (to connect the main valve placed just ahead of the turbine). all complete.
Synchronous generator: 25 kVA, brushless, rated to continuously deliver 11 kW (KEL or equivalent)	Synchronous generator 25kVA, brushless, rated to continuously deliver 11 kW, 230/400 volts, 50 Hz, 0.8 load power-factor, 1500 rpm, 3 phase, self-excited, Connection Star, Insulation class F, Environmental Protection: IP 23 and Efficiency at full load : 85% with Compounding excitation system, all complete
Civil works supervision	Supervision of all civil works (Intake to Tailrace canal, all civil components with maintaining quality)
Installation, erection, testing, commissioning including maintenance for one year, all complete	Installation, erection, testing, commissioning including maintenance for one year, all complete.

Table 5.9 demonstrates the difference in specification between hydro-mechanical, electrical equipment and civil components. For the turbine and generator, specific information is given which can be later verified. For civil structures, the specification is not detailed, does not refer to the design submitted in the DFS, and its achievement is difficult to measure.

5.6.2 Design and manufacture

Upon selection of the M/IC and contract signing, the first instalment of subsidy can be paid. The company that wins the tender is expected to visit the site to check the outputs of the DFS. If there is any disagreement, they can submit a request for changes to the AEPC. Once these changes are agreed, design begins. As shown in Table 5.9, the tender document provides some of the specification for the turbine (e.g., rated flow and rated speed) but manufacturing companies are still responsible for the detailed design. For Pelton turbines, designers use a spreadsheet (provided by the AEPC) which determines the nozzle diameter, bucket size and number of buckets based on information from the DFS. In interviews, manufacturers explained that they have sample buckets in a range of standard sizes. The spreadsheet assists designers in determining the correct bucket size, number of buckets and pitch circle diameter. All of the manufacturers interviewed used Autocad to produce engineering drawing, typically by adapting a previous hydro-mechanical design. For Crossflow turbines, manufacturers own drawings of an Entec T-15 design, provided by the AEPC. This drawing package instructs designers on which dimensions should be changed in relation to site characteristics. The design is adapted in Autocad and the required drawings produced.

For both types of turbine, the manufacture of most components takes place at the manufacturing company, key exceptions are Pelton runner buckets and the generator. In the manufacture of Pelton turbines, the runner buckets are produced at separate casting companies. In all cases, the interviewed manufacturers explained that these individual buckets were then welded onto a hub and machined. Cast steel was the most commonly used material although cast iron and bronze were also mentioned. For Crossflow runners, end plates are gas cut or machined. In [34], it is suggested that gas cutting of discs is expensive and inaccurate, with laser cutting proposed as a superior alternative. Of the interviewed manufacturers, all said that laser cutting was not available within the local market. The blades of the Crossflow runner are cut from pipe and welded in place. The manufacturers stated that they typically chose between mild and stainless steel for the material of the blades. In most cases, both types of turbine require pulleys to transmit power from the turbine to the generator. All of the manufacturers explained that they use Habasit belts. In [34], it is observed that whilst manufacturers use these expensive belts (often imported from Europe), the pulleys are often not manufactured to the required specification. This could contribute to the misalignment and vibration seen during the field study.

In 2005, with assistance from national and international experts, the AEPC drafted the *Reference Micro Hydro Power Standard* [33]. The document is comprehensive and provides detail on all hydro-mechanical, electrical, and civil structures. The level of detail is important in ensuring high standards of quality. To consider a specific example, rusting was observed during the site study. Within the *Reference Micro Hydro Power Standard,* the following painting specification is provided for the turbine: “All turbine surfaces made of steel shall be protected from corrosion by one coat of a zinc rich primer (50 μm dry film thickness) and two finish coats for tar epoxy (180 μm) or equivalent”. By meeting this standard, the early onset of rusting can be avoided. Whilst comprehensive, the *Reference Micro Hydro Power Standard* is not mentioned elsewhere in policy documentation. Within tendering documents, as shown in Table 5.9, an AEPC standard is mentioned but it is not explicit what this is referring to. Within the *Subsidy Delivery Mechanism*, there standards are not mentioned directly [91]. Whilst hydro-mechanical equipment is in production, there is no monitoring conducted by the AEPC and upon completion, the *Subsidy Delivery Mechanism* does not stipulate any specific forms of factory testing. Interviews with manufacturers revealed that typically the only factory tested components were penstock pipes.

5.6.3 Construction

The construction of the civil structures is primarily the responsibility of the community, AEPC guidelines suggest that a sub-committee of the MHFG/C is formed for this purpose [35]. It is the responsibility of this sub-committee to arrange for the collection of raw materials and the purchase of concrete and reinforcement bar. These materials are used by the community to construct all of the civil structures up to the penstock. A respondent from a M/IC explained that communities often collect poor quality materials, e.g., “the aggregate is the wrong size, and the sand is mixed with mud”. Another respondent said that they face situations where the community “cannot purchase sufficient cement, sufficient reinforcement bar.” The quality and quantity of the materials affects the civil construction. The beneficiaries are not paid for their time and for some households, it is difficult to manage the time for farming and construction work. A M/IC respondent explained that people are only able to give so much time as “they need to feed themselves as well.” In many villages, young men have moved abroad for employment leaving largely only women, children, and older people. This is compounded by a lack of “trained skilled labour” which affects the level of precision that civil structures are built to. However, it should be noted that the process of civil construction is important in developing community ownership of a project.

RSC engineers and representatives of M/ICs companies take a supervisory role in the construction of civil structures. As shown in Table 5.9, “supervision of all civil works” is an item line within tendering documentation. All but one of the interviewed manufacturers said that they send a technician to site to oversee construction works. This company stated that they “don’t do civil works.” The other interviewees explained that the length of time a technician stays on site depends on the project but is typically in the range of 3 to 6 months. The role of M/IC technicians or RSC engineers is particularly important in the construction of certain civil structures. Ineffective de-silting bays and forebay tanks can lead to increased damage to turbine runners due to a higher silt content passing through the system. Inadequacies in these sub-systems can occur due to poor construction quality but also due to poor execution of design. A respondent explained that the technicians sent to site can lack knowledge and experience of civil elements. The technicians are not necessarily aware of “the importance of shape and size of de-silting basin”. All manufacturers showed awareness of these problems, however, only one described action to mitigate against this. They explained that in-house training is conducted annually to their installer team to emphasise “that [the] shape and size of [the] de-silting basin is very important”.

At the institutional level, the minimum expectation is that a representative of the RSC periodically checks the work completed at the site and reports to the AEPC. The interviewed government official stated that “most of the [civil construction] of micro-hydro is supervised by our district engineer”. However, they also noted that the recent transition to a federal government system - where new institutional structures are being put in a place -is an obstacle to achieving this. In [35], it is suggested that each RSC is unable to provide regular quality control to all of the sites within its given area. The AEPC has developed the *Micro Hydro Project Construction & Installation Guideline* which provides instruction to installers on the expected approach for construction and installation of micro-hydropower projects [203]. The guidelines are useful in providing information about the best practice construction methods for particular civil sub-systems. Following the guidelines would increase the quality of the completed civil works.

5.6.4 Installation and commissioning

The M/ICs send employees to the site with the finished hydro-mechanical and electrical equipment for the installation phase. According to an interviewee, the installation of hydro-mechanical equipment is completed without special equipment, e.g., the alignment of shafts is typically done using string. Installers are skilled using this method and designs allow for some misalignment between shafts. However, poor installation practice could lead to misalignment between multiple components. During installation, the plant operator (chosen by the community) will have the opportunity to learn from representatives of the manufacturing company, as one M/IC interviewee explained, “they are supposed to follow us”. This provides an opportunity for the operator(s) to learn directly at the plant.

From the community, several people are chosen to receive training for the roles of operator and manager. The selection of these people affects the reliability and financial sustainability of the plant at the operational phase. The MHFG/C or the community as a whole will typically select someone to be the plant operator. It is recommended that they have completed a certain level of schooling, however, this is not compulsory. In some cases, plant operators are selected for social and economic reasons; for example, their land might be in use for the powerhouse, or they are related to someone in a position of authority [101]. In these cases, the selected person may not possess the same motivation or capacity of someone chosen through a fair selection process.

The NMHDA delivers a 22-day course which teaches plant operators how the system operates, regular preventative maintenance and correct maintenance activities [94]. The training is paid for as part of the subsidy [91]. According to [94], the NMHDA has also run 10 advanced operator training courses, although these are only reported up to 2012. They are intended to provide a more advanced level of training for operators who have been working as an operator for a reasonable length of time. More recently, AEPC has introduced training for plant managers. Unlike operator training, this has not been a longstanding approach but is valuable in ensuring that plant managers understand the importance of tariff collection, book-keeping and financial management.

When construction and installation of a project is complete, the installation company must send a testing and commissioning report to the AEPC. Subsequently, the AEPC will arrange for Power Output Verification (POV). The *Micro-Mini Hydro Power Output and Household Verification Guidelines* describes the process that should be followed. The POV test is conducted by an independent consultant, the system must demonstrate it can generate rated power, distribute the electricity to the originally proposed households and that the performance of all components and the complete system is in line with the standards [91]. For systems rated less than 20 kW, the power must be within 10%. For systems rated between 20 and 100 kW, it must be within 5%. For the households, the consultant must determine:

- The number of households that were initially on the list that are connected.
- The number of households that were initially on the list that could be connected, as transmission line is within 50 metres of the household.
- The number of households that were initially on the list that cannot be connected, as the transmission line is too far away.

All elements of the POV test are important in ensuring the operational sustainability of the plant. The technical elements of the test ensure that flow rate is sufficient, the turbine can generate the expected amount of power and that the quality in construction of civil and hydro-mechanical components is adequate. However, sometimes with the available equipment, testing may only demonstrate the output power and the quality check may be largely superficial [35]. Checking the number of connected households is important in ensuring that the plant will be able to deliver the benefits to the planned households, and that enough households are connected to generate sufficient income. After approval of the POV report, the installer company is paid its third instalment of the subsidy. Following a year of operation, another POV test is performed. If the plant passes this test, the final 10% of the subsidy is released.

At some MHPs, energy meters are also installed. Within the field study, this was common with 23 of the 24 sites using household energy meters. Once a plant is operational, this allows the tariff to be set at different rates depending on consumption meaning household usage can be monitored and charged fairly. This is important for differentiating between the energy consumption of beneficiaries; some households may only use several lightbulbs and charging, whilst others may use a range of appliances e.g., television, radio, and fridge. In the interview with the government representative, it was explained that use of meters was not universal. It tends to be that energy meters are installed at “most of the newly constructed MHPs”, the “larger size of micro-hydro” (>60 kW) and those where “there is a bazaar or small town”.

5.6.5 Operation

After a project is complete, tendering documents (as shown in Table 5.9) state that a company provide maintenance for one year. When asked in interview, one M/IC representative explained that as this is the government expectation, they “attend to [these] rules”. This maintenance warranty is never extended beyond this period meaning that after “one year the villagers, the operators, they need to pick it up [themselves]”. During the field study, operators explained that after the warranty period, when a problem occurs, they will inform the manager or management committee. Some parts may be available from towns close to the plant, for example, in the field study some replacement parts could be bought in Baglung. However, usually the original M/IC (most often in Butwal or Kathmandu) will be contacted. According to one interviewee, the community “trust the company who has been involved in the installation”. Interviews revealed that the initial response of the manufacturing company often depends on the knowledge of the operator. In some cases, the problem can be diagnosed or even resolved over the phone. At other times, the manufacturers explained that plant operators might have no knowledge of component names or were only able to say that “the lights have gone off”. Under these circumstances, M/ICs will typically send someone to the site from Butwal or Kathmandu. Two M/ICs mentioned that they employed people who worked in the field who could reach MHPs in certain districts more quickly. These people had worked on multiple installations and were capable of checking electrical and mechanical problems; due to their experience they only report to the M/IC "if there is a serious mechanical problem". Without a good initial diagnosis, there can be long travel times only to identify the problem; in these cases, the time it takes to resolve the issue can be considerable.

Interviewees at M/ICs were asked what the most common issues encountered with turbines were. It was commonly stated that most problems occurred due to mishandling by the operators, typically resulting in problems with the belt alignment and the ELC. One manufacturer explained that operators did not appreciate that as a mechanical system, elements were liable to vibrate, move and then require adjustment. Given that a technician from the manufacturing company will align the turbine in the first instance, some operators may not be familiar with the method to align the belt. Within each year, there are typical maintenance activities where the operator will require assistance from members of the community. Repair of the civil structure and reconstruction of the intake following the monsoon are required each year. Without assistance, the operational team will take a longer time to perform these tasks.

Alongside O&M, the manager's responsibility is to ensure that the required income is collected. From the field study, it is understood that approaches for the tariff collection depend on the local geography. In some cases, it was possible to have an office where beneficiaries came to pay each month. In others, tariff collectors would visit individual households to collect payment on a monthly basis. The experience of some plant managers was that the "scattered" nature of beneficiaries' houses made tariff collection a difficult and time-consuming task. Even where tariff collection practices were good, some of the plant managers observed that the total income was insufficient to pay for repairs. In these cases, beneficiaries would be asked directly to contribute additional money for repairs, or the MHFG/C would use banks to take out a loan. Often, tariff levels are not set at an appropriate level to generate an income [35]. Following the initial tariff setting, there is a reluctance to change the tariff due to the money that has been contributed at the outset of the project.

Operational plants deliver benefits to beneficiaries through electricity services in the household and in the community. Electricity in the home can reduce the drudgery of household tasks [204], increase opportunity for leisure activities [16] and improve education [205]. In the community, electricity can increase agricultural productivity [92], increase employment opportunities [93], and improve healthcare [206]. These improvements to lives contribute to willingness to pay amongst consumers of electricity. With a greater diversity in productive end uses, electricity is used throughout the day resulting in a higher load factor and higher income. Plants that depend largely on domestic consumers tend to generate electricity predominantly at night and in the early morning. Without productive end uses consuming electricity in the daytime, a plant's load factor will be low and the income far below its potential.

At some plants, low load factors are compounded by poor managerial practices. From the field study, it was found that some plant managers believe there is a need to "rest" the generating equipment, sometimes for multiple hours in a day, reducing the amount of time when income can be generated. During the field study and in [194], it has been found that when new people request to join the MHP, an extremely high connection fee is charged; during the field study the highest cost encountered was NPR 70,000. For many people, particularly those of lower socio-economic status, this extremely high cost may prevent people from joining [207]. Consequently, the plant will not receive the monthly income that they might have done.

The operators are responsible for the O&M of the turbine and generating equipment, whilst at the end of the distribution network consumers are responsible for their own electricity use. Particularly at sites where households do not have energy meters installed, consumer behaviour is important. In these locations, consumers usually pay a flat rate. Therefore, it is expected that there is not a significant difference between consumers. If one consumer uses significantly more electricity than their 'fair' share, it may reduce the electricity that is available for other consumers. Even at plants that do have meters installed, often consumers are placed on to different tariff structures depending on the electrical current of their connection. In these cases, using multiple appliances and exceeding their current rating is a threat to the electrical protection installed in each household.

At the POV test and one-year check, the MHP's ability to deliver rated power is checked. Over time, degradation of the equipment and civil structures, and environmental changes can affect a plant's ability to deliver its rated power. If insufficient flow rate is entering the system, the overall power available is reduced. Similarly, if the efficiency has reduced then the amount of power generated will also be lower. If a plant is at capacity, i.e., supply and demand are approximately equal, it can cause frustration amongst consumers who are unable to use their regular amount of electricity.

Alongside the tariff payment, additional mechanisms should be implemented and enforced to ensure regular and timely payment of the tariff. Within the site study, many of the sites mentioned that they used a rebate system for early payments. Consumers who paid within a certain time period were reimbursed a small percentage of their monthly fee. Conversely, those who paid late were fined. Typically, a late payment fee would increase on a weekly basis. The use of these measures can be effective, however, it depends on enforcement. In [194], it is mentioned that whilst measures are often described, they are rarely enforced.

5.7 Discussion

The process that results in the construction of a MHP is complex, depending on the actions of multiple stakeholders that are often dictated by the subsidy policy. In every project, sustainable operation of the plant should be the objective, however, by considering the current project process and results in the field, it is clear that this does not occur universally. Within each project, the policy and industrial landscape remain constant, but the community, local government, RSC, M/IC and CC does not. Whilst certain actions are dictated by the policy mechanism, others are not. Furthermore, for all activities, stakeholders complete tasks in different ways and to different standards. Added to this, the interrelation between stakeholders' actions means that in some cases, different stakeholders bear greater responsibility for certain outcomes. In addition, particular actions are required at certain times with dependencies between them. To show the relationships between these actions, a graphical method of analysis has been used that considers the actions (throughout the project process) of the stakeholder groups related to a particular issue. The purpose of the method is to demonstrate that strengths or weaknesses develop due to the combined actions of the stakeholder groups. In this section, the graphical method will be used to consider 3 specific issues related to the 3 areas of sustainability highlighted in Chapter 4: technical reliability, financial viability and community engagement. Subsequently, four focus points are identified and discussed with corresponding recommendations made.

5.7.1 Graphical analysis

The interrelation between the actions of stakeholders is critical in the development of operational strengths and weaknesses. To aid understanding of the connection between these actions, they have been categorised as critical, supporting and 'quality control'. Critical actions are those that directly lead to an outcome. Supporting actions involve a transfer of capacity or capability which aids achievement of an outcome. In the Oxford English Dictionary definition, it is stated that in general use the term 'quality control' can be used to describe “any process for maintaining a desired quality of product or output”. For the purpose of discussion in this section, ‘quality control’ actions are defined as those where the output of another action is checked. This categorisation of the actions is used to consider the significance of their interrelation in the occurrence of particular issues. Figure 5.3 shows a graphical analysis of the stakeholder responsibilities that determine the quality of civil structures. The concentric rings represent the 5 phases within the project process, with the outer ring representing the earliest phase. For each stakeholder group, a development path identifies the key actions that are taken. These actions are categorised with colours used to differentiate between them. Linkages between the actions are indicated by arrows that connect them. At the centre of the diagram an outcome is identified, in this case: quality of civil structures.

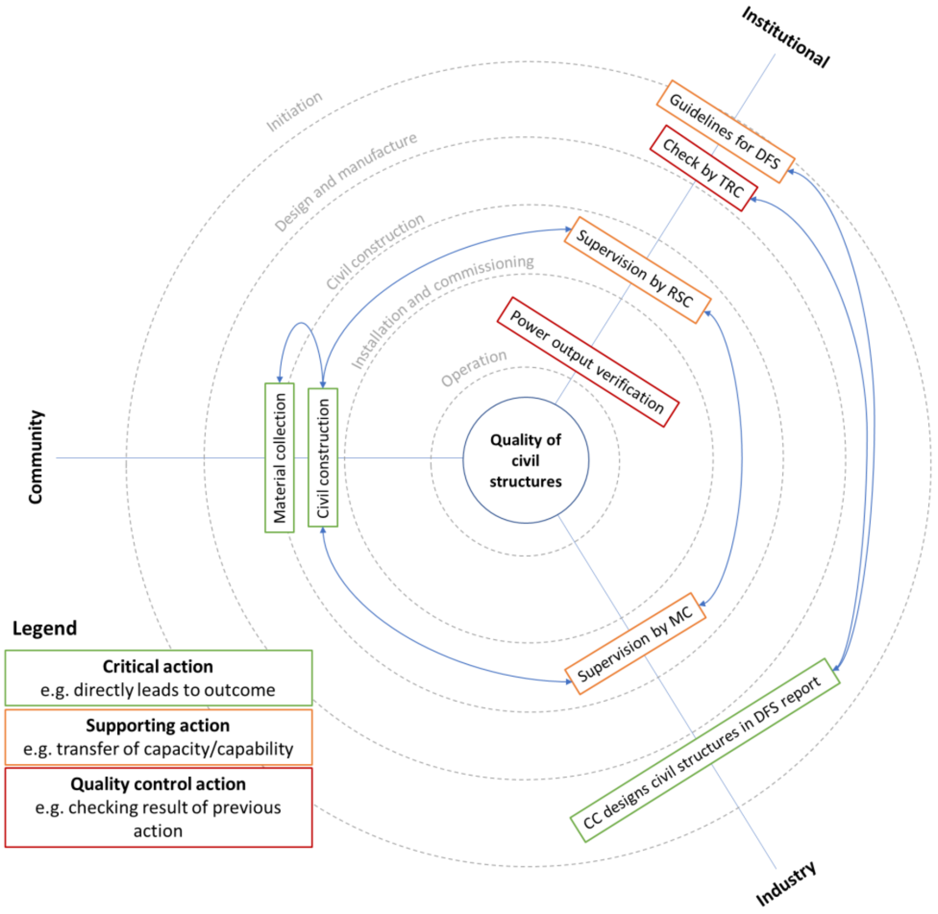


Figure 5.3 - Graphical analysis of stakeholder responsibilities in determining the quality of civil structures.

From the figure, it can be seen that during the civil construction phase, processes involve stakeholders from all 3 groups. Two of the critical actions are the responsibility of the community but the M/IC and RSC should provide supervision at this stage. Without these supporting actions, the civil construction becomes solely the responsibility of the community. There are quality control actions that are dictated by the subsidy policy, one early and another late in the project process. Whilst the design for the civil structures is checked by the TRC, the timing of the final check (during POV) suggests that if there is an issue, remediation may be expensive and time consuming. The probability of identifying and resolving problems would be increased by an additional quality control action during construction. Evidence indicates that this does occasionally happen when RSCs report on construction progress to the AEPC. However, reporting up a stakeholder level (i.e., to those less involved) is unlikely to have a significant impact.

Figure 5.4 shows the graphical method applied to evaluate the income generated from households. Three of the critical actions are the responsibility of the community and occur during installation and commissioning, and at the operation stage. In support of these, institutional stakeholders may be responsible for assisting in the development of the business plan, education of the community and training of plant managers, and the M/IC may install household meters. These actions do not always take place. Without these, the community may not set the tariff at an appropriate level or develop an effective approach for tariff collection. The only checking action occurs during the TRC evaluation. This may be an opportunity to identify potential issues relating to the ability of the community to pay.

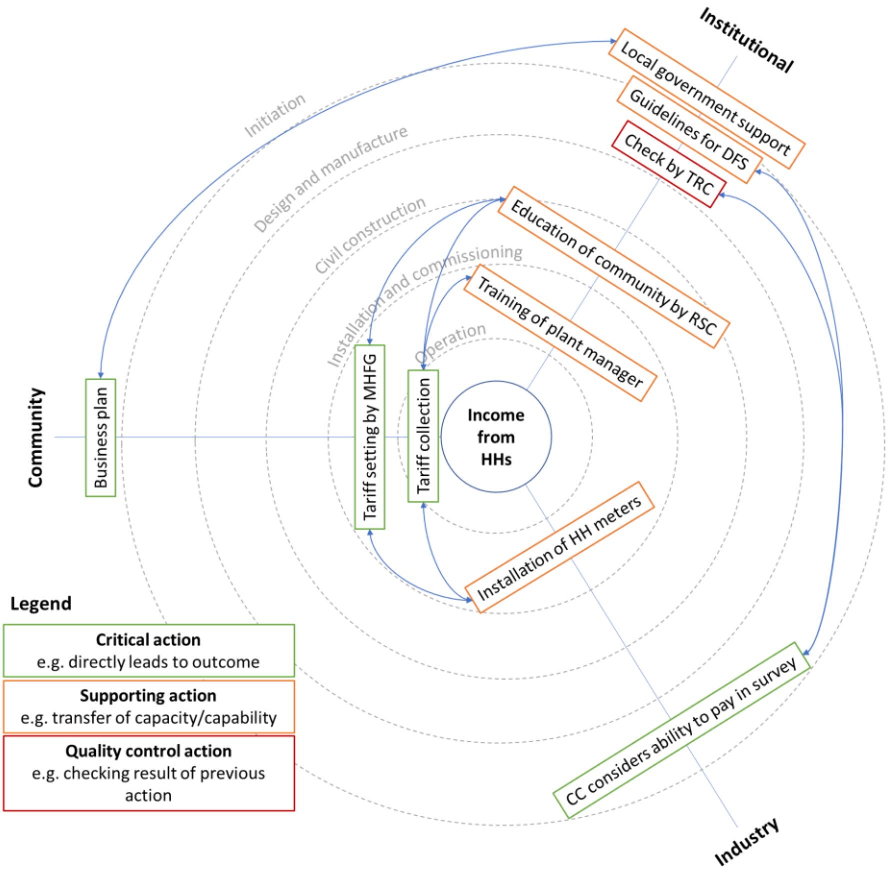


Figure 5.4 - Graphical analysis of stakeholder responsibilities in determining the income from households (HHs).

Without a subsequent quality control action, it is difficult to verify whether issues have been acted upon. At the operational stage, the operational team will learn whether the method for tariff collection is effective and how much income is generated from households. If they encounter problems at this stage, it may be difficult to implement new approaches or changes to the tariff structure as community expectations will have solidified.

Figure 5.5 shows the graphical method applied to evaluate the level of community support that is present at the operational stage. Compared to the examples in Figure 5.3 and Figure 5.4, the outcome is much harder to quantify and is likely to be transient during the operational phase. The level of community support affects the willingness of beneficiaries to help with repairs, the interest shown in the MHFG/C, and the probability of providing extra financial support when problems occur.

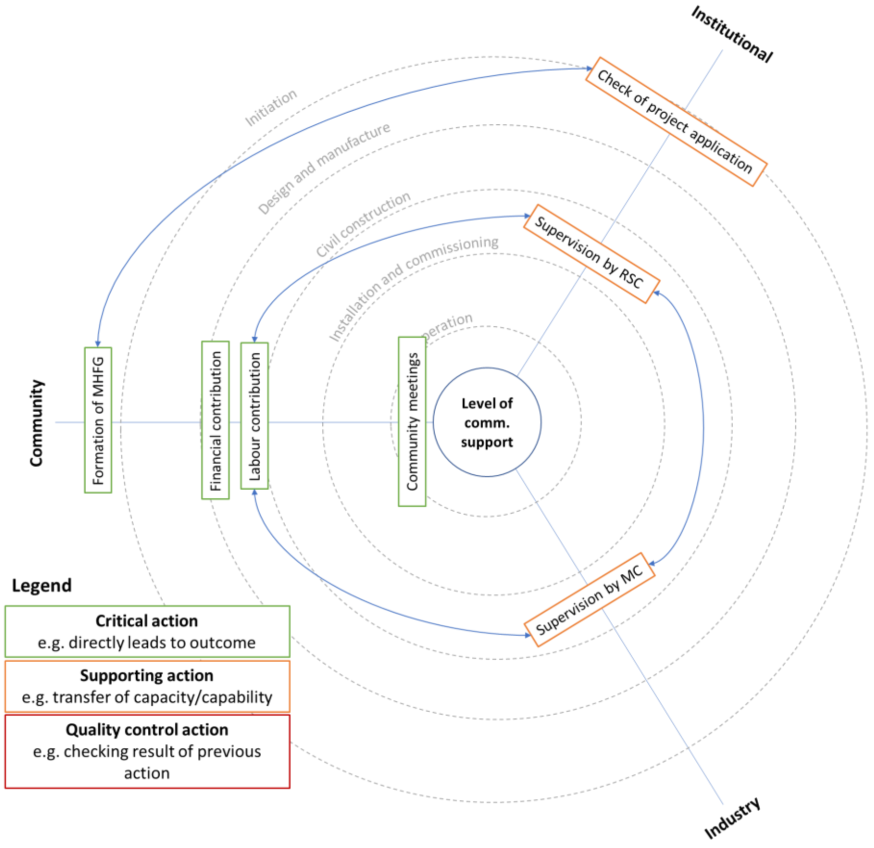


Figure 5.5 - Graphical analysis of stakeholder responsibilities in determining the level of community support.

The critical actions are all the responsibility of the community with several supporting actions. The qualitative nature of this outcome is a factor in there being no quality control actions. Informally, the RSC may perceive the level of community engagement throughout the project. Experience suggests that the 4 actions that are the responsibility of the community are effective in developing community engagement. However, given the heterogenous nature of the community, it is difficult to confirm whether this engagement is experienced by all. It should be considered that the level of community engagement is particularly sensitive to the sustainability of the plant and external events. For example, in relation to the plant’s sustainability, if the service delivered is poor the community may not feel that assisting with repair is an effective use of their time. External to the plant, local development and the arrival of alternative energy sources may also distract community focus.

5.7.2 Focus points

In this section, four focus points are used to frame the findings and make specific recommendations.

1. **Despite processes that foster community engagement, supporting actions from all stakeholders are required to ensure that the actions of the community are directed towards sustainable project outcomes.**

Throughout the project process, there are multiple phases where community engagement is developed. At the outset, the formation of a MHFG/C aligns the interest of the community, provides representation to marginalised groups, and creates a platform for the community to interact with the other stakeholders. Assuming that the project application is successful, the requirement for financial contribution is important. Monetary investment is useful in engaging individuals and as this is expected (at an appropriate level) from all beneficiaries, it is an opportunity for every household to contribute. Individual commitment to the collective cause is reinforced during the civil construction. At this stage, physical rather than monetary commitment is required, with some community members working for at least 6 months. The physical and financial engagement of the community fosters ownership, providing a platform for sustainability. The sense of collective achievement by the community (acknowledged during the field study) contributes to a desire to sustain the MHP.

However, the sustainability of the plant cannot be ensured through community engagement and ownership alone. The community is reliant on external input for the technology, supervision, and capacity building. In the construction phase, a combination of the RSC and M/IC must support the community to build the civil structures. Later, the training of the operator and manager by the NMHDA or a M/IC is needed to prepare the management team for the operational phase. Whilst training of operators is common, training of plant managers is essential and should be practiced at every new installation. It should be conducted locally by RSCs to maximise the number of participants. Without this knowledge transfer, the community will not be able to fulfil their responsibilities during the project's construction or at the operational phase. The collective physical and financial effort from the community may be misdirected, e.g., poor standard of civil construction or regular payment of insufficient tariffs. The collective action of the community has significant potential, the number of constructed MHPs in Nepal demonstrates this.

However, without the actions of other stakeholders, the actions of the community can lead to weaknesses in sustainability.

2. **The AEPC has expectations regarding standards and quality assurance, but the capacity of institutional stakeholders is a barrier to implementing them rigorously.**

The AEPC has produced an extensive range of guidelines that describe their expectations for how multiple phases of the project process should be completed. These are comprehensive examples of good practice that when followed can motivate the creation of operational strengths and limit weaknesses. Alongside the guidelines, there are multiple quality assurance processes, including several that are directly related to the delivery of subsidies. As the government administers both the documentation and the quality assurance, there needs to be correlation between these two areas.

For both CCs and M/ICs, pre-qualification is a good method to assess whether companies possess the human resources and experience required. From the DFS stage, the guidelines demonstrate what should be included in the report. Following the submission of this report, a quality control process (the TRC panel) is an early opportunity to flag technical, social, and economic issues that might affect the project. It is encouraging that the members of the TRC panel are diverse in their professions, with the breadth of knowledge to assess the project in relation to reliability, financial viability, and community engagement. The tendering document provides specification of all the sub-systems of the MHP. In the case of some sub-systems such as the turbine and generator (as shown in Table 5.9) this is well defined. For the civil structures, whilst poorly specified, the RSC is responsible for checking on the quality of construction. The observed quality of civil structures suggest that this does not always happen, as did the response from the interviewed AEPC staff member. The inspection that occurs (as part of the POV test) when the installation is complete occurs too late for any meaningful changes to be made. For the manufactured components, although well specified in the documentation, there is no factory acceptance test or inspection of the equipment before it is sent to site. Consequently, without independent inspection, it is likely that equipment could be sent to site with faults. On behalf of the AEPC, independent consultants should use the *Reference Micro Hydro Power Standard* to check the adherence, quality and key dimensions of manufactured and bought-in hydro-mechanical equipment before they are dispatched to site. Similarly, civil structures should be formally checked against the project drawings and AEPC standards by the RSC during construction and before commissioning. A subsidy payment to the M/IC for the supervision of civil works should depend upon it. For both civil structures and manufactured equipment, the subsidy policy provides an opportunity for the AEPC to enforce the standards that must be met.

3. Manufacturers possess the experience and capacity to deliver sustainable MHPs, but the current structure does not maximise their potential.

Many of the M/ICs have installed a large number of projects. Most of the companies provide a range of services: feasibility study, civil design, electro-mechanical design and manufacture, and installation. This depth and breadth of experience means that M/ICs should understand what a sustainable project is and how it can be achieved. From observation during the field study and interviews with the 5 manufacturers, the approach of the different M/ICs to hydro-mechanical design and manufacture is largely similar, leading to similar results. Since 1989 [32], the subsidy has driven the way projects are approached; manufacturers do what is required to receive the subsidy. New companies may enter the market, but according to the interviewees they focus on cost reduction rather than innovation. Unless a prior relationship exists or an RSC is providing specific advice, the community will usually select the lowest bid. This has stifled innovation in Nepal and means that technology has remained unchanged for the last 20 or 30 years. Technical advancements, particularly in relation to power electronics and sensing, have not been integrated into projects in Nepal. The subsidy could be used to encourage innovation from manufacturers by supporting the integration of particular technologies that could improve reliability.

As a cost saving mechanism and a successful tool in improving community engagement, the responsibility of the civil construction is given to the community. However, given the experience that most manufacturers possess, their supervision in this process is important. In the tender documents, the expectation that manufacturers provide “supervision” is not a prescriptive obligation. Manufacturers sending inexperienced technicians to site or for only short periods of time does not result in a good quality of construction. There are examples of M/ICs integrating their own approaches. For example, using an experienced local person ensures that the construction can be completed to the required standard with reduced cost. However, in most cases, as the contract does not stipulate the quality of the civil structures, M/ICs do only what is required. Supervision of civil structures should be made the complete responsibility of the M/ICs. The terms of supervision should be clearly defined so that the community can hold the M/IC accountable if they fall short of expectations.

4. **Financial viability is considered in the project process but needs to be integrated; productive end uses and effective tariff collection do not develop organically once a MHP is installed.**

During the project process, there are multiple activities that consider the financial viability of the project. Initially, the submittal of a project business plan ensures that the MHFG/C consider the importance of the plant's economic operation. In addition to the business plan, the DFS quantifies consumer's willingness to pay and the opportunities for productive end uses in the local area. Observation of the business plan and the assessment of the DFS ensures that institutional stakeholders have considered the financial viability alongside the technical viability. Between the TRC review and training of the plant manager, there are no scheduled activities that focus on preparing the plant for sustainable financial operation. The business plan should include clearly defined actions that can be checked by the RSC. Sites with low potential for economic activity should be identified and supported. A second stage business plan which indicates progress should be submitted when the equipment is delivered to site.

At the operational stage, households and businesses will begin to use electricity, and the management team must collect tariffs. The amount of electricity that is used by households and businesses, and the effectiveness of tariff collection determine the financial viability of the plants. Literature and the experience of the author show that an inability to do either of these tasks will prevent a plant from operating sustainably. The results of the field study indicated that some plants did not take a considered approach to tariff collection. Many plants have low load factors due to minimal day time usage and a lack of productive end uses. Plant managers did not keep up to date account records. These outcomes suggest that the current activities are not successful in developing financial sustainability; management teams are failing to generate and manage their sources of income. Whilst some communities may take their own actions, e.g. purchasing milling equipment to generate income, it is not universal.

For community renewable energy technologies, in general, the established project cycle in Nepal is able to provide a number of lessons. The initiation of the project by the community and their ongoing involvement is effective in fostering ownership. Finding a financial or physical contribution that is appropriate for each household is important. A subsidy driven process provides an opportunity to introduce quality control mechanisms. However, to administer these effectively requires sufficient capacity, and is more effective if overseen at the local level. Each project develops within a socio-economic and physical landscape which affect the project process and its outcomes. To operate sustainably, the location of some schemes means that they require greater support during the project process. Proper evaluation of the market opportunities and ongoing support to introduce productive end uses are important in ensuring that plants have high load factors and generate sufficient income. Furthermore, the responsibility of operation and maintenance usually resides with a handful of individuals; they must be properly trained and fairly paid.

5.8 Summary

In this chapter, a variety of methods were used to collect information regarding the project process, actions of stakeholders, and the operational strengths and weaknesses that occur. By connecting these areas, it was possible to assimilate findings from the field with a broader understanding of the institutional landscape that MHPs are developed in. The findings indicated that there are opportunities to address sustainability issues through quality assurance and capacity building. Meanwhile, the subsidy driven process provides a (currently unfulfilled) opportunity to ensure that the required standards are met. From this chapter, an improved understanding of local context and the influence of the institutional landscape has been developed. However, to develop appropriate design solutions requires an awareness of local manufacturing capacity, and the availability of materials and processes.

In summary:

- Literature sources, interviews and the results of the field study were used to understand the project process, its stakeholders, and the operational strengths and weaknesses that can occur.
- There are opportunities within the project process to address sustainability issues through quality assurance and capacity building.
- The subsidy driven process provides an opportunity to ensure that required standards are met.
- In general, for community energy projects which involve diverse stakeholders, sustainable operation of projects depends on coordinating their actions throughout the project process.

Chapter 6

Design and development of a Turgo turbine runner for local manufacture

6.1 Introduction

The preceding chapters established an understanding of the local context of MHPs, the issues that occur in operation, and the project process that leads to their development. Considering the DFL methodology, these findings have contributed to its first stage: developing an understanding of the local context. In this Chapter, the understanding of local context is extended to consider the capacity of manufacturing companies using a survey. Additionally, a survey is used to establish a baseline cost for the established turbine technologies in Nepal. The understanding of local context (particularly in relation to manufacturing) is used to inform the digital development of a Turgo turbine runner design using CFD. The internet, additive manufacturing and cooperative design facilitate the transition to a locally appropriate design. Finally, the experiences manufacturing the resulting design locally are shared and discussed.

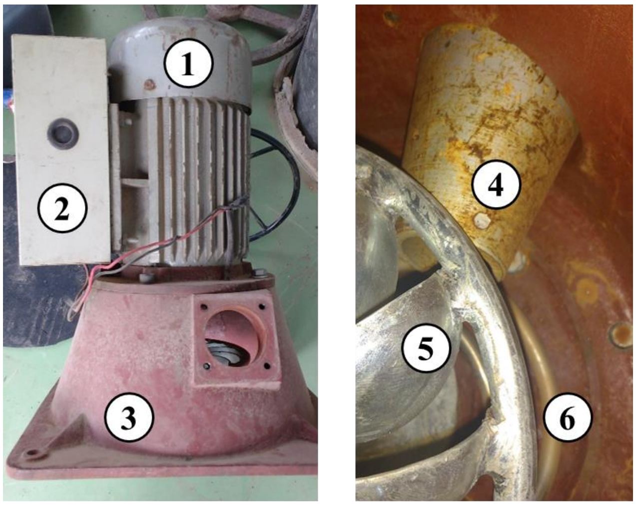
6.2 Methodology

This Chapter presents the transition from the first to the second stage of the DFL methodology. It requires the application of knowledge regarding the local context and using it to develop appropriate design solutions. As previously discussed, there is not a readily available Turgo turbine design. Between the Pelton turbine and the Turgo, the runner is the only uniquely different sub-system. For any turbine, the runner is the most complex part and is the most significant determinant of the turbine's efficiency. Consequently, the focus of the DFL methodology was the Turgo turbine runner.

The starting point for design development was an imported Turgo turbine-generator set. Henceforth, this will be referred to as the 'Imported' turbine or runner. Table 6.1 lists the turbine specification as provided by the supplier, whilst Figure 6.1 shows the key components of the set, and Figure 6.2 shows the runner in detail. The set comprises a single nozzle vertical axis Turgo turbine, connected directly to the shaft of an induction motor running as a generator. It includes an air heating element inside the casing that is used as a ballast load. For hydro-turbines at the pico- and micro- scales, it is common to control the turbine electrically rather than mechanically [208]. The electronic load controller 'dumps' any excess power to the ballast load to ensure the turbine runs constantly at close to the generator's rated speed. The turbine's nozzle is convergent and has no spear valve, however, flow to the turbine can be shut off using a gate valve positioned upstream of the nozzle. The runner of the turbine consists of sheet metal pressed blades that are welded internally onto a central hub and externally to a concentric outer ring, as shown in Figure 6.2. The profile of the blades is largely uniform, however, evidence of deformation or 'crinkling' from the manufacturing process can be seen. The information supplied by the manufacturer was limited. It stated that the system had an expected efficiency of 70% but without supplying any supporting data.

Table 6.1 - Imported Turgo turbine specification, adapted from [209].

Characteristic	Value
Rated head	18 – 25 m
Rated flow	8 – 10 L/s
Rated power	1.5 kW
Generator rated speed	1500 rpm
Pitch circle diameter	0.1 m
Nozzle orifice internal diameter	0.0307 m
Number of blades	14
Jet inclination angle (to the horizontal)	22.5°



(a) (b)

Figure 6.1 (a) and (b) - Imported Turgo turbine set including 1. induction motor, 2. electronic load controller, 3. turbine casing, 4. nozzle, 5. runner and 6. ballast heating element. Photo credit, author.

Figure 6.2 - Imported Turgo turbine runner. Photo credit, author.

In hydropower, experimental testing under laboratory conditions is widely used to confirm the expected performance of a turbine. This information can then be used to predict the turbine's performance at a site installation under a range of conditions. Experimental testing is often expensive and time consuming, particularly when attempting to improve a design. When compared with experimental testing, commercially available computational fluid dynamics (CFD) software can be used to quickly and cheaply optimise simple turbine designs for improved efficiency [68, 210]. Due to the knowledge, experience and computational power required, the use of CFD within hydropower has largely been in academic and industrial applications, focused on the improvement of high-performance turbines for medium and large-scale hydropower projects. For a relatively low efficiency of 70%, CFD can be used as a tool to quickly improve the efficiency of the Turgo runner design.

In Chapter 5, it was found that the interviewed manufacturers used Autocad to produce engineering drawings. Alongside CAD, internet use was common. The combination of these technologies offers opportunities for novel approaches to design development. The internet enables access to digital designs and the opportunity to communicate with fellow designers and manufacturers through website such as *Thingiverse, Instructables and GrabCAD* [211-213]. Designs available online can be downloaded, opened in CAD software, and printed for use by technicians. Many of these online platforms provide designs for additive manufacturing, enabling rapid prototyping or the production of moulds, e.g., rapid tooling. In Nepal, additive manufacturing was not currently available at the visited manufacturing companies, however, it is available at Kathmandu University. Thus, investigating the local manufacture of the Turgo turbine in Nepal provides an opportunity to explore the potential of a new design approach which uses the internet, CAD, and additive manufacturing.

In this chapter, the primary focus is developing a route towards local manufacture of a Turgo turbine runner. Figure 6.3 shows the process that is used to achieve this. CAD is used to model the Imported runner with CFD simulation used to replicate its performance under typical operating conditions. A survey of manufacturers is used to improve knowledge of their capacity. This is applied to specify restrictions for the CFD design progression that maintain a focus on ease of manufacture. Subsequently, a cooperative design process with NYSE is used to ensure the design could be manufactured. Finally, using the internet, the design can be shared digitally in a 3D CAD format and reproduced using additive manufacturing to provide a precise replica. Depending on the chosen process, additive manufacturing could be used to develop moulds or templates to facilitate local manufacture.

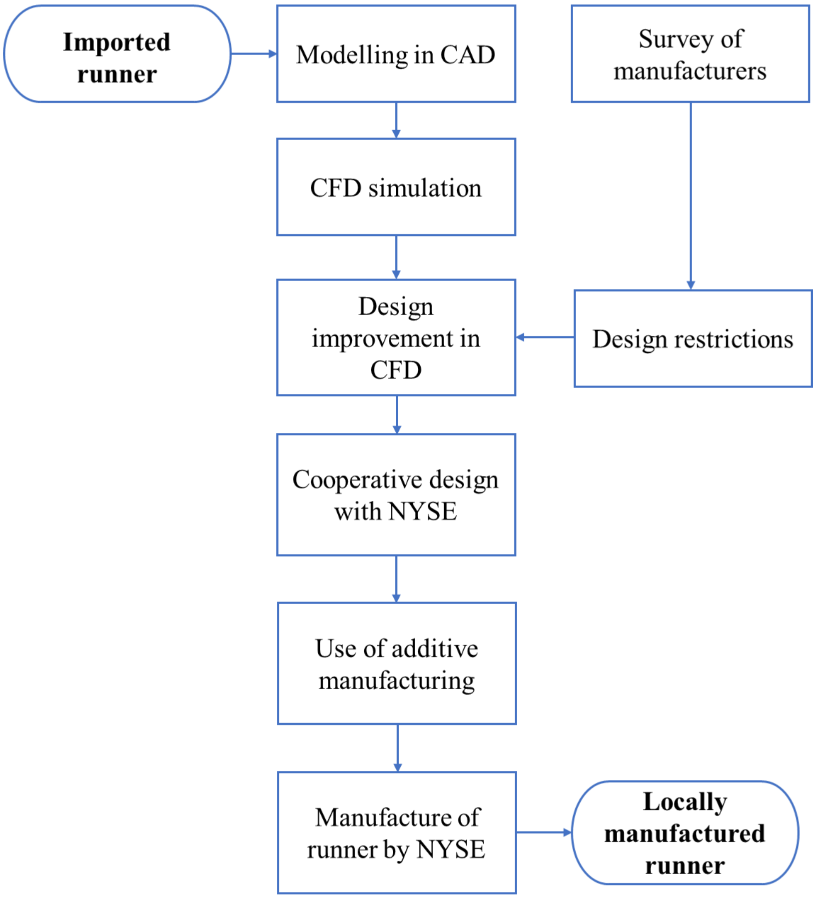


Figure 6.3 - Process for runner design improvement.

6.3 Manufacturing capability

Within Chapter 5, interviews with manufacturers were used to understand their role within the project process. Whilst these interviews identified key actions, they did not provide significant detail on the capacity of the companies. To develop locally appropriate solutions depends on knowledge of the available processes and materials. In addition, the interviews did not consider specific actions during the design and manufacture process, particularly in relation to quality control and quality assurance. In the discussion section of Chapter 5, 'quality control' was used as a general term to describe processes where the quality of something was checked. Whilst in general usage, quality control is often used interchangeably with quality assurance, in the context of engineering they have specific definitions. Quality assurance (QA) can be defined as "the maintenance of a desired level of quality in a service or a manufactured product, especially by means of attention to every stage of the process of delivery or manufacture" [214]. Whilst quality control (QC) is "a system of maintaining standards in manufactured products by testing a sample of the output against the specification" [214]. Using these definitions, QC processes can be considered a form of QA. As a number of reliability issues had been encountered in the field and in the literature, an additional objective was to understand measures for QA and QC within the design and manufacturing process.

A survey was used to extract qualitative and quantitative information relating to the experience of manufacturing companies, their approach in the manufacture of key components, and the available manufacturing processes. Alongside manufacturing companies, the interviews conducted in Chapter 5 identified the presence of casting companies within the turbine production process. Consequently, several were also interviewed. The findings of these surveys could be used to select a viable method for the manufacture of the Turgo turbine, and to identify opportunities for quality assurance during the manufacture of turbines of all types.

6.3.1 Methodology

Based on the initial interviews conducted with manufacturing companies in Chapter 5, experience of the author and review of literature, a survey for micro-hydropower manufacturing companies was devised with 3 main areas of focus:

- Experience - to understand the capability and capacity of the company and the services provided.
- Components - to understand how key micro-hydropower components are manufactured, which materials are used, and any methods used to ensure the quality of these components.
- Processes - to understand the manufacturing processes that are typically available at micro-hydropower manufacturers in Nepal.

Most of the questions were closed and led to a mixture of qualitative and quantitative responses. The survey was reviewed by experts within the field and their suggestions were incorporated. A trial survey was conducted at NYSE and the feedback of Dr Suman Pradhan was integrated. It was aimed to gather survey information from at least 6 companies (10% of the 60 companies registered with the NMHDA [191]). Of these, companies with at least 10 years trading experience were targeted which resulted in surveys with 8 manufacturing companies. The interviewees were the managing directors, project coordinators or senior engineers from these companies. Irrespective of their position, the interviewees are referred to collectively as ‘manufacturers’. In some cases, multiple staff were present to provide supporting answers. Alongside these, separate interviews were conducted with managing directors of 2 casting companies. The objective of these interviews was to understand their experience and capability, and the role they fulfil within the turbine production process. The interviews were conducted in English; however, a Nepali speaker was present to translate when necessary. Alongside the interview, photographs were used to document the types of manufacturing equipment that were present at each workshop.

6.3.2 Results

Experience

Responses indicated that the interviewed companies had been trading for between 17 and 58 years, with a mean of 31 years. The experience of the primary respondents themselves ranged from 20 to 50 years, with a mean of 33.5 years. Figure 6.4 shows that of the 7 asked (one interviewee was not asked this question), most of the companies had completed more than 50 Pelton turbine projects (5 of 7) and 50 Crossflow turbine (7 of 7) projects. Two of the interviewees also mentioned working on a small number of propeller turbines.

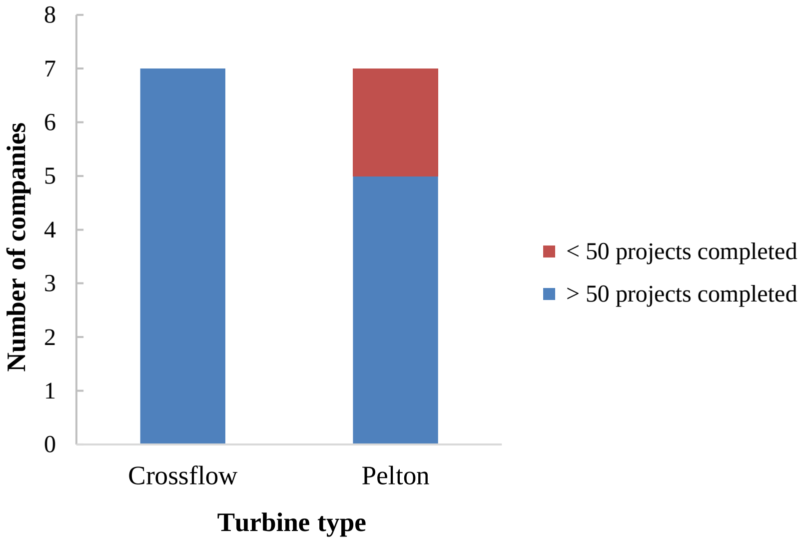


Figure 6.4 - Project experience by turbine type.

When asked about the core services provided, responses from all of the manufacturers indicated that the main service offered was design and manufacture of hydro-mechanical systems. Figure 6.5 shows that in addition to this core service, electrical design & manufacture, survey, and civil design were also common.

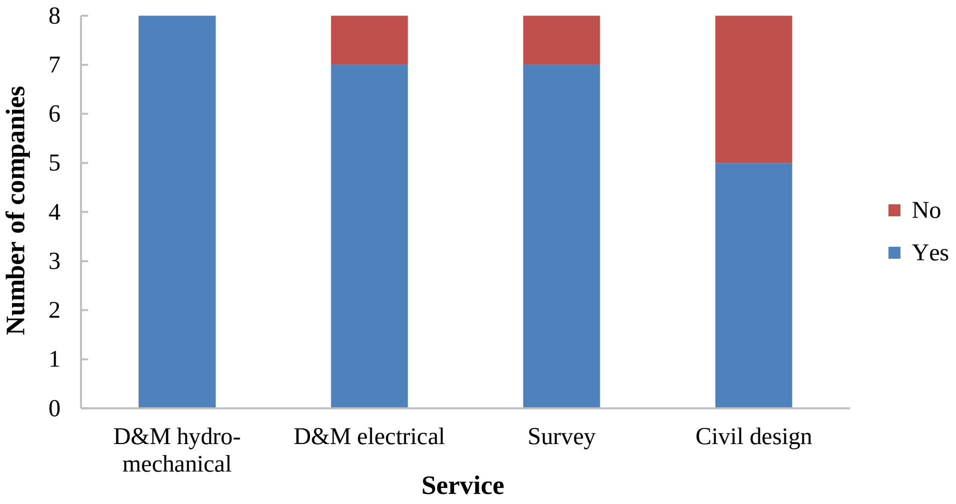


Figure 6.5 - Services offered by the micro-hydro companies.

Components

The available processes determine the approach used in the manufacture of key components. In the production of Pelton and Crossflow turbines, there are many components which are similar for both turbine types, e.g., incoming pipework, penstock, shaft, and casing. The components that differ most are the turbine runners. The Pelton runner consists of multiple buckets that are centred around a hub. Figure 6.6 shows a Pelton runner being machined on a lathe. The manufacturers explained that Pelton buckets are sand cast individually and then usually welded onto a hub. In the past, bolted runners were more common but now welding is preferred. No manufacturer does single piece casting of Pelton runners. The most common material choice is cast steel, although bronze and brass are sometimes used but less than in the past. Casting takes place externally at specialist casting companies in Butwal, Bhairahawa (29 km from Butwal), and India (the border is 31 km from Butwal). Figure 6.7 is a diagram that shows the typical manufacturing process for a Pelton turbine runner in Nepal. This diagram was generated based on the responses of all the interviewees. It indicates the key manufacturing, QA/QC approaches and processes, and opportunities for greater QA that were identified during the surveys.

Figure 6.6 - Machining operation on a Pelton turbine runner. Photo credit, author.

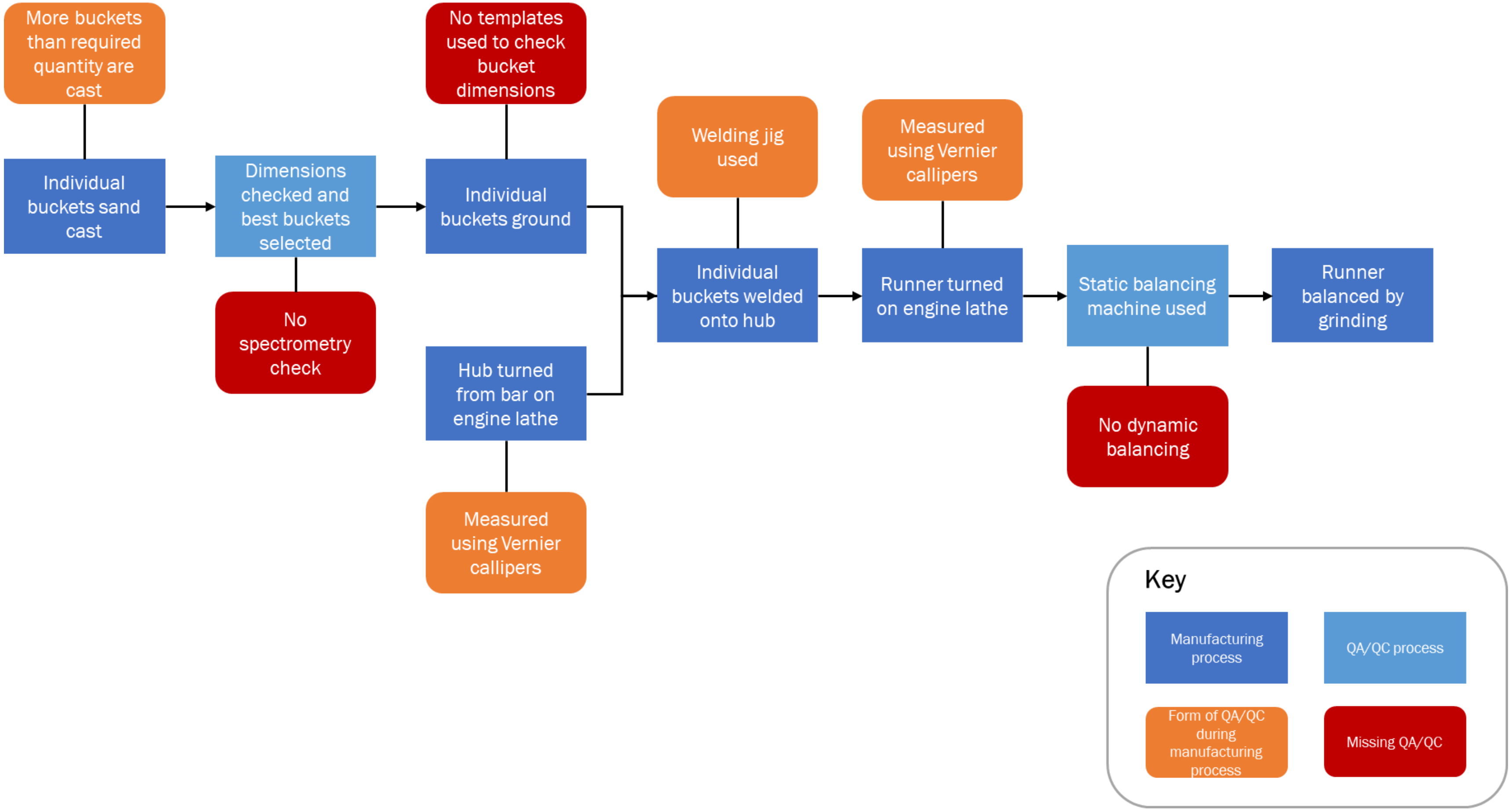


Figure 6.7 - Pelton turbine runner manufacturing process.

The Crossflow runner consists of end plates mounted perpendicular to the axis of rotation with blades located between them. Figure 6.8 shows a machining process on a Crossflow runner. The blades are either cut from pipe, or cut from sheet metal, bent, and checked against a jig. Material choices for the blades were usually mild steel but sometimes stainless steel. For mild steel (MS), specifications included MS ST40, MS ST88. In stainless steel (SS), specifications included SS204, SS304, SS308, SS316, and SS37. The decision to use stainless steel was usually based on the rated power of the site; 2 manufacturers mentioned a ‘rule of thumb’, using SS blades for turbines with a rated power of 100 kW. Figure 6.9 shows the typical manufacturing process for a Crossflow turbine runner. At several early stages in the process, manufacturers described using different methods; this is shown in the diagram using a larger blue box divided by a dashed line.

Figure 6.8 - Machining operation on a Crossflow turbine runner. Photo credit, Topaz Maitland.

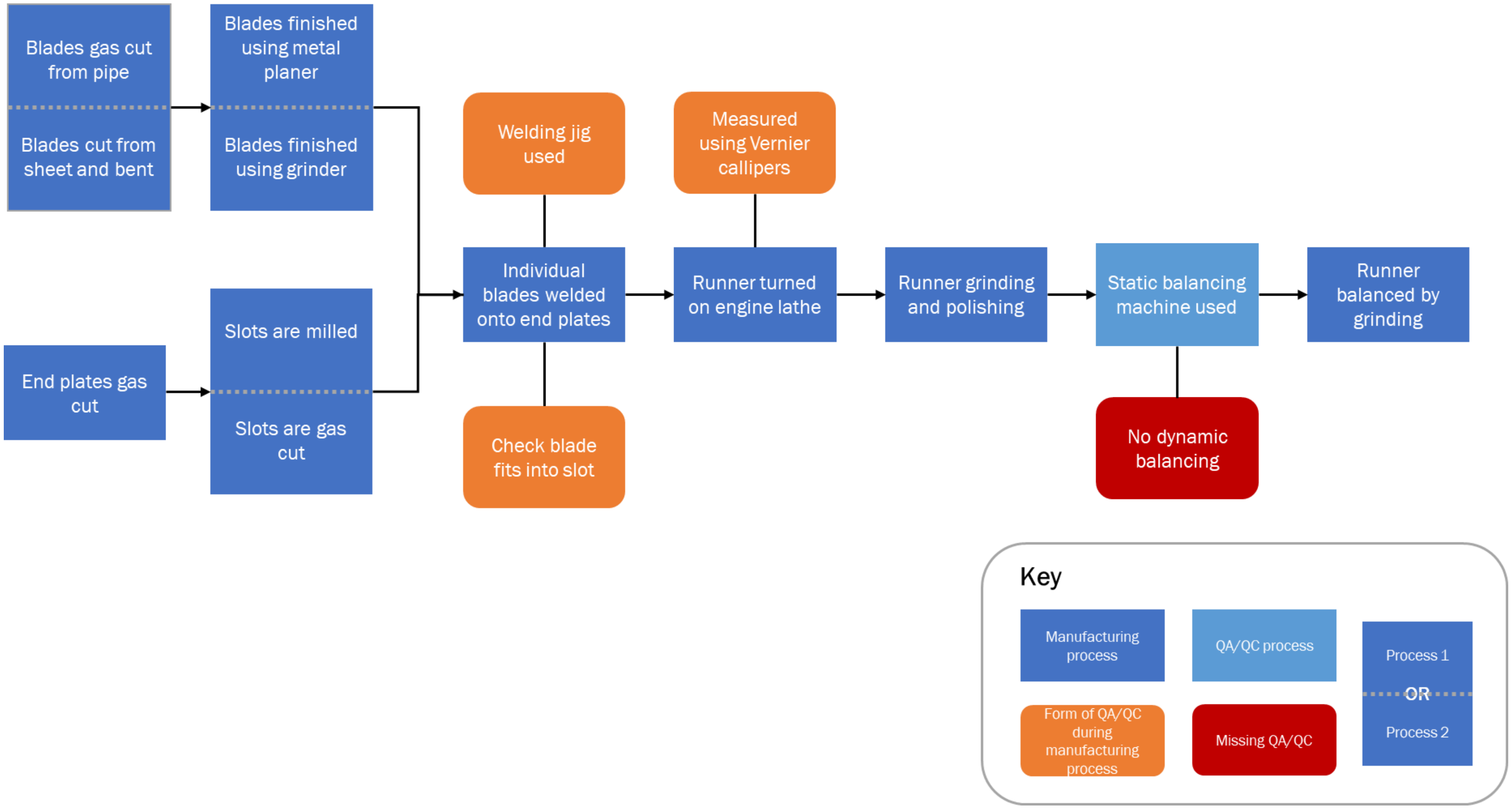


Figure 6.9 - Crossflow turbine runner manufacturing process.

The other components considered in the survey were the main shaft, Pelton spear valve and spear, and generators. The primary material used for shafts was EN8 steel, mentioned by 5 of the 8 manufacturers. Mild steel and stainless steel were also mentioned but specifications were not provided. According to the interviewees, the material choice depended on both the dimensions and the rated power of the site. For the end section of the Pelton nozzle (which is prone to erosion where the high velocity jet is released), 7 of the 8 manufactured used stainless steel (SS 304 was mentioned most often). The remaining body of the nozzle is manufactured from mild steel with a spigot and bolted connection between these 2 components. Similarly, for the Pelton spear, stainless steel was the typical material (SS 308 mentioned most) for the spear tip with the shaft of the spear made from mild steel. All of the interviewees asked about generators usually purchased them from KEL, a manufacturer based in Kerala, India but with a supplier in Kathmandu. Generators are purchased as one-offs with the quoted lead time ranging from 1 month to 6 months. Several manufacturers observed that the lead times had recently increased. Three manufacturers mentioned other suppliers that they had used in the past: Kirloskar and Crompton, both Indian companies.

Processes

For welding, all manufacturers used exclusively manual metal arc welding. One manufacturer had MIG welding equipment but did not use it as they did not currently employ any staff qualified to do so. The fabricators had been trained internally, or externally at the Butwal Technical Institute. For cutting sheet metal, oxy-acetylene gas cutting was used. For straight lines, PUG machines – moving gas cutters that follow a rail - are used. Jigs were used for circular profiles. Four manufacturers owned shearing machines for cutting thinner sheet metal. No manufacturers used any form of CNC cutting or machining. Of the 8 companies, 7 owned at least one bending machine. Six of these were 1.2m in width and the other was 1.8m. One manufacturer (without a bending machine) said that they visited another manufacturer to use their bending equipment when they needed to. All of the manufacturers had spray painting facilities and used this in combination with brush painting. Two of the manufacturers said that they only spray painted the turbine. No manufacturers used sandblasting before painting despite one of the companies owning sandblasting equipment. Several manufacturers mentioned using metal oxide paint for surfaces in contact with water.

The available processes determine the achievable tolerances. The manufacturers were asked what the general tolerance that they aimed for was and what the best total tolerance that could be achieved in their workshop. Figure 6.10 shows the responses from manufacturers. All manufacturers used dial test indicator gauges, micrometres, Vernier callipers and balancing equipment.

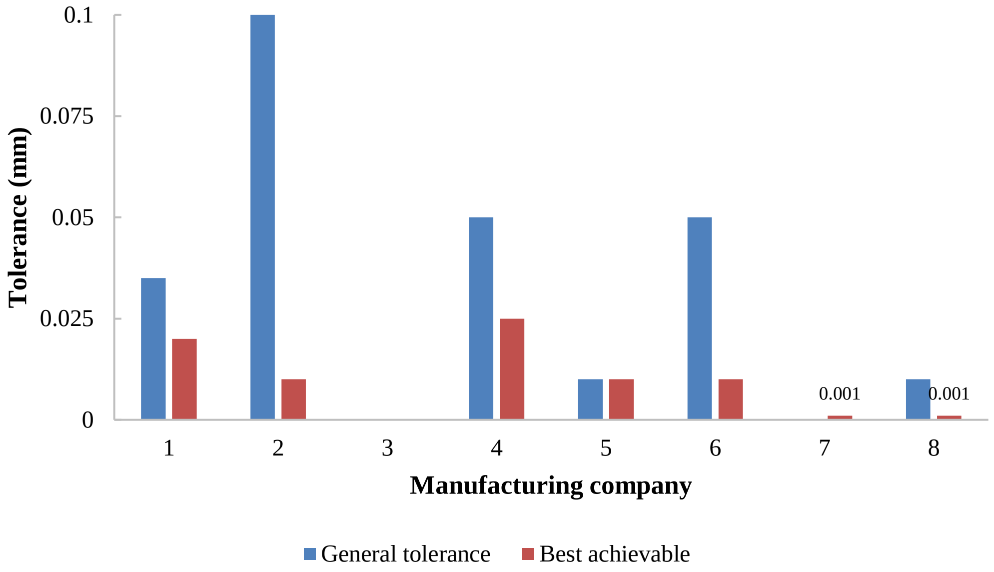


Figure 6.10 – Total tolerances achievable according to interviewees.

Results from casting companies

The casting companies visited were different in scale and size. The interviewee at the first company (referred to as Company A) claimed that the company was the first casting foundry in Nepal, founded in 1976. They have made over 4,000 Pelton buckets and specialise in making smokeless stoves. The maximum weight that can be cast is 80kg. In contrast, Company B can cast up to 10 tonnes. Company B has been operational since 1994, claim to be the largest foundry in Nepal, and their focus is on larger casting pieces, yet they maintain an interest in micro-hydropower to satisfy their clients.

At both companies, Pelton buckets are sand cast. Whilst investment casting is available, the typical production runs for Pelton buckets (20 to 25 pieces) make it too expensive. In the sand-casting process, the interviewees responded differently regarding the availability of silica sand. The interviewee for Company A said that it was not available in the local market, instead they mix green sand with bentonite, coal dust, and silica. Company B used silica sand or green sand depending on the product. For both, available materials included varieties of iron, bronze, aluminium, and mild steel. The material for casting is purchased from scrap. At Company A, material is selected based on observation and experience, whilst at Company B, for certain products, the composition of the scrap is tested.

Upon receipt of a bucket model, the interviewee at Company A explained that material is added to the model using an epoxy filler to account for shrinkage. The quantity added is based on tabular data and experience. At Company B, sand is removed from the mould to account for the shrinkage. After casting, both companies occasionally test pieces by cutting them open. For Company B, if casting higher volume orders, some cast pieces will undergo destructive testing. Neither of the interviewed companies had ever cast a Pelton turbine runner as a single piece.

6.3.3 Discussion

From the survey, it has been found that most of the manufacturers provide similar services with a similar range of equipment and processes available. The core service for all the companies is the design and manufacture of the hydro-mechanical components. Responses indicated that electrical design & manufacture and civil design are also commonly offered services. All of the interviewed companies had extensive experience with most having completed over 100 projects. Most companies had the same processes available and their approach for key components was largely similar. Figure 6.7 shows the processes used by all manufacturers for producing Pelton turbine runners. For the Crossflow runner process, shown in Figure 6.9, there was some variation. All of the observed manufacturing equipment depended on manual control, with some equipment at least 30 years old. Figure 6.11 and Figure 6.12 show manufacturing equipment typical of workshops in Nepal.

Figure 6.11 – An engine lathe in a workshop. Photo credit: author.

Figure 6.12 - Roller bending machine in a workshop. Photo credit: Topaz Maitland.

In terms of knowledge and availability of materials, there was more diversity between the companies. Some of the interviewees used and were aware of a range of materials. Their responses demonstrated that for some components, specific material choices were made. However, these choices tended to be motivated by the overall rated power of the plant rather than by individual calculations. For the various manufacturing processes, there was some evidence of quality assurance and quality control. Manufacturers used metrology equipment which was capable of measuring to their target tolerance ranges. Turbine runners were statically balanced by all manufacturers, but none performed dynamic balancing as they did not own the required equipment. Casting of Pelton buckets took place at external companies. Surplus components were cast so that the best castings could be chosen, however, this choice was based on measurement and observation. Whilst non-destructive testing and spectrometry are available in Nepal, the low production runs in micro-hydropower means they are not used.

The surveyed companies are well known micro-hydropower manufacturers with a good reputation in Nepal. In the earlier interviews (presented in Chapter 4), it was explained that there are newer companies that are submitting very low quotations in the bidding process. Evidence suggests that this is at the expense of quality. As such, it should be considered that the experience, capability, and approach of the surveyed manufacturers represents a high standard for Nepal. Other manufacturers may be less knowledgeable and less diligent in their approach.

6.4 Cost in the context of Nepal

To introduce the Turgo turbine to Nepal, it is important to understand whether its cost of production will be competitive with established technologies. To establish this information, it was necessary to understand the cost baseline for the other available technologies, the Pelton and Crossflow turbines. As established in Chapter 5, the subsidy driven project process demands low cost. Evaluation of typical costs is useful in understanding the micro-hydropower market internally and comparing the cost of the equipment externally with other countries.

6.4.1 Methodology

When quoting for projects, micro-hydropower manufacturers provide a detailed breakdown for costs for the various sub-systems that are specified within the bidding documentation [202, 215, 216]. Using these documents as a template, a survey was developed which considered the cost of the turbine, power transmission system, penstock, butterfly valve, generator, control & protection system, and installation & commissioning. The cost of micro-hydropower civil structures varies considerably depending on the topography of the site and geographical features. Furthermore, the community contribution of collection of materials and labour is difficult to quantify. Consequently, the cost of civil structures was not considered.

The survey was conducted with 7 manufacturing companies, all with at least 10 years of experience, who also responded to the manufacturing survey. Using information from the field study and [79], typical ranges in head and flow rate were identified for Pelton and Crossflow turbine sites in Nepal. Using these ranges, a selection of randomly generated site details was produced. Appendix C.3 lists the 100 random sites generated. From this list, each manufacturing company was provided with the characteristics (head and flow rate) for 4 sites, chosen using a random number generator. For simplicity, it was assumed that for all the random sites, the penstock angle was fixed at 45°. Table 6.2 lists the questions in the cost survey for each random site.

Table 6.2 - 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).

6.4.2 Results

The results were useful for evaluating the total costs and how this varied in response to the rated power of the site. Figure 6.13 shows the overall cost per kilowatt 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 good correlation ($R^2 = 0.753$). The shape of the line indicates that as the rated power increases, the rate of change of the cost decreases. Figure 6.14 compares the cost per kilowatt for the Crossflow and Pelton sites. Across the power range, the results suggest that Crossflow sites tend to be lower cost. For both types, the results follow a similar trend. There is less variation amongst the Crossflow ($R^2 = 0.850$) than the Pelton sites ($R^2 = 0.823$).

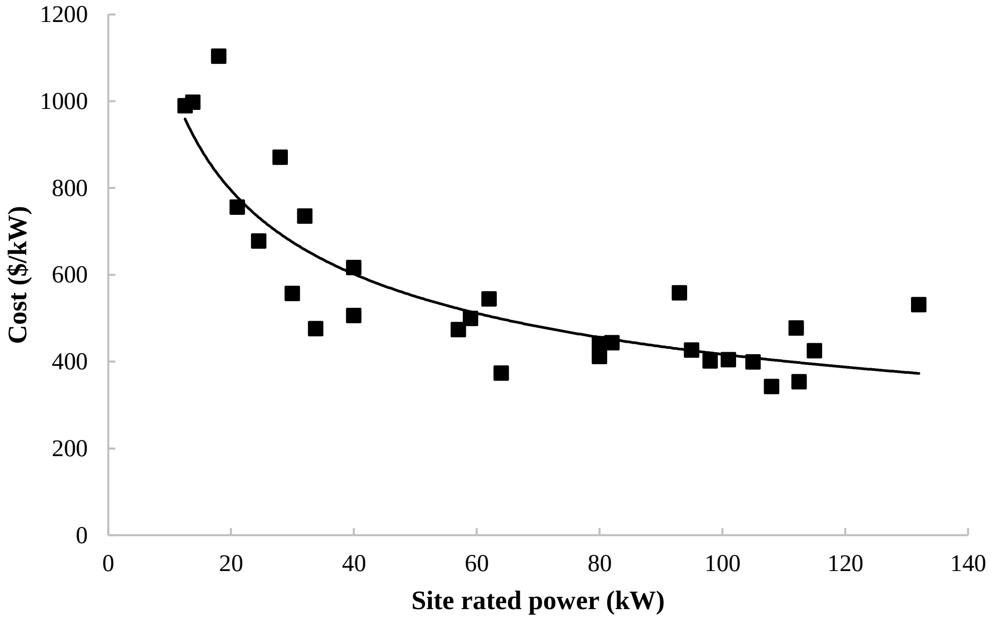


Figure 6.13 - Cost per kilowatt for all sites.

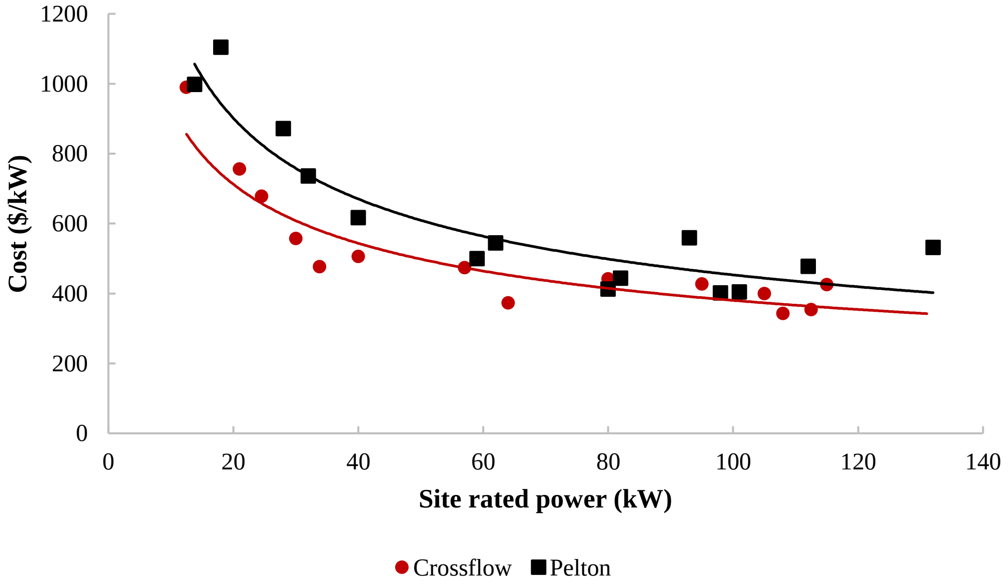


Figure 6.14 - Cost per kilowatt comparing Crossflow and Pelton sites.

In Figure 6.15 and Figure 6.16, the cost of each site is broken down by item for each turbine type. In these figures, it can be seen that the generator, penstock, and turbine sub-systems tend to 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, often contributing at least 25% of the total cost alone.

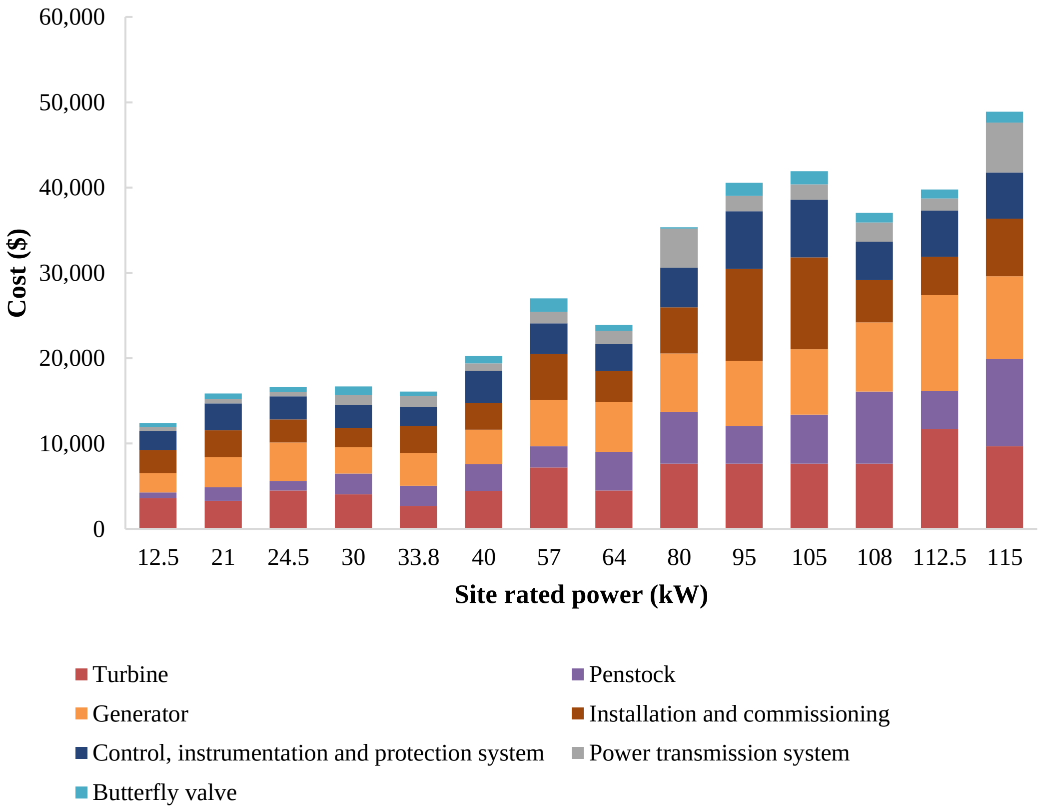


Figure 6.15 - Cumulative cost by sub-system of Crossflow sites.

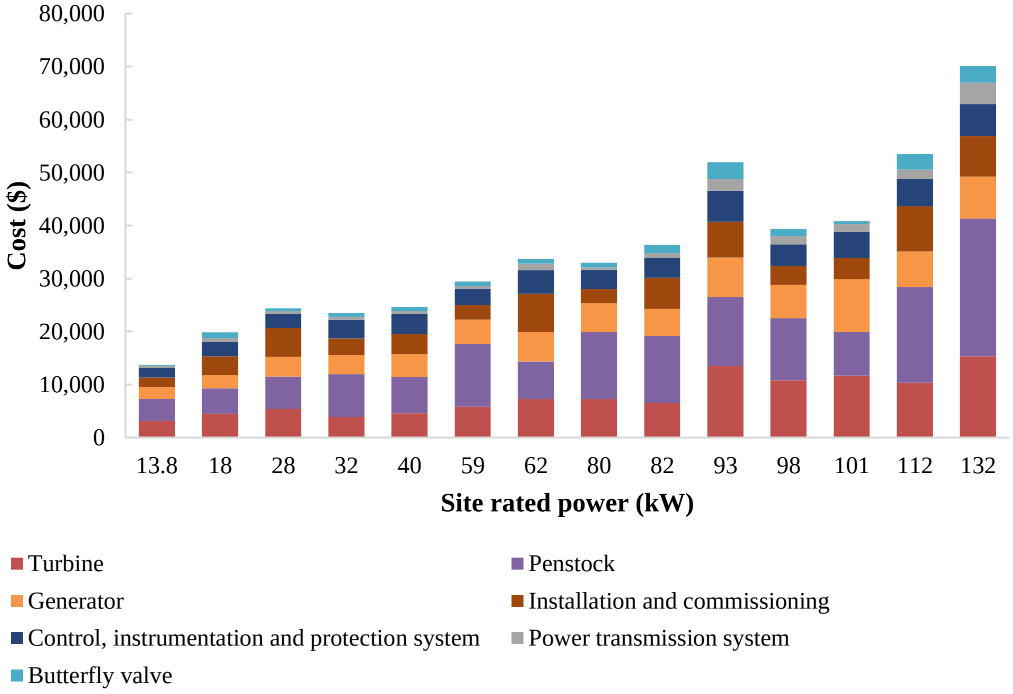


Figure 6.16 - Cumulative cost by sub-system of Pelton sites.

In Figure 6.17 and Figure 6.18, the average proportional cost for these sub-systems is shown for Crossflow and Pelton sites respectively. The proportional cost of the penstock for Crossflow sites is much lower at 14%, compared to 30% for Pelton sites. The cost of the turbine is consistent across both types, contributing 22%. Most other components have a greater proportional cost amongst Crossflow sites to account for the lower cost of the penstock pipe.

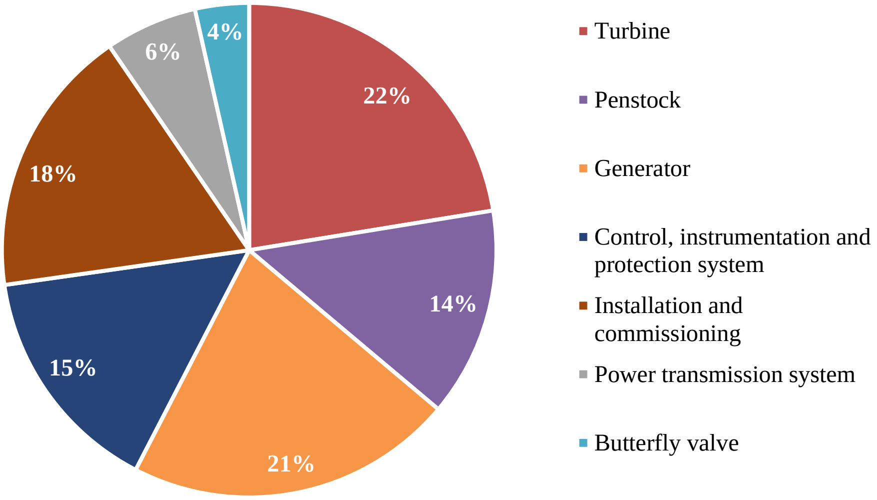


Figure 6.17 - Average proportional cost by sub-system for Crossflow sites.

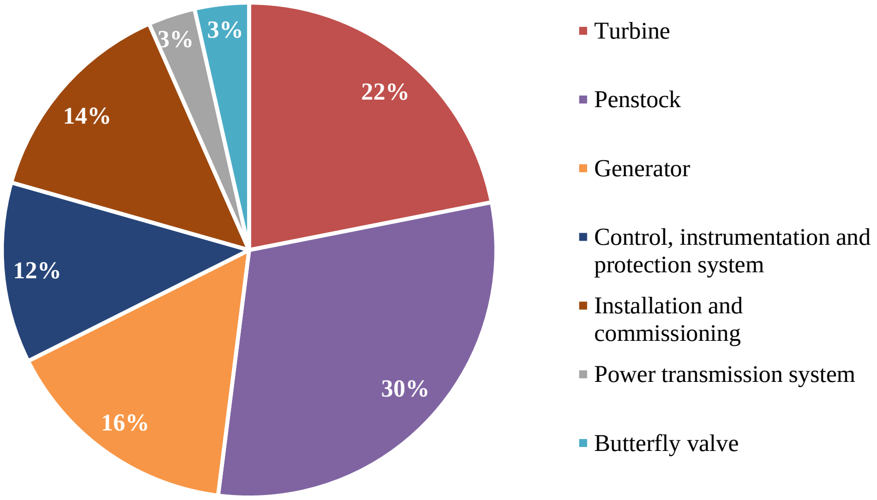


Figure 6.18 - Average proportional cost by sub-system for Pelton sites.

In Figure 6.19, Figure 6.20 and Figure 6.21, the cost per kilowatt is plotted against the site rated power for the three most costly sub-systems: penstock, turbine, and generator respectively. In Figure 6.19, it can be seen that for Crossflow sites, there is almost no variation in the cost per kilowatt as the rated power of the site 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 Figure 6.20, 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, Figure 6.21 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.

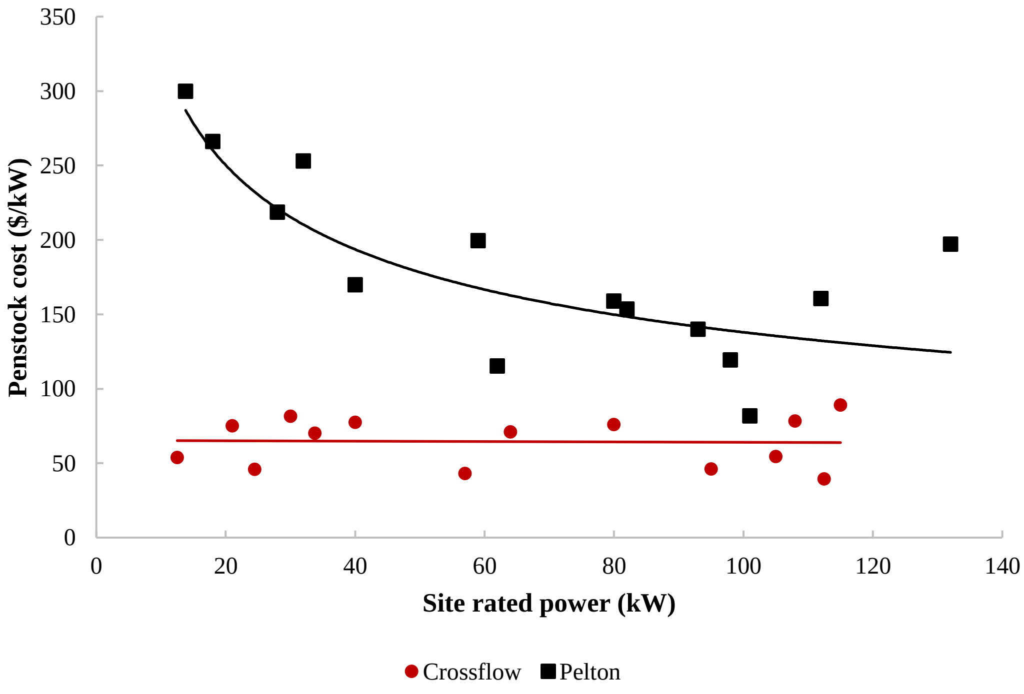


Figure 6.19 - Cost per kilowatt for penstock.

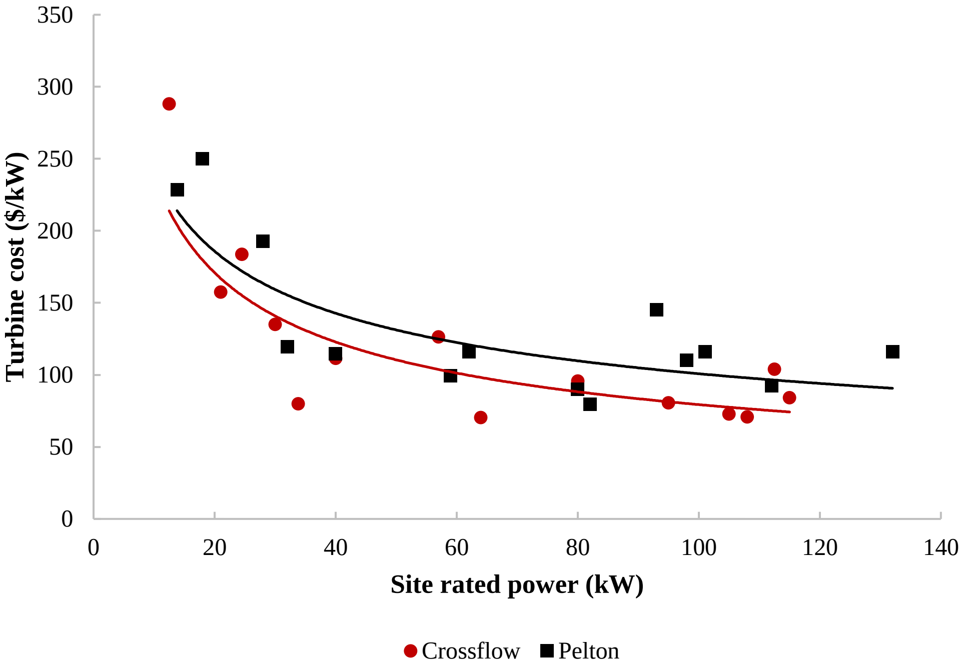


Figure 6.20 - Cost per kilowatt for the turbine.

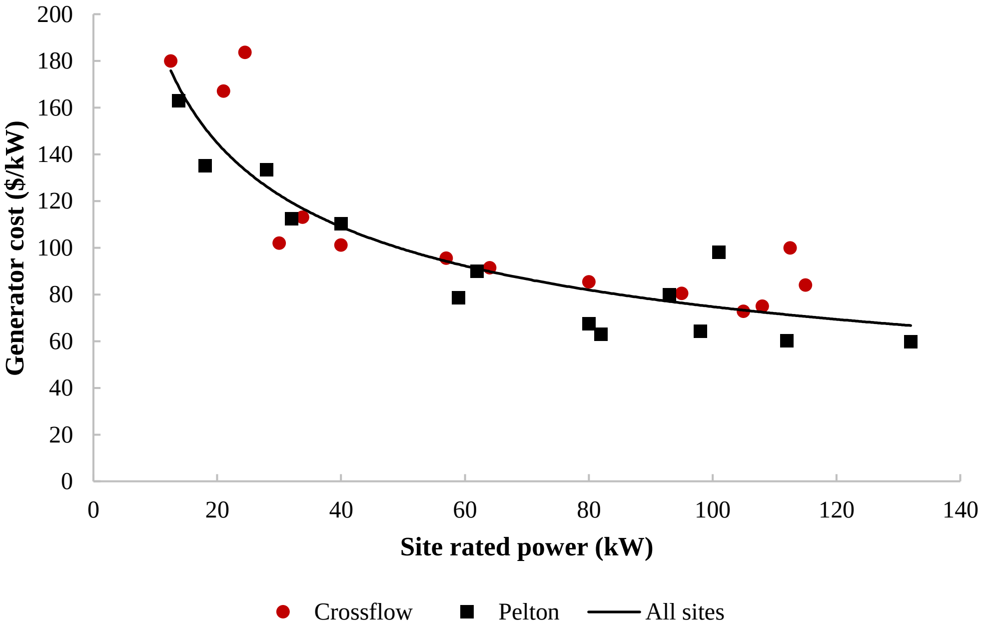


Figure 6.21 - Cost per kilowatt for the generator.

6.4.3 Discussion

The results of the cost survey are useful in giving an indication of the approximate cost per kilowatt for many of the components of an MHP. From Figure 6.13, it appears that in the typical range of micro-hydropower sites in Nepal, between 10 and 100 kW, the cost per kilowatt decreases from approximately 1,000 $/kW to 400 $/kW. By looking at the separate turbine types in Figure 6.14, one can see that Pelton sites are typically more costly than Crossflow sites. However, the gap between the two types narrows as the rated power of the site increases.

Figure 6.15 and Figure 6.16 show that the penstock, turbine, and generator are the most expensive sub-systems. Of all the components, the penstock and turbine both require skilled workmanship to produce new products from stock material. Figure 6.17 and Figure 6.18 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 Figure 6.20. Similarly, for the cost per kilowatt of the generator, Figure 6.21 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 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 Figure 6.19, there is only a small variation in the cost of the penstock for Crossflow turbines, with all sites lying in the range of 40 to 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: 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, Figure 6.22 plots the volume of material per metre against the cost per metre. In this figure, as expected, there is a strong positive linear correlation 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.

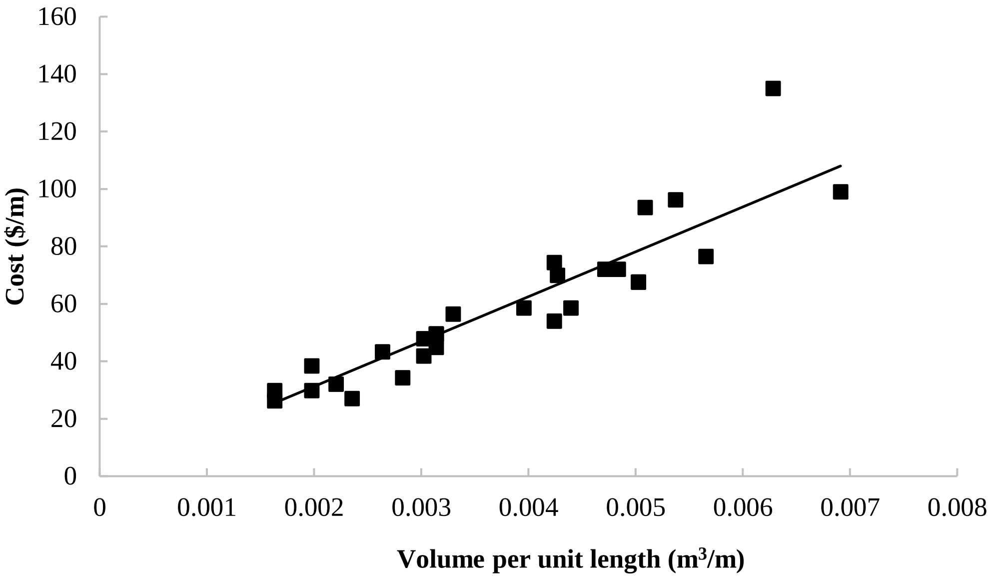


Figure 6.22 – Cost per metre of penstock material against volume per metre.

Previous work exploring prediction of the cost of hydropower sites has found that using site rated power and the head alone can give a reasonable estimate of the total project cost. Various literature [217-219] has suggested that a reasonable estimate of the cost can be determined from the power (P) and head (H) of the site:

$$COST = aP^{b}H^{c} \tag{6.1}$$

where a, b and c are coefficients to be determined.

In [219] , Ogayar and Vidal demonstrate using a regression method to derive an expression for the prediction of the total cost of hydropower equipment based on multiple site characteristics. In their method, the cost does not include civil structures and is only for hydro-mechanical equipment. A similar approach was performed with the collected data. Using a multiple variable regression, the following 2 expressions can be derived for the Crossflow and Pelton sites respectively.

$$COST_{Crossflow} = 4001P^{0.798}H^{-0.358} \quad (\$) \tag{6.2}$$

$$COST_{Pelton} = 3582P^{0.573}H^{-0.021} \quad (\$) \tag{6.3}$$

In predicting the cost, the expression for Crossflow sites has $R^2 = 0.973$ and the error between the actual and predicted costs range from -14.0% to 17.2%. For Pelton sites, the expression has $R^2 = 0.910$ and the errors range from -24.7% to 20.3%.

By using the same approach with 7 manufacturers, the information collected provides a reliable estimate of the cost of micro-hydropower in Nepal. It demonstrates that there is a large variation in the cost of a project depending on the rated power. The largest contributors to the cost are the turbine, generator, and penstock. Between Pelton and Crossflow turbines, the longer penstocks of Pelton projects have the potential to add significant costs. For the Turgo turbine, one can expect that most costs will be similar to the other turbine types. It is expected that the penstock lengths will lie between the lengths typical at Crossflow and Pelton sites. Consequently, it is likely that cost of the Turgo may lie between the other two turbine types. Using existing methods, expressions for predicting the cost of Pelton and Crossflow installations have also been calculated from the data. They provide a reasonably accurate indication of the combined cost of the turbine, power transmission system, penstock, butterfly valve, generator, control & protection system, and installation & commissioning. This is useful for comparing the cost of sites in Nepal with those located elsewhere in the world. However, it must be considered that the expressions do not account for the cost of civil structures.

6.5 Design progression of the Turgo blade

The survey of manufacturing companies had demonstrated the availability of materials and processes in Nepal. The results of the survey were used to inform design choices. Selection of a manufacturing method was useful in defining restrictions for the design optimisation process; there would be no advantage in optimising a design that could not be manufactured. The optimisation process was driven by geometrical changes to the Turgo blade.

Typically, for impulse type turbines, there are 3 main approaches to the production of blades (for Turgo turbines) and buckets (for Pelton turbines): machining, casting, and sheet metal pressing [54]. Machining of impulse turbine runners - either as a composite of individual blades or as a single component - depends on access to 5-axis CNC machining. The surveys indicated that this was not an option for manufacturing companies in Nepal. Whilst rare for Pelton turbines, simplified Turgo turbines (e.g. the Imported runner) use sheet metal pressed blades [72]. The surveyed manufacturing companies had access to hydraulic presses and casting, which could be used to create a form, making this a viable option. Alternatively, casting of runners has been used for Pelton and Turgo runners for over 100 years [54]. Using investment casting complete runners can be cast, and elsewhere (including Nepal) sand casting of individual buckets is common. The results of the survey demonstrated that in the manufacture of Pelton buckets, sand casting is used with the material choice varying between cast steel, bronze, brass, and cast iron. When comparing the two available processes, casting was selected as the superior process for the production of the Turgo blades. It was expected that producing a die and developing a jig for the pressing process could be time consuming, with significant potential for inaccurate results. Furthermore, the repeatability and existing local familiarity of casting were deemed advantageous.

With the selection of casting, the following restrictions were applied to the process of design improvement:

- **Minimum thickness of 2.5 mm should be maintained.** In available literature [220] and responses from a casting company, 3 mm is cited as a minimum section thickness for sand casting. Through a subsequent grinding process this could be reduced to 2.5 mm.
- **No undercuts or re-entrant features.** The blade surface should not include features that are susceptible to poor flow of the casting material.
- **The front face of the blade should be maintained as a plain surface.** A flat front surface increases simplicity of the subsequent machining processes.

6.5.1 CFD modelling

This section describes the process used to computationally improve the efficiency of the Turgo turbine runner. For accurate CFD simulation, a CAD model of the Imported runner was required. The supplier of the turbine had provided replica blades produced using the same process as those on the runner. Using a Faro Edge Laser Scanner, a blade was scanned in 3D and the resulting point cloud was loaded into a CAD package and used to create a solid body. Figure 6.23 shows the meshed body generated from the point cloud.

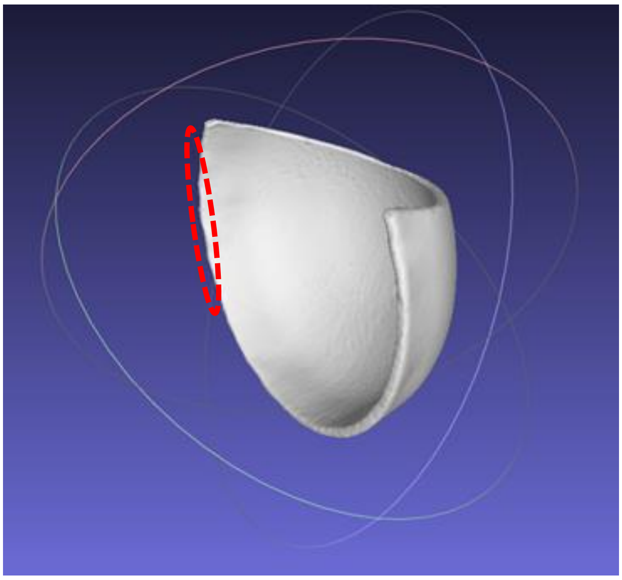


Figure 6.23 – Mesh generated from the point cloud. The red dashed area indicates the location of crinkling along the blade's edge.

In Figure 6.23, it can be seen that the resolution of the scan was sufficient to capture the physical surface defects; crinkling can be seen along the edge of the blade (indicated by the red dashed area). Measurements were taken from the Imported turbine and used to develop a CAD model of the complete system.

In CFD modelling, assumptions are commonly used to reduce the complexity of the model, and therefore the computational power required. For an impulse turbine, it can be assumed that the torque acting on an individual blade passage (as it passes through the jet) is periodic and can be used to calculate the total torque acting on the runner. As such, it is possible to reduce the number of blades within a CFD model. Previously for Turgo turbines, it has been shown that a 2-blade model provides similar results to a 7-blade model and is able to accurately predict runner performance [154]. In the 2-blade model, the sum of the torque acting on the front and back face of a single blade passage is measured so that the total torque can be determined. Using the summed torques (for all the blades) and the rotational speed, the mechanical power at the shaft can be calculated. The jet velocity and the known mass flow rate into the system is used to calculate the power of the jet. From these values, the hydraulic efficiency can be calculated.

For this study, a two-part CFD model (generated from the CAD model of the turbine) was developed, consisting of a rotating and stationary domain. The rotating domain comprised

2 blades (providing a periodic blade passage), the hub and outer ring. The stationary domain represents the flow of water from the nozzle and its interaction with air. For simplicity, the profile of the jet is assumed to be uniform. To simulate the interaction of the jet with the blades, the flow of water passes from the stationary domain to the rotating domain, whilst it is rotated through a prescribed angle. Figure 6.24 shows the separately meshed domains. For the stationary domain, a high-density mesh was used at the air – water interface. For the rotating domain, small inflation layers and mesh sizing were specified along the blade edges where torque is measured. A mesh convergence study compared the hydraulic efficiency when using a fine mesh (with 1.4 million cells) and a coarse mesh (0.6 million cells). The difference in efficiency was only 0.07% and for the purpose of this study, the coarse mesh was deemed acceptable.

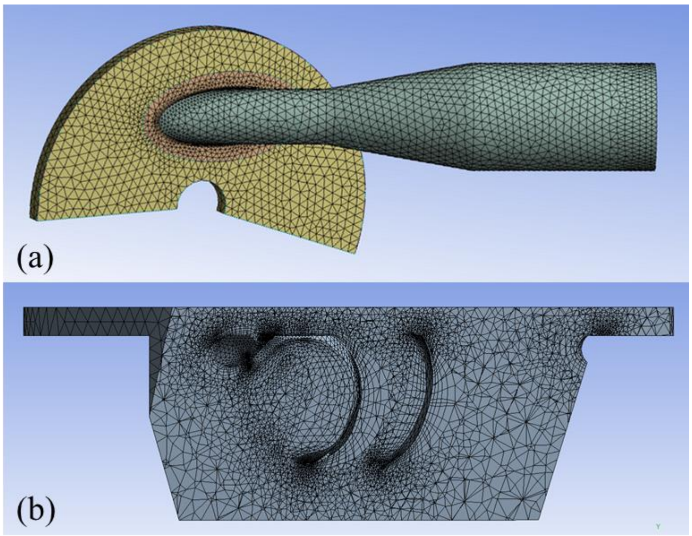


Figure 6.24 - (a) Stationary domain and (b) rotating domain. Image credit, Shaun Benzon.

The simulation used a homogeneous multiphase model which is simulated using the commercial Eulerian solver ANSYS CFX. This is commonly used in CFD modelling of impulse turbines and has been shown to closely match with experimental testing results [55]. For turbulence modelling, the two equation k-ω SST turbulence model was chosen, as it is often used for impulse turbines [55]. Despite a lower accuracy than a direct turbulence model, it is considered appropriate for the nature of this study. Within the model, the effect of gravity and surface tension were assumed to be negligible. For Turgo turbines, where flow enters and leaves on opposite sides of the runner, the interaction between the runner and casing is minimal (particularly when compared to Pelton turbines) and was not modelled in this case [68].

Several features of the Imported turbine provided the input parameters for the CFD simulation. Firstly, the upstream valve could be used to vary the flow rate but its proximity to the nozzle would result in highly turbulent flow leaving the nozzle orifice. Instead, it was assumed that the turbine would always be operated with the valve fully open. Secondly, the position, i.e., pitch circle diameter, and geometry of the nozzle, i.e. its angle and internal diameter, would remain fixed. Thirdly, as the turbine's control system is designed to maintain the speed at the generator's rated speed, the target rotational speed for the turbine was 1500 rpm. The initial study evaluated the best efficiency point (BEP) for the Imported turbine. The first step was to evaluate the speed ratio: the ratio of jet velocity to peripheral velocity of the runner, at the point where the jet impacts.

For best efficiency in impulse turbines, the impact of the jet upon the runner should transfer all of the kinetic energy from the fluid [221]. To consider an ideal case where (as with Pelton turbines) the incoming jet is colinear to the bucket's direction of motion, the maximum change in momentum (and greatest force generated) is achieved if the fluid is deflected through 180°, and leaves the bucket with an absolute velocity of zero [221]. This occurs when the velocity of the fluid, relative to the bucket, is equal to the velocity of the bucket, but in the opposite direction. For this ideal case (where there assumed to be no losses through the bucket), a momentum balance demonstrates that the ideal jet velocity is twice the velocity of the bucket. As a result, the theoretical optimum speed ratio is 0.5. In reality, for Pelton turbines, the design must ensure that the fluid leaving a bucket is directed away from the following one. Therefore, the fluid must be directed at an angle less than 180°. In addition, losses through the bucket reduce the relative velocity of the fluid on exit. As a result, peak efficiency for Pelton turbines tends to occur at a speed ratio of approximately 0.46 [54, 221] . For Turgo turbines, the inclined jet influences the theoretical speed ratio; the optimum occurs when the component of jet velocity colinear to the blade's direction of motion is twice the peripheral velocity of the blade. It is under these circumstances that the absolute velocity at the exit of the blade is zero. Thus, the following equations (using nomenclature from Figure 2.7) can be used to determine the theoretical optimum speed ratio:

$$v_I \cos \alpha_I = 2u \tag{6.4}$$

$$\frac{u}{v_I} = 0.5\cos\alpha_I \qquad (6.5)$$

For a Turgo turbine with a jet inlet angle of 22.5°, this leads to a theoretical speed ratio of 0.46. As with the Pelton turbine, losses through the blade reduce the velocity at exit, decreasing the practical value for speed ratio.

Using the assumed rotational speed of 1500 rpm, the simulations modelled varying speed ratios by changing the jet velocity, which is dependent on head. Figure 6.25 shows the efficiency plotted against the speed ratio.

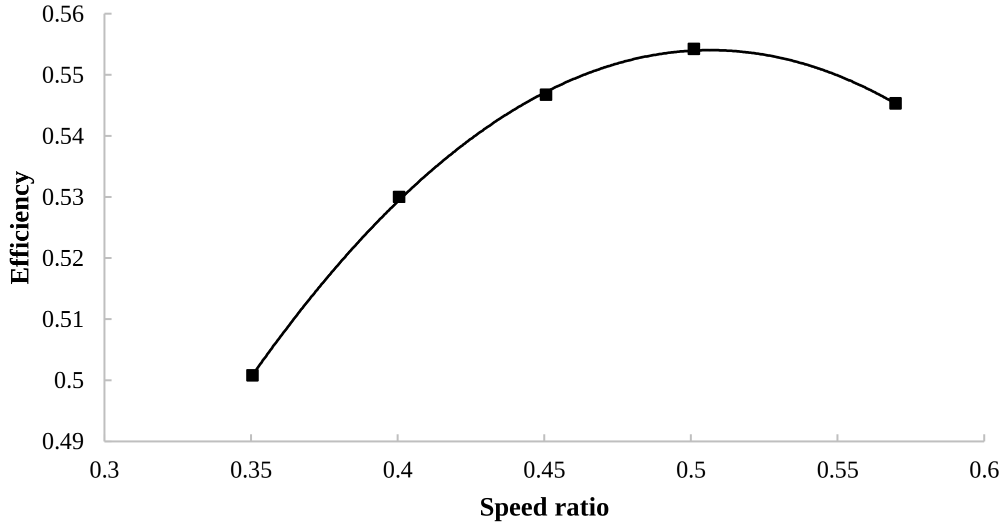


Figure 6.25 – Efficiency calculated from CFD against speed ratio for the Imported turbine.

The highest value of efficiency occurred with a speed ratio of 0.5 which corresponds to a head of 14.7 m at the nozzle outlet, and flow rate of 12.6 L/s. This is outside of the manufacturer’s recommended operating range of 18 to 25 m head and flow rate of 8 to 10 L/s. It can be seen that the Imported blade design has a flat efficiency curve in response to varying speed ratio. Consequently, this means that either side of the optimum speed ratio, a change in operational head of ± 3m results only in a decrease in efficiency of less than 1%. By fixing the head to 14.7 m, it was possible to investigate the sensitivity of the efficiency to changes in the rotational speed. Figure 6.26 plots efficiency against rotational speed for a fixed head of 14.7 m. It can be seen that the BEP lies between 1500 and 1550rpm and that the turbine maintains a similar efficiency either side of this point. For simplicity, it was assumed that the BEP was nominally 1500rpm.

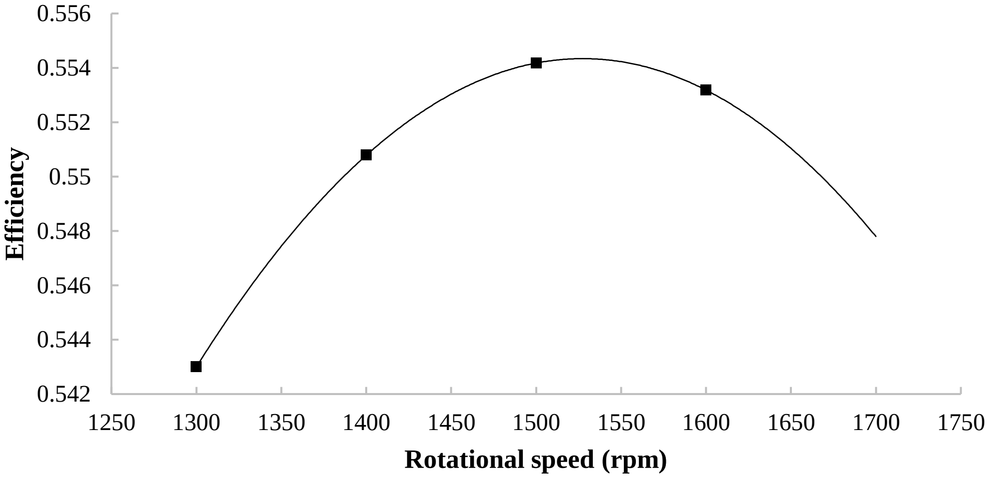


Figure 6.26 – Efficiency calculated from CFD against rotational speed for the Imported turbine when operating at a head of 14.7 m.

Thus far, each simulation had maintained the original offset between the nozzle and runner that had been measured from the Imported turbine. By varying the offset, it was possible to optimise the position of the runner in relation to the jet. From the starting position, the runner was moved vertically upwards closer to the jet. Figure 6.27 shows the simulation for the original runner position and the optimum position, an offset of 7.5 mm, at the same rotated angle. It can be seen that the original runner position results in a significant amount of flow passing over the outer ring. For the optimum position, the centre of the jet engages lower in the blade resulting in a more evenly distributed fluid film over the exit surface of the blade. It was found that beyond an offset of 7.5 mm, continuing to change the offset did not continue to increase the efficiency. Eventually, the position resulted in splitting of the jet which negatively affects the performance.

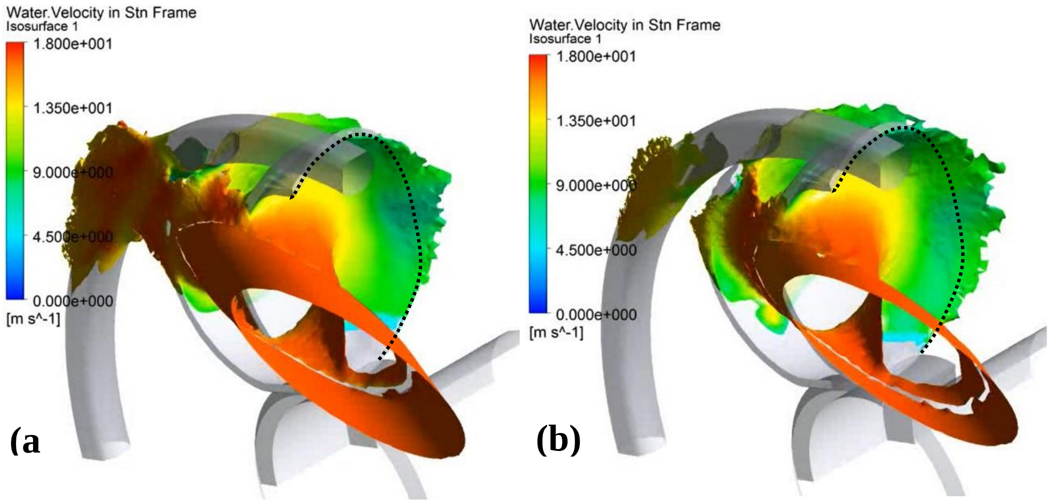


Figure 6.27 - Comparison of fluid velocity for the blade in its (a) original and (b) optimum position. Image credit, Shaun Benzon.

From the initial study, the BEP was identified as occurring at a head of 14.7 m with a corresponding flow rate of 12.6 L/s. In addition, through variation of the offset between nozzle and runner it was possible to identify a position for the Imported runner (offset from the original by 7.5 mm) that resulted in an increase in the efficiency from 56% to 69%.

6.5.2 Results and parameterised design progression

To optimise the blade, a controllable parametric model was developed. Using the CAD model of the Imported blade, a section cut was taken through the central plane of the blade and at 45° to this plane. Parametric sketches were developed to match the key dimensions of these section cuts. Similarly, a projected cut of the front face of the scanned blade was taken and a parametric sketch developed to match it. A loft between these three sketches created half of the blade which was mirrored. By varying the parameters, the controllable model could be adapted and compared to the scanned model. The parametric values which resulted in the most similarity between the models were found by minimising the volumetric difference between the two. Using the BEP settings, the parametric blade was tested, achieving an efficiency of 69.5%. The increase in efficiency of 0.5% is assumed to have resulted from the removal of defects from the surface profile. From this baseline, a design of experiments (DOE) study was used to understand the influence of geometry upon efficiency. Within the parametric model, it was decided to vary the height, depth, and width of the blade. Figure 6.28 shows these dimensions in relation to half of the blade and identifies the leading and trailing edges, where the flow enters and leaves the blade respectively. The complete blade is formed by mirroring along the central plane. These changes were easy to implement in the parametric model, maintained the simple profile of the blade and enable assessment of how the geometry affects efficiency. A 2^3 factorial design was used where high and low levels (±7% from their original values) were used for the height, width and depth dimensions, resulting in a total of 8 combinations. As these dimensions were changed, the exit angles from the blade also changed. The baseline parametric model had a trailing edge exit angle of 29° in the central plane, Figure 6.29 shows a section view of the blade through its central plane and identifies several key features. A variation of ± 7% was selected as this resulted in a maximum change in this exit angle of 20°. It was expected that changes greater than this would not result in an improvement in performance: excessively shallow angles result in interference of the exit flow with the outside of the oncoming blades, and too steep angles result in a higher momentum of the exit flow reducing the efficiency.

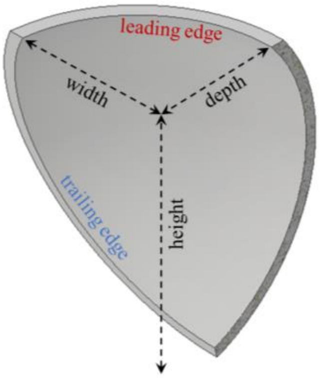


Figure 6.28 - Half of a blade with the height, width and depth dimensions shown. Image credit, author.

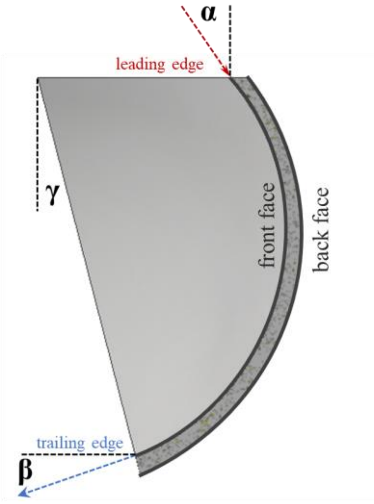


Figure 6.29 – Section view of the blade in the central plane which identifies α – entry angle, β – exit angle and γ – blade cut back angle.

Figure 6.30 shows the main effects plots from the DOE study. It shows that the main effects of height and depth were strongest; all cases of minimising height and maximising depth led to an improvement in efficiency. These main effects were generally more significant than the interactions between factors. Figure 6.31 plots the most significant interaction which was between the height and depth. This significance of this interaction was due to the low efficiencies achieved when height and depth were at +7% values. For all other cases, changes of width were not highly significant.

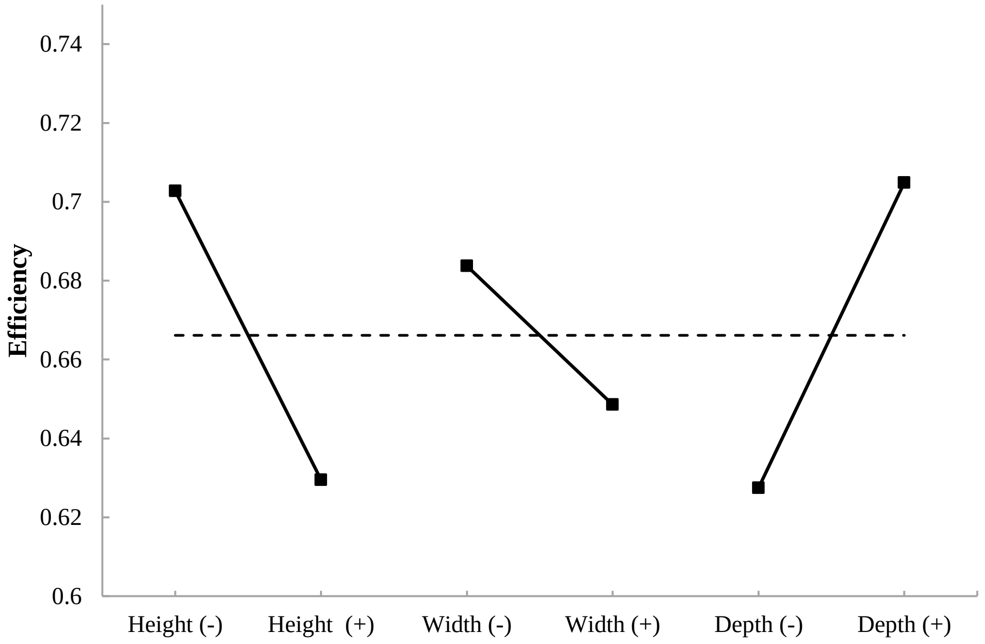


Figure 6.30 - Main effects of height, width and depth in the DOE study.

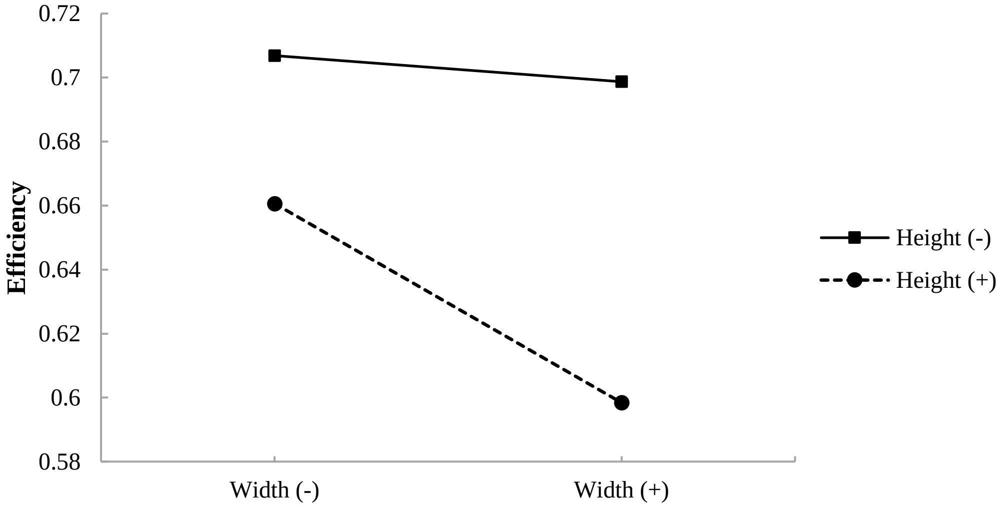


Figure 6.31 - Interaction between width and height in the DOE study.

Consequently, the next set of runs explored the change in efficiency with the width held at its original value. This allowed the blade to maintain a similar form whilst continuing to decrease the height and increase the depth. Figure 6.32 shows the results of simultaneously changing height and depth whilst maintaining the original blade width. The height (negatively) and depth (positively) were both changed by 7% and 12%. Using these results, as shown in Figure 6.32, a quadratic relationship was assumed suggesting a best efficiency could be achieved with a ± 10.9% change to depth and height respectively. When simulated in CFD this geometry, henceforth known as the DOE blade (where relative to the original, height = 0.891, width = 1 and depth = 1.109), resulted in an efficiency of 77.3%. Further runs with changes of 12% and 15% were used to test the validity of the relationship. With these additional points, the DOE blade result lies above the expected peak of the trendline.

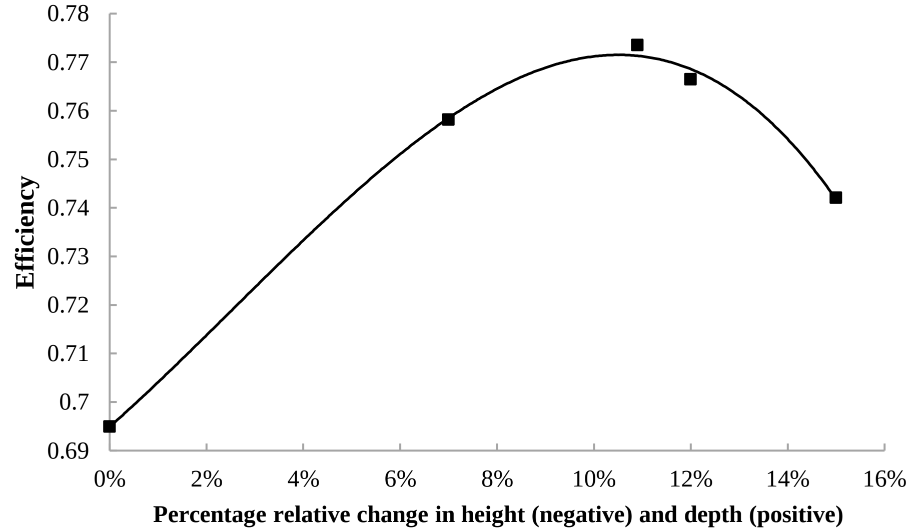


Figure 6.32 - Efficiency against simultaneous variation in height and depth.

An alternative approach explored fitting a response surface to the results. The changes to geometry had not been governed by a response surface methodology (RSM), therefore this process was used only as an indication of possible alternative geometry changes. Figure 6.33 compares the fit between the actual results and those predicted by the response surface. It can be seen that the response surface has a better fit amongst lower efficiency runs with more variation at higher efficiencies. An optimisation solver was used to indicate values of height, width and depth which would achieve the highest efficiency. The optimised geometry, henceforth known as the RSM blade, using height = 1.01, width = 0.93 and depth = 1.18 resulted in an efficiency of 77.8%.

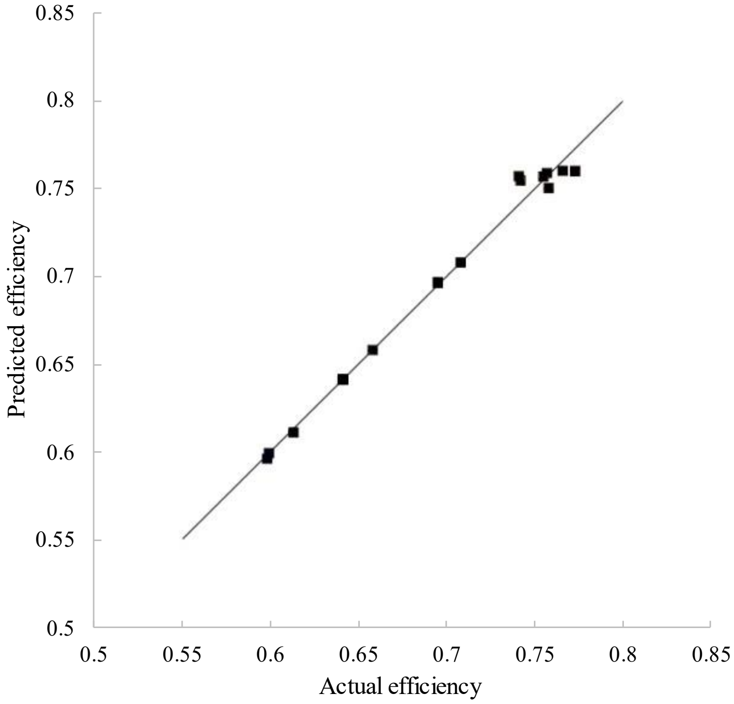


Figure 6.33 - Normal probability plot from the response surface. Figure credit, Shaun Benzon.

To this point, the two highest efficiencies had been achieved with significantly different geometries. When comparing the two, it was decided to explore further adaptation to the RSM blade using a larger section of consistent profile in the central plane of the blade, whilst maintaining the same overall width. It was assumed that for the blade with highest efficiency, a larger section with optimum entry (**α**) and exit (**β**) angles (see Figure 6.29) could lead to an improvement in efficiency. However, the change to geometry resulted in an increased amount of interference between the exiting flow and the trailing blade, also known as choking. Figure 6.34 shows fluid leaving a blade and interfering with the back face of the trailing blade. The solid black line identifies the back face of the trailing blade whilst the dashed red line indicates the area of interference. As a result of this interference, both geometries with an additional central section resulted in lower efficiencies.

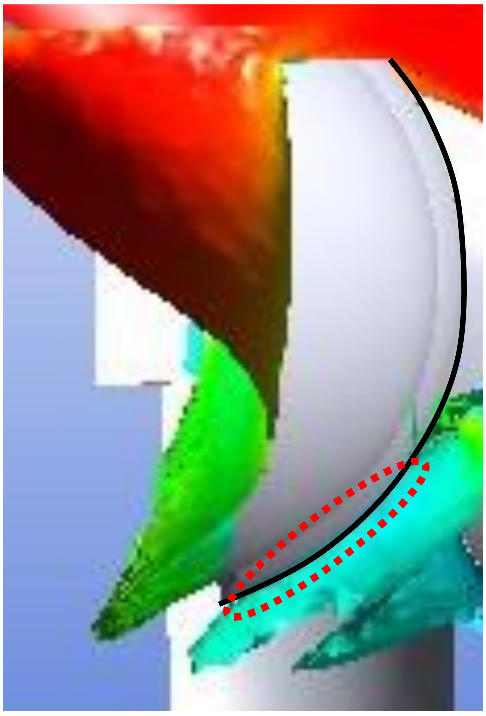


Figure 6.34 – An example of interference between exiting flow and the trailing blade. Image credit, Shaun Benzon.

A subsequent consideration was the blade cut back angle (γ in Figure 6.29) on the front face of the blade which had remained unchanged from the original design. Figure 6.35 shows the torque measured on the front and back faces, and the resultant torque for the RSM blade. It can be seen that there is a significant negative torque that occurs on the back face of the blade at a rotated angle of approximately 70°. This negative torque indicates the point at which choking occurs. It was assumed that an alteration in the cut back angle could be used to minimise this interference by directing the exiting flow away from the following blade. However, it was found that both geometries with increased γ led to no improvement in efficiency. Whilst the change in γ was successful in reducing the negative torque, it increased the exit angles and changed the exit velocities which resulted in less torque generation from the front face of the blade. These simulations demonstrated that despite the presence of the choking effect, the RSM blade was able to generate sufficient positive torque to overcome the negative torque that was generated.

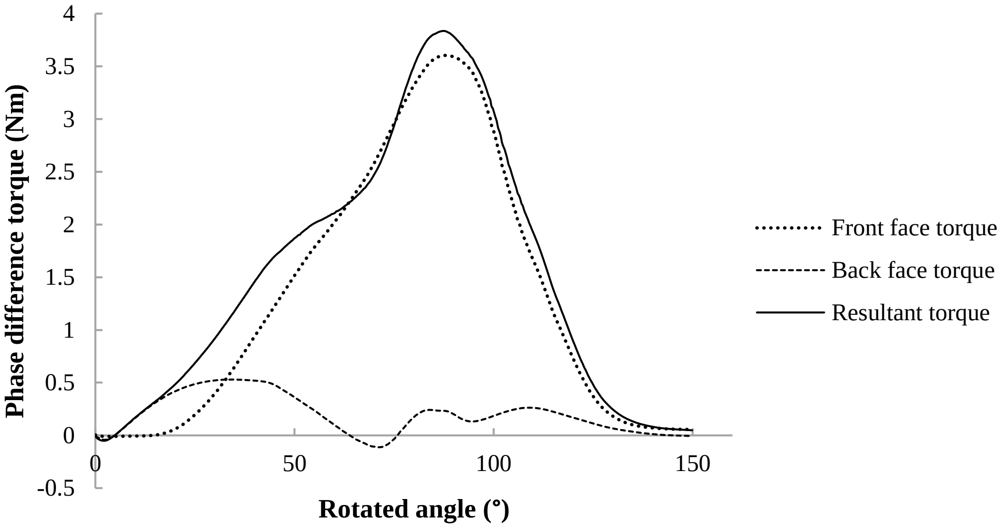


Figure 6.35 – Measured torques on the response surface (RSM) blade.

Another adaptation to the geometry was proposed to minimise this choking effect. By implementing a V-shape into the central plane of the blade it was thought that the increased free space between blades would reduce the flow interference. In addition, as the V-shape introduced a shorter flow passage through the blade, it was assumed that the effect of skin friction on the fluid's velocity could be reduced. A new parametric geometry was developed with a controllable angle (or V-shape profile) in the central plane of the blade. The simulations explored the RSM blade geometry with 35°, 55° and 75° angles. Whilst these resulted in similar efficiencies to the original RSM blade, the effect of the V-shape did not lead to an improvement in efficiency. The V-shape simulations did increase the peak front face torque due to a higher exit velocity. However, this defined spike resulted in a lower efficiency than the more consistent torque profile of the RSM blade.

An alternative approach was to consider the exit angles in multiple positions along the blade. The parametric model was adapted so that the exit angles could be adjusted along a number of vertical planes within the blade. Figure 6.36 shows the distribution of these planes over half of the blade. On each of these planes, a controllable sketch (similar to Figure 6.29) allowed the exit angles to be varied. At first, it was decided to attempt to direct more flow to the centre of the blade. By implementing shallower exit angles in the planes closest to the outside edge, it was hoped more flow would exit through the effective 'dip' at the centre of the blade. In this simulation, similar to the V-blade designs, there was an increase in the front face torque, however, concurrently the back face torque decreased (to a larger negative value) due to more interference with the trailing blade.

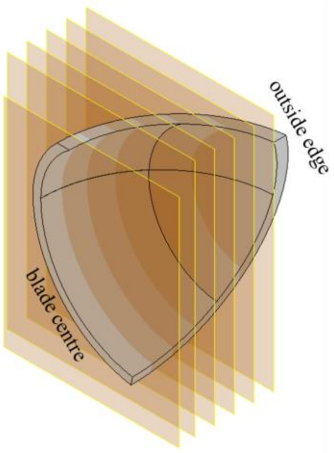


Figure 6.36 - Distribution of interstitial planes through half of the blade.

In order to investigate the trade-off that occurs between exit angles that focus flow towards the centre of the blade, and those that tend to result in a more even flow film leaving the blade, two blades were generated with inverted distributions of angles going from the centre to the outside edge. A blade had angles that increased from the centre to the outside whilst the other had angles that decreased from the centre. The distribution of angles was identified from an earlier simulation where there had been low interference, known henceforth as the LI blade. The angles were mapped on to the interstitial planes whilst the height, width and depth dimensions were derived from the RSM blade. Figure 6.37 plots a comparison of the resultant torques for the variations of the RSM blade. In comparison with the RSM blade (77.8%), the simulation with a shallower angle in the central plane gained a higher efficiency (78.0%), whilst the blade with the greater angle resulted in a lower efficiency (76.4%).

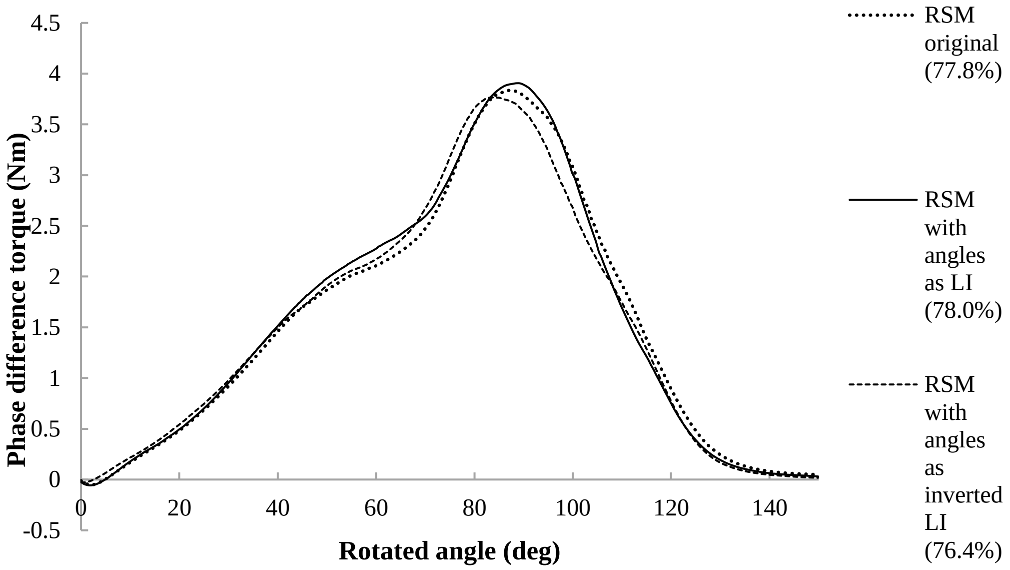


Figure 6.37 - Resultant torque against rotated angle for the response surface blade and two variations.

It was decided to examine using the height, width and depth dimensions of the LI blade. By using this blade, due to the decreased interference there was a greater margin to optimise the exit angles without generating a negative torque. With this greater margin, two simulations were generated that both adopted the method of using the largest exit angle in the central plane to drive more flow towards the blade centre. For one blade, the variation from centre to outside was from 10° to 6° and resulted in an efficiency of 77.9%. The other where angles varied from 12° to 8° achieved 77.8%. For both runs, the change resulted in an increase in both the positive and negative torque. However, the positive torque was sufficient to result in an improvement of efficiency compared to the original LI simulation (75.7%). Figure 6.38 plots a comparison of further adaptations to the LI. To combat the increased negative torque, the values of the higher efficiency run were inverted placing the shallowest angle of 6° at the centre. This increased the back-face torque without substantially affecting the torque on the front face resulting in a higher efficiency of 80.4%. A further change was implemented using a consistent 8° exit angle in all of the interstitial planes. It was expected that this would provide more consistent exit velocities without causing substantial choking. The resulting front face torque profile was almost unchanged, but the improved back face torque resulted in an efficiency of 81.0%. Further runs were conducted using 7° and 9° constant exit angles but neither led to an improvement suggesting an optimum had been found.

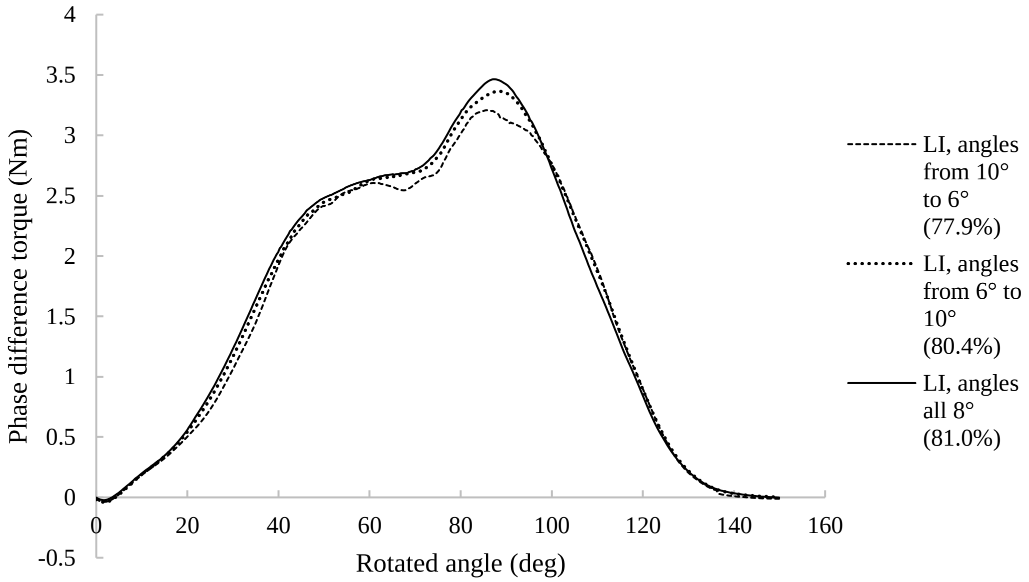


Figure 6.38 - Resultant torque against rotated angle for 3 variations of the 'low interference' blade.

Continuing with the LI blade with a constant 8° exit angle, a further optimisation explored the effect of blade thickness upon performance. The model was adapted so that the thickness of the blade could be controlled in 3 places in the central plane: at the leading edge, trailing edge and in the middle of the blade. From a constant baseline of 2.5 mm, the effect of decreasing thickness at the leading edge whilst increasing at the trailing edge concurrently was explored. Table 6.3 shows the improvements in efficiency achieved as the trailing and leading edge thicknesses were changed.

Table 6.3 - Effect of variation in thickness upon efficiency.

Leading edge thickness (mm)	Trailing edge thickness (mm)	Efficiency
3.0	2.0	81.0%
2.5	2.5	81.6%
2.0	3.0	81.6%
1.5	3.5	81.7%
1.0	4.0	82.5%

Discussion

From the configuration process at the start of the CFD simulation, it was found that when operating with an open nozzle, the BEP lay outside of the recommended ranges for head and flow rate provided by the manufacturer. Whilst variation of the flow could be achieved using the upstream gate valve, it is unlikely that the efficiency could be maintained close to 70% due to the introduction of turbulent flows. In addition, results for the variation of speed ratio suggest that for heads close to the manufacturer's highest rated head (25m), there will be a large difference between the operational speed of the turbine and rated speed of the generator. Through varying the offset, the efficiency was significantly improved from 55.4% to 69.0%. For small-scale hydro-turbines, the difference could be significant in providing extra power to homes or generating additional income. As in [72], it demonstrates how important it is to install machines correctly or provide supporting information that allows users to do so.

Throughout the CFD study, the torque curves and visualisation were used to understand results. From this analysis, changes were implemented into the parametric model which progressively became more complex. As such, the improvements did not require a very large number of simulations. This approach meant a total of 41 simulations were required to improve the efficiency from 69.5 to 82.5%. Figure 6.39 shows the design progression and corresponding efficiency improvement. The central 4 images show the central parametric sketch and half of the blade. Table 6.4 describes the design actions taken during the optimisation process. From the scanned blade, the first model (labelled No. 1) was generated and after adjustment of the jet position achieved an efficiency of 69%. A parametric blade was developed to match the scanned blade and an initial DOE study of 8 runs resulted in an increase of 6.2%. Subsequent adaptions explored more varied geometrical changes leading to the 'DOE blade'. From the results, it was identified that the key trade-off was often between generating positive torque on the front face and minimising the negative torque on the back face; optimum exit angles tended to result in choking and the generation of negative torque. Compared to many Turgo designs, the proportionally large nozzle diameter and mass flow rate meant that each blade 'passed' a large volume of water. As a result, the tendency for interference was high due to thick flow films leaving the trailing edge. The design process eventually identified that consistent exit angles along the trailing edge could lead to the optimum trade-off. The refinement of the parametric model allowed the exit angles to be controlled. Compared to the initial changes to height, width and depth, this development allowed the geometry (and therefore the water flow through the blade) to be incrementally adjusted resulting in the ‘Final’ blade.

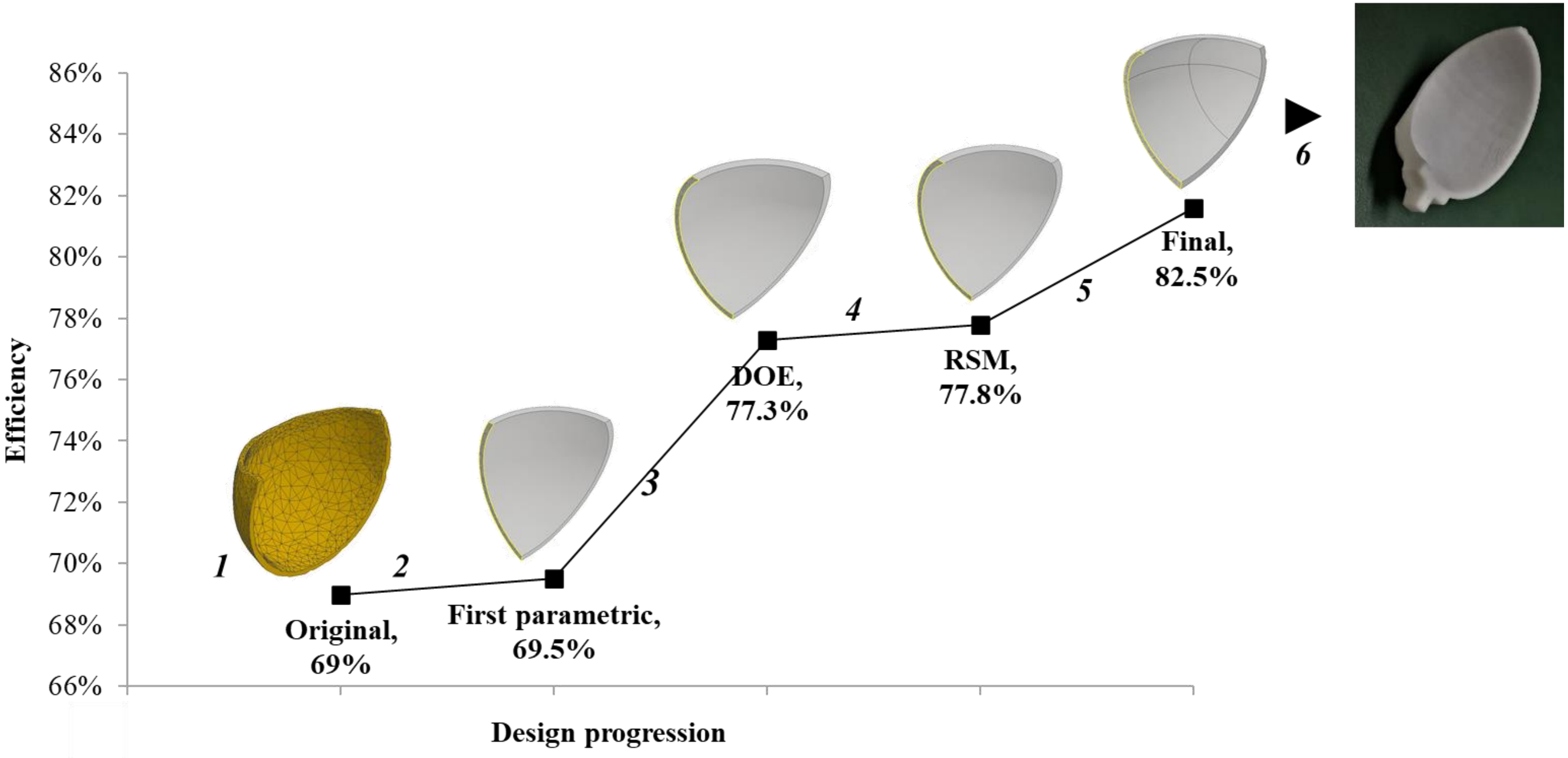


Figure 6.39 – Design progression with corresponding improvements in efficiency.

Table 6.4 - Designs actions during the optimisation process.

CAD model	Design actions	
	1	Imported blade is scanned in 3D and CAD model generated.
Original		
	2	Parameterised model generated to represent scanned blade.
First parametric		
	3	DOE approach used to vary height, width, and depth dimensions.
DOE		
	4	Existing results fitted to response surface to identify optimum.
RSM		
	5	Model adapted to include multiple parametric sketches.
Final		
	6	Final blade is produced using additive manufacturing.

During the development of the parametric model, the changes to geometry have maintained the original simple profile of the blade. It contains no re-entrant features, and both the external faces to the leading and trailing edges remain flat. The greatest complexity was added through the variation in blade thickness. However, as shown in Table 6.3, a consistent blade thickness of 2.5 mm compared to a variable thickness results in a change in efficiency of only 1%.

6.6 Design solutions for local manufacture

Through parametric modelling and CFD simulation, the expected efficiency of the blade was improved. To verify this experimentally, the improved blade profile needed to be produced physically. The design process was conducted in collaboration with NYSE. The survey of manufacturers had indicated the availability of processes, however, the author recognised that the experience of NYSE would be valuable in developing a locally replicable design. Furthermore, it was hoped that a collaborative process would foster design ownership, motivating quality in the prototype and ensuring ongoing interest. As a prototype, both the process (of design & manufacture) and its outputs required evaluation and a close working relationship was permissive to this.

During this research, two new Turgo turbine runners were manufactured. The design and manufacture of the first runner (Mark 1) resulted in significant dimensional deviation from the intended design. The effect of this in experimental testing is addressed in Chapter 7. Within this section, the design choices for both the Mark 1 and Mark 2 runner are explained, and the differences between the two (in terms of design, manufacture, and its outcome) are discussed.

6.6.1 Design choices

The design changes driven by CFD simulation had focused on the surface profiles of the Turgo blade. Figure 6.40 shows a CAD model of the final blade design. Within CFD, the connection to the hub and outer ring were assumed to be insignificant in relation to the efficiency of the runner. As such, the dimensions of hub and outer ring had been maintained from the Imported runner. To manufacture a new complete runner, the function of the other features and their interface with the blades required consideration. With casting chosen as the manufacturing process for producing individual blades, the key design choices were a method of attachment to the hub and outer ring, and the material of the parts. To maximise material thickness in the casting process, the objective was to achieve an approximate thickness of 3 mm and use grinding to decrease the thickness of the leading edge close to 2 mm. As such, it was hoped to gain a small improvement in efficiency as shown in Table 6.3.

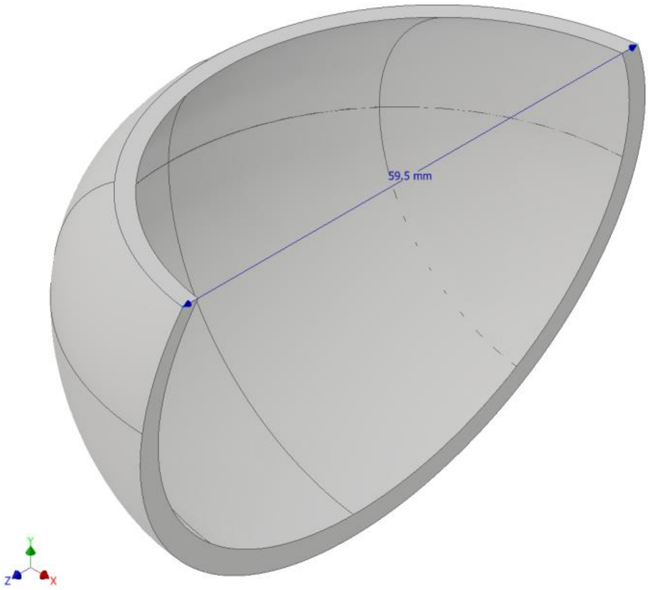


Figure 6.40 - CAD model of the blade design.

Attachment to the hub and outer ring

The blades of a Turgo turbine are typically attached to a hub which transfers torque to the shaft. The method of attachment is often dictated by the manufacturing process used for the blades. Where runners are 5-axis machined in a single piece, the blades and hub are cut from the same billet of metal. Where blades are manufactured individually, they are attached by welding or with fasteners. The blades of the Imported runner are welded onto the hub and the outer ring. Tack welds are used as there is insufficient material on the blade for appropriate welding preparation. In Nepal, Pelton buckets are cast with a stem which is designed for either welding or bolting. After casting, the stem is machined in preparation for either of these methods, whilst the design of the hub must be appropriate for the method of attachment. Whilst not present in all Turgo designs, the outer ring provides additional strength. Typically, where steel is used, it is welded to the outer edge of the blades. In some designs, a tapped hole on the outer edge of each blade is used as a mounting point for the ring.

Material

From the survey of manufacturers, it was established that the materials used for Crossflow and Pelton turbines included mild steel, stainless steel, cast steel, brass, bronze, and cast iron. The material choice can depend on the type of turbine, the rated power, and head. Where sheet metal is used, mild steel and stainless steel are available. For casting, the material choice in Nepal is limited to cast steel, brass, bronze, and cast iron. In the manufacturing survey, all the manufacturers explained that their preferred choice for Pelton buckets was cast steel. Some mentioned that for sites with lower rated power, brass and bronze remained acceptable choices.

Design considerations

To make the design choices, there were number of key considerations. In their evaluation, their influence on both the experimental prototype and the future consequence for manufacture at scale were considered. Table 6.5 lists the design considerations and explains their importance.

Table 6.5 - Design considerations for the development of a prototype.

Consideration	Why is it important?
Available manufacturing processes	The manufacturing method should be appropriate for the typical processes and capability amongst micro-hydropower manufacturers in Nepal.
Available materials	The material choice should be appropriate for those available in Nepal.
Scalability	The design should be scalable for higher rated powers.
Replicability	For the blade surface profile, the design must ensure similarity (within tolerance) between the blades.
Assembly	The hub design should allow the runner to be easily assembled to the runner shaft.
Maintainability	The design should be easy to maintain.
Durability	The design should be resistant to wear, particularly due to abrasion by silt particles.

6.6.2 Mark 1

The available options for casting were steel, bronze, or brass. In collaboration with NYSE it was decided to use cast steel due to its machinability, weldability, higher strength, and durability. Considering the scaling of the Turgo runner to higher rated powers, bronze and brass would not be feasible. Thus, the material choice could be standardised for the micro-hydropower range. In casting the individual blades, the approach used in Pelton turbines could be replicated whereby a stem is used to join each blade profile to the hub. The typical preference for Pelton turbines in Nepal today is to weld the buckets, regardless of the power rating of the runner. Consequently, it was decided to weld the individual blades onto a hub. If successful, the same manufacturing method could be replicated for upscaled designs.

Following guidelines in [54], a stem design was developed that used a ‘tab’ which locates into a recess on the hub. Figure 6.41 shows the blade design and its interface with the hub. The front and rear faces of each stem are designed to be flush to those on its neighbouring blades. The required separation between blades is governed by the dimensions of the stem.

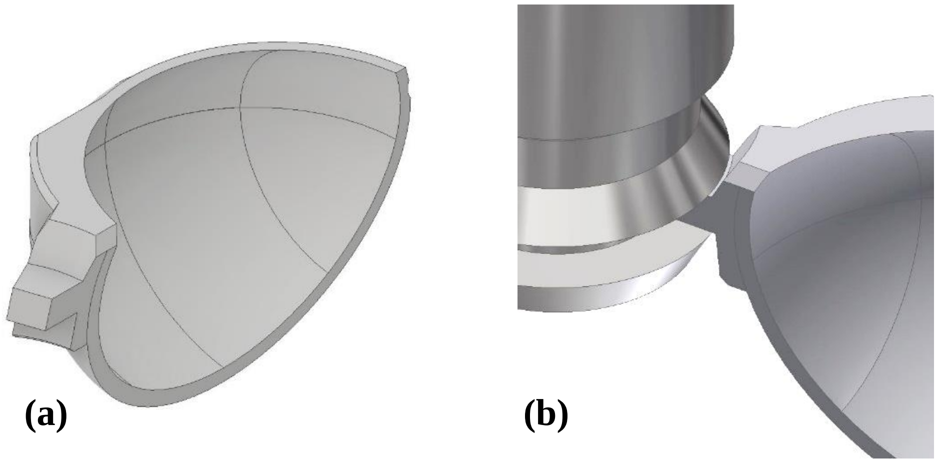


Figure 6.41 - (a) Blade design including stem and (b) interface between stem and hub.

Due to the orientation of the front face of the blades and their concentric arrangement, the front and rear faces of the stem were not parallel. The dimensions of the stem allow a v-notch weld and a single bevel on the bottom face, both with a leg length of 7 mm. Calculations confirmed that this area of weld was acceptable with a factor of safety of 2.5. The weld stress calculations are provided in Appendix D.3. At the outer edge, the ring is welded into place, using a 3 mm v-notch weld.

Manufacture, outcome and lessons learnt

To cast the blades, a 3D CAD model was developed with additional material added onto all faces to account for shrinkage during the casting process. This amount of material was specified by NYSE based on their personal experience. A rapid prototype model was produced using additive manufacturing and sent to the casting company, based in Butwal. After the blade had been cast, it was returned to NYSE. Figure 6.42 shows the cast blade where the thickness of the leading and trailing edges was found to be over 7 mm. Discussion between NYSE and the casting company revealed that upon receipt of the rapid prototype model, additional material had been added to account for shrinkage, using an epoxy filler. As such, the die for the cast blade had included both NYSE’s and the casting company’s allowance for shrinkage. In machining the stem, the technicians had trouble aligning the workpiece. Figure 6.43 shows the arrangement used to machine the stem of the blades. Without parallel or perpendicular faces available for clamping, it was difficult to ensure that from one blade to another, similar alignment was achieved.

Figure 6.42 - Cast steel blade before machining. Photo credit, author.

Figure 6.43 - Machining process on the steel blade. Photo credit, author.

The additional cast thickness required removal to match the ideal surface profile. The amount of material was significant (> 2mm) and it was found that work hardening slowed this process. Furthermore, the extra material made it difficult to verify the dimensional similarity in relation to the intended design. Due to constraints of time and cost, the final runner was not manufactured to design. The deviation from the final design was captured by 3D scanning; it was found that on key surfaces, the typical dimensional difference was 3 mm. Variation in the stem dimensions meant that the blades required some manual positioning in relation to the hub and ring. All of the components were tack welded in place, before a full weld sequence, and post-machining. Figure 6.44 shows the completed Mark 1 Turgo runner.

Figure 6.44 - Mark 1 runner. Photo credit, author.

6.6.3 Mark 2

To address the thickness of the blade, NYSE suggested repeating the casting process using brass. Compared to ferrous alloys, thinner sections can be cast more easily using copper alloys [220]. Whilst brazing was available, NYSE’s preference for brass blades was to use a bolted connection. The internal area available at the hub meant that there was only space for a single bolt. The clamping force is achieved through friction between neighbouring blades. Calculations confirmed that a single bolt would be strong enough for the applied force, see Appendix E.2.

In collaboration with NYSE, a new stem design was developed. In this design, the hub is split into 2 components: a hub and hub cap. These 2 components are fastened on either side of the stem. Figure 6.45 shows the Mark 2 blade design and interface with the hub. A spigot with an interference fit is used to locate the components of the hub with the top and bottom of the blade stem.

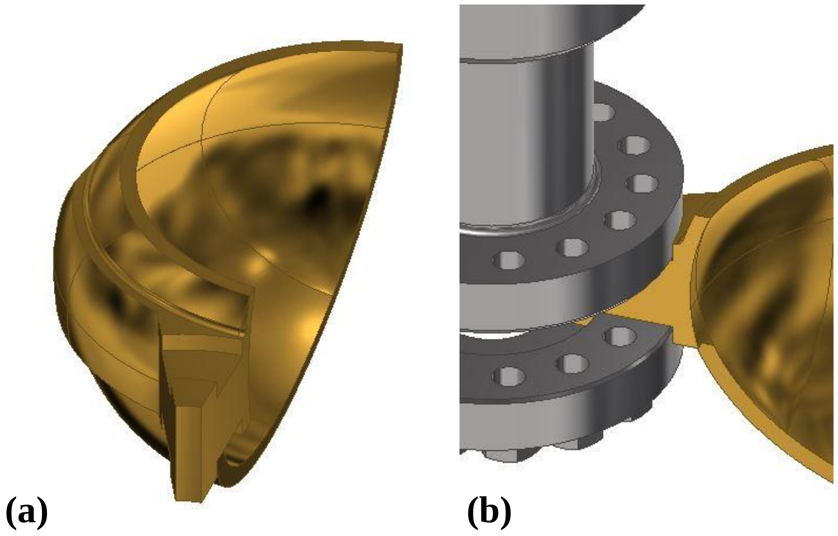


Figure 6.45 - (a) Revised blade design for bolted assembly and (b) interface between bolted blade and hub components.

The stem was also changed so that the front and rear faces are oriented parallel to the rotational axis.

Manufacture, outcome and lessons learnt

An advantage of casting in brass rather than steel was the location of the casting company. For brass, the casting company was located in Kathmandu allowing the mould to be delivered personally and the desired outcome explained in person. The unfinished brass casting achieved a much thinner blade profile.

The alteration to the stem design simplified the machining process. The flat front face made it easier to clamp the workpiece. In the production of the Mark 1, the stems of the blades were milled individually. For the Mark 2, the addition of the bolt hole (which was initially tapped) allowed the blades to be mounted onto a disc and machined on a lathe, similar to the process shown in Figure 6.6. The limited space in the centre of the hub meant that machining operations remained difficult. There was little space between the clamped workpiece and the cutting tool. However, technicians explained that the machining process was easier and quicker than for the Mark 1 stem design. For the grinding process of the Mark 2 blade, 3D printed templates were used. These were inverse projections of the internal surface of the blade. Split into 3 sections (e.g., left, middle, and right), they could be inserted into the blade to check whether the ground surface matched the required profile.

The use of brass presented several challenges which required ongoing observation during experimental and field testing. Brass bar stock is not readily available in the Nepali market [222]. Without brass bar stock, it was also not possible to braze an exterior ring around the blades. Calculations suggested that the bending moment applied on the stem of the bolted blade alone would have a safety of factor of approximately 9, refer to Appendix E.1. These issues were considered acceptable for the prototype yet required observation during experimental testing. Figure 6.46 shows the completed Mark 2 Turgo runner.

Figure 6.46 - Mark 2 runner. Photo credit, author.

6.6.4 Discussion

Whilst two locally appropriate design solutions were developed and manufactured, unexpected challenges arose. Between NYSE and the casting company used for the steel blade, the physical distance and a lack of communication resulted in a significant deviation from the expected casting tolerance. The challenge of manufacturing a new product using a process similar to the manufacture of Pelton buckets was overlooked. For the casting of Pelton buckets, the interaction and approach (despite a physical distance and no transfer of drawings) is sufficiently well practiced that little communication is required to achieve the desired result. For both Turgo prototypes, the small central area between the blades resulted in a small volume of stem material. This was a challenge both in the methods of connection (area of weld and size of bolt) and the machining processes required. As the blade scales up, the increased available volume should improve the ease of manufacture.

A benefit of producing 2 prototypes was that the process has been repeated using different materials and designs. It has been shown that both cast steel and brass, and welding and bolting, are feasible design choices in manufacturing Turgo turbine runners in Nepal. The design changes made in transferring from the steel to the brass design improved the ease of manufacture. In addition, lessons learnt during the production of the first prototype led to the introduction of templates which enabled physical examination of the blade's accuracy. Initially, it was hoped that a single design could be scaled for a range of site characteristics. However, it appears that for small scale runners, casting with brass is more effective due to the potential for thinner section profiles. As the design scales and greater strength is needed, cast steel can be used. The limit for this transition should be identified.

Reflecting further on the connection between the manufactured output and the design process, the consideration of a locally appropriate manufacturing method imposed several restrictions upon the design changes tested in CFD. It was considered that the thickness of the blade could not be less than 2.5 mm and that changes to the geometry should not introduce re-entrant features. However, whilst these considerations focused on the ease with which the blade could be reproduced, they did not consider the supporting manufacturing processes that would be required to do so. The original Imported design had used a cut back angle which was maintained and resulted in alignment problems during vertical milling operations. Removal of this cut back angle and the creation of a parallel surface on the rear face of this blade would have created a pair of parallel surfaces that could be easily clamped. Within the design improvement process, imposing this additional restriction would have improved the ease of manufacture and replicability of the individual blades.

6.7 Summary

In this chapter, specific knowledge regarding the local context has been used to develop design solutions appropriate for local manufacture. A survey was devised to evaluate the experience, capacity, and process availability within the micro-hydropower industry in Nepal. The survey was conducted with representatives of 8 micro-hydropower manufacturing companies. It demonstrated that despite many years of experience, there were opportunities to integrate further quality assurance. The survey led to the identification of the range of processes and materials that could be used in the manufacture of a Turgo turbine runner. Additionally, a cost survey was used to establish baseline costs for Pelton and Crossflow turbines in Nepal. It found that the penstock, turbine, and generator were the most expensive sub-systems. The collected data was used to develop numerical expressions for predicting the cost of Pelton and Crossflow installations (excluding civil structures). In the subsequent development of the Turgo turbine runner, CFD was used as a tool for design improvement. A parametric blade design allowed the effect of dimensional variations upon the efficiency to be explored. Through design changes, the efficiency was improved from 69.0 to 82.5%. Working with a local manufacturing partner, the digital model was developed into a locally appropriate design with additive manufacturing used to produce a mould for casting. Several challenges in the manufacturing process resulted in the production of 2 prototypes. These resulting designs require experimental testing to verify their efficiency and validate CFD results.

In summary:

- The results of the survey of manufacturing and casting companies provided insight into their experience, capability, and the availability of processes.
- The cost survey led to expected costs for Pelton and Crossflow micro-hydropower projects and expressions that could be used for the prediction of any project based on head and flow rate.
- The parametric approach used within CFD resulted in an improvement in efficiency from 69 to 82.5%.
- In collaboration with a Nepali manufacturing company, the digital model was developed into a locally appropriate design.
- A cast steel welded runner and cast bronze bolted runner were manufactured.

Chapter 7

Experimental results: lab and field

7.1 Introduction

Following the development of a Turgo blade and the resulting manufacture of two runners, the performance of these runners (in relation to efficiency and reliability) required evaluation. Experimental testing can be used to compare the efficiencies of similar turbine runners by holding particular variables constant. Field based testing is useful in understanding how a design performs over an extended period of time and when exposed to environmental conditions. In this chapter, the design of an experimental testing rig, the testing method, and the calculation of uncertainty are explained. The results of a first phase - where the Mark 1 and the Imported runner were tested - are presented and discussed, with regression analysis used to determine coefficients that could be used to predict Turgo turbine efficiency. The issues faced in conducting a second phase of testing (with the Mark 2 runner) are discussed. The development of a pilot site and results from testing in the field are also presented.

7.2 Design of experimental testing rig

The purpose of the experimental testing was to compare the efficiency of the three Turgo runners (Imported, Mark 1, and Mark 2) across their expected operating range. Hydraulic efficiency (η) is the ratio of mechanical power (P_m) to available hydraulic power (P_h), and derived in Equation 7.1:

$$\eta = \frac{P_m}{P_h} = \frac{\omega T}{\rho g Q H} = \frac{2\pi N T}{60 \rho g Q H} \tag{7.1}$$

where ω is the rotational speed (rad/s), N is the rotational speed (rpm), T is torque (Nm), ρ is the density of water (kg/m^3), g is acceleration due to gravity (m/s^2), Q is flow rate (m^3/s), and H is head (m). Therefore, to evaluate efficiency it is necessary to measure rotational speed, torque, flow rate, and head.

In experimental testing, it is typical to vary head, flow rate, and rotational speed and evaluate their effect on the efficiency of the turbine. An experimental rig was required that allowed the variation of these parameters. Table 7.1 summarises the primary design requirements of the experimental testing rig.

Table 7.1 - Design requirements of the experimental testing rig

No.	Design requirements
1	Allow runners to be changed.
2	Allow variation in height of runner ± 10 mm from design point.
3	Allow variation in head from 0 to 25 m.
4	Allow variation in flow rate from 0 to 20 L/s.
5	Allow variation in rotational speed from 0 to 2000 rpm.
6	Measure rotational speed, torque, head, and flow rate.
7	Transmit torque with minimal mechanical losses.

The rig needed to facilitate testing of each of the three runners. The ability to change them allowed replication of the testing environment and procedure. As CFD had established the sensitivity of efficiency in relation to runner height (jet aim position), the rig needed to allow variation of this. The rig needed to supply pressure head up to 25m so that the runners could be tested to the upper limit of the operating range suggested by the manufacturer of the Imported runner. In the open nozzle configuration, a head of 25m theoretically required a flow rate of 15.8 L/s. Therefore, 20 L/s was assumed to be a reasonable upper limit for the flow rate requirement. The rated speed of the Imported turbine and its generator was 1500rpm. In CFD simulation, this rotational speed had been maintained as the target and the highest efficiency was achieved at this speed. To capture this peak, the rotational speed required variation on either side. A change of ± 500rpm was considered a reasonable estimate of the required range with further extension possible if required. In CFD simulation, as indicated by Equation 7.1, the calculation of efficiency depended on the measurement of rotational speed, torque, head, and flow rate. The torque generated needed to be transmitted by the shaft and measured. For accurate measurement, the rig needed to transmit torque with minimal losses.

7.2.1 Casing, frame, and bearing housing

To reduce cost, and save time, it was decided to use the existing casing and the induction motor supplied with the Imported turbine set. To measure torque, a transducer can be used 'in-line' between the turbine runner and the generator shaft. Consequently, to address requirements 6 and 7 in Table 7.1, a bearing housing and shaft were designed to interface with a coupling that connected to the torque transducer's shaft. Figure 7.1 shows the arrangement of the bearing housing, shaft, and Imported turbine casing. Based on their ability to deal with a combination of overhung axial (due to the weight of the runner and component of the jet's force) component and radial loads (due to the jet's force), angular contact ball bearings, as opposed to deep groove ball bearings, were used. The bearing housing used a top cap to supply the necessary preload to the bearings. The bearing selection is detailed in Appendix F.2.

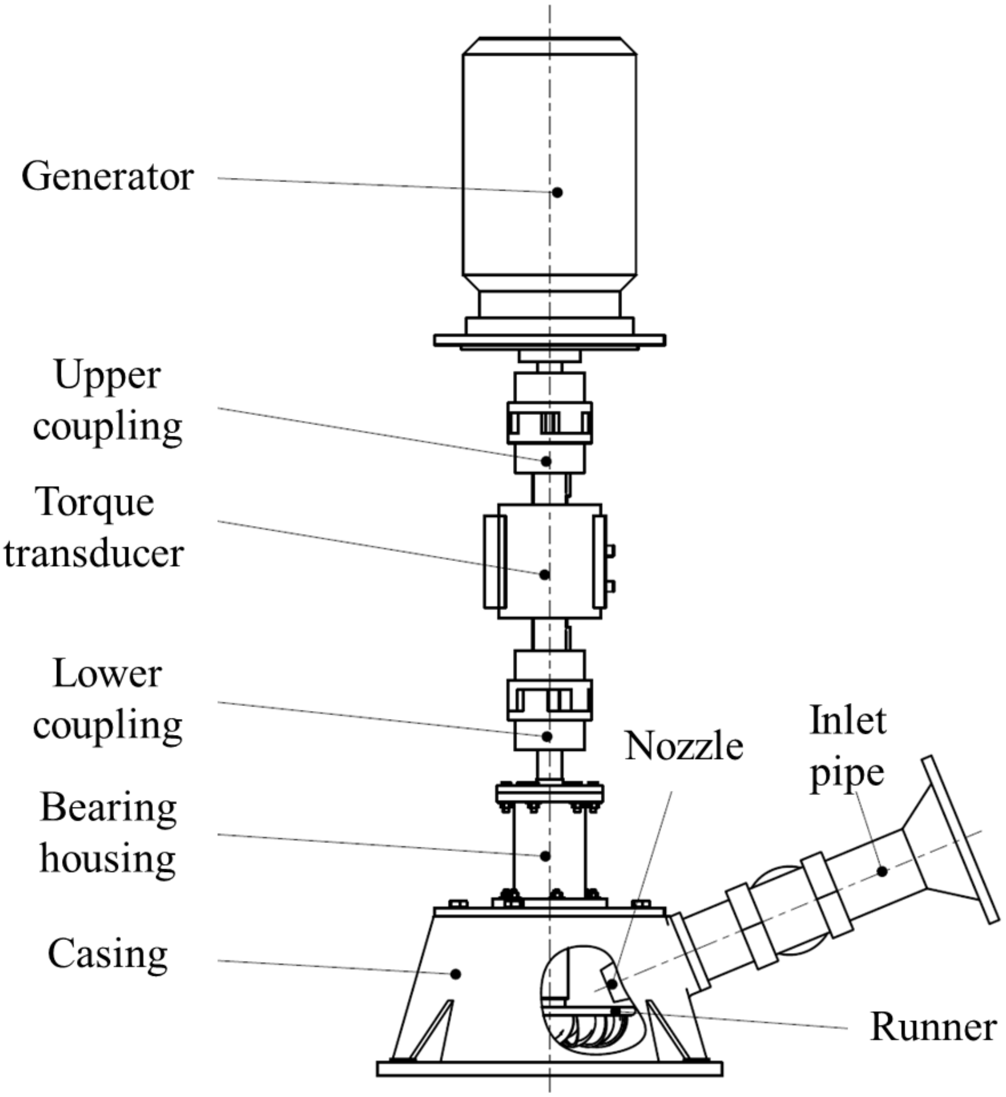


Figure 7.1 - Assembly drawing showing test rig components without frame.

Above the torque transducer, a second coupling was used to connect its shaft to the induction motor’s shaft. The induction motor and torque transducer are supported on a frame, allowing adjustment of their alignment which is maintained once securely fastened.

7.2.2 Water supply and pipelines

The Turbine Testing Laboratory (TTL) at Kathmandu University has a reservoir, pipe network, and pump system capable of delivering 150 m of head and a flow rate of 300 L/s. New pipework was required to direct flow from the high pressure tank to the turbine and to allow sufficient straight pipe sections for stable readings from the hydraulic sensing equipment. Figure 7.2 shows the pipeline, turbine, generator, and their supporting frame. The head is set by adjusting a pump motor using a variable frequency drive. To make finer adjustments, a bypass valve is used to vary the flow rate that either enters the turbine system or is returned to the reservoir. The Imported turbine set included a shut off valve and further downstream, a simple conical nozzle without a spear valve. Due to the proximity of the shut off valve to the nozzle, operating with the valve partially closed would create turbulence in the jet. Thus, it was decided not to use this valve to incrementally vary the flow rate. Instead, the turbine would be tested with the shut off valve fully open simulating the likely use case in the field. Consequently, each testing point for a particular head would have a corresponding flow rate determined by the nozzle’s discharge coefficient.

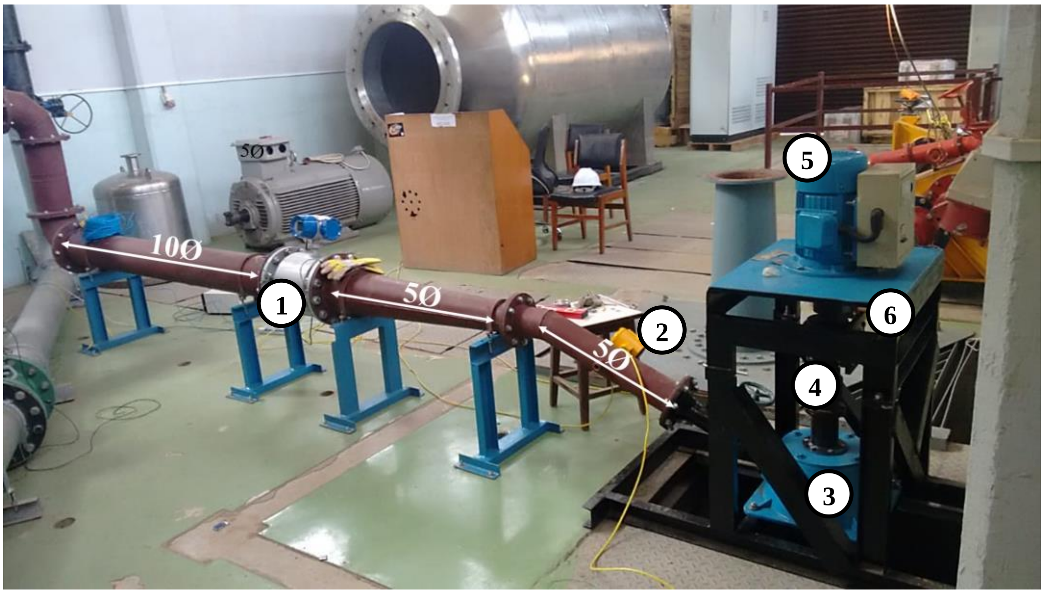


Figure 7.2 - Photo of the testing rig. The numbered labels indicate: 1 – flow meter, 2 – pressure transducer, 3 – turbine, 4 – torque transducer, 5 – generator, and 6 – supporting structure. Photo credit, author.

7.2.3 Control and measurement

For turbines, the flow of water causes the turbine to rotate at a particular speed with a particular torque. The rotational speed depends on the torque that the turbine is acting against. In testing, rather than applying a known torque to the shaft, the turbine is rotated at a set speed. As the runner and motor are directly driven, when there is no jet impinging on the runner, there is no difference in torque between the motor shaft and the runner. When the jet is applied, the interaction between the water and the runner applies a greater torque to the runner end of the shaft, which can be measured.

The rotational speed of the induction motor and the turbine runner is controlled using a variable frequency drive (VFD). Readings are taken from a pressure transducer during the adjustment process. The pressure is measured close to the turbine nozzle using two Aplisens APR-2000 ALW pressure transducers with a range of 0 to 7 bar. They are installed 180 degrees apart in the main pipeline of the turbine test rig, close to the turbine nozzle but 2.5 × pipe diameters (D) away from nearest joint in the pipeline, in both directions. The average value of the two pressure transducers is used to calculate the head. Flow rate is measured upstream of the turbine using an inline DN200 KO Meter KTM-800 electromagnetic flow meter. The range of measurement is approximately 0 to 320 L/s. The flow meter is installed in the pipeline 10D away from the nearest upstream joint or bend and 5D away from the nearest downstream joint or bend, as shown in Figure 7.2. The torque transducer measures the difference in torque that is applied to the runner by the jet as it is rotated at each speed. The torque is measured using a SETech YDRM – 50KM foil strain gauge torque transducer with capacity of 50 Nm. As they are directly connected, the rotational speed of the turbine runner is equal to that of the induction motor. The rotational speed is measured using an Ono Sokki MP-981 sensor (integrated with the torque transducer) that measures the speed of a toothed wheel. The results were recorded using a data logging programme created in LABVIEW by staff at the TTL. The programme could be used to record data for a specific time period and number of data points per second.

7.2.4 Hydraulic system diagram

Figure 7.3 shows the complete experimental testing rig including all elements of control and measurement. Table 7.2 lists experimental equipment, their specification, and identifies the abbreviations used within Figure 7.3.

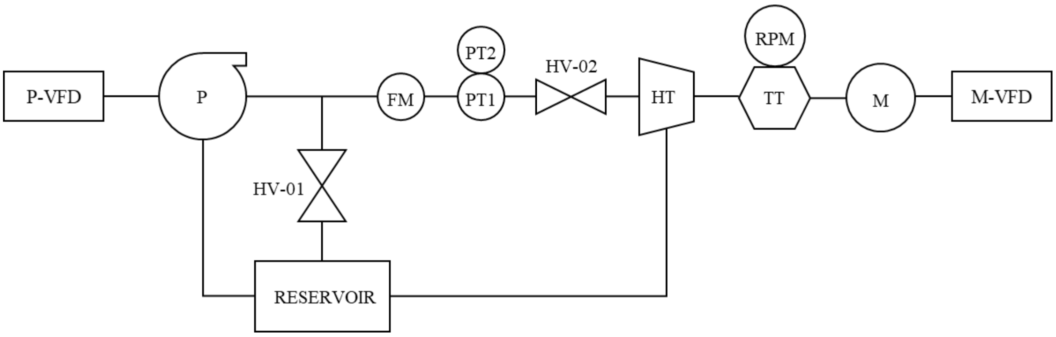


Figure 7.3 – Hydraulic system diagram of the experimental testing rig.

Table 7.2 - Specification of equipment.

Abbreviation	Equipment	Specification	Measurement range
P-VFD	Pump variable frequency drive	-	N/A
P	Pump	-	N/A
HV-01	Bypass valve	-	N/A
FM	Flow meter	KO Meter KTM-800	0.1 – 10 m/s
PT1/2	Pressure transducers	Aplisens APR-2000 ALW	0 – 16 Bar
HV-02	Turbine shut-off valve	-	N/A
HT	Hydro-turbine	-	N/A
TT	Torque transducer	SETech YDRM – 50KM	0 – 50 Nm
RPM	RPM sensor	Ono Sokki MP-981	1 – 20,000 rpm
M	Motor	Mindong Type Y 100L2-4	N/A
M-VFD	Motor variable frequency drive	Delta VFD-EL&E BUE-40037	N/A

7.3 Testing regime

7.3.1 Establishing uncertainty

In the measurement of a quantity, the error is the difference between that measurement and the true value of a quantity [223]. The range of values that the true value of a measured quantity lies within is the uncertainty of the measurement [223]. Errors that contribute to uncertainty can be defined as three types [223]:

- Spurious errors arise due to human mistakes or instrument malfunction that result in incorrect measurements. These errors should not be incorporated into statistical analysis.
- Systematic errors are those that have the same magnitude for every measurement. They are caused by faults with measuring equipment and inaccuracy in calibration.
- Random errors occur due to random events during the testing process that prevent individual measurements from providing the same value. Through repeated measurement, the mean value can be found as the measured values should be normally distributed.

The total uncertainty in a measurement is the combination of the systematic and random uncertainty.

Systematic uncertainty

For the speed sensor, pressure transducer, and flow meter which all had not been used since factory calibration, the manufacturer’s accuracy can be used as an approximation of the systematic uncertainty. Table 7.3 provides the manufacturer’s quoted accuracies for these instruments. The torque transducer was calibrated up to 50 Nm, whilst the maximum expected torque reading was approximately 15 Nm. It was calibrated using a rig that locks a counter-arm in place whilst known masses are applied at a known distance. The results of this and the calculation of systematic uncertainty are presented in Appendix F.1. The resulting systematic uncertainty for the torque transducer was ± 1.307%.

Table 7.3 - Accuracy of measuring equipment.

Instrument(s) and measurand	Manufacturer’s quoted accuracy	Reference for systematic uncertainty
Speed sensor and connected data logger (ω)	± 0.05% of reading	[224]
Pressure sensor (H)	± 0.05% of full scale	[225, 226]
Electromagnetic flow meter (Q)	± 0.5% of reading (0.3 m/s – 10 m/s) ± 1% of reading (0.01 m/s – 0.3 m/s)	[227]

Table 7.4 shows the calculation of systematic uncertainty for the measuring instruments. For rotational speed, head and flow rate, the manufacturer's quoted accuracies are used to consider the systematic uncertainty at a control point repeated throughout experimental testing, a nominal head of 19.5 m and rotational speed of 1500 rpm. Based on the information provided in Table 7.3 and the calibration of the torque meter, the absolute error is determined. This error is either relative to full scale for head or relative to the measured value for torque, rotational speed, and flow rate.

Table 7.4 - Calculation of systematic uncertainty.

Measurand	Units	Measured value	Absolute error	Systematic uncertainty
Torque	Nm	9.684	± 0.12657	±1.307% (δ_T)
Rotational speed	rpm	1501	± 0.7505	±0.050% (δ_ω)
Head	m	19.46	± 0.08160	±0.419% (δ_H)
Flow rate	m^3/s	0.0139	± 0.00007	±0.500% (δ_Q)

The total systematic uncertainty for the efficiency, δ_S, can be calculated using:

$$\delta_S = \sqrt{{\delta_T}^2 + {\delta_\omega}^2 + {\delta_H}^2 + {\delta_Q}^2} \tag{7.2}$$

The total systematic uncertainty, δ_S, is ± 1.46%. It should be noted that this value provides an indication of the systematic uncertainty within the core range of testing. As the accuracy of the pressure sensor is related to its full-scale range, the systematic uncertainty will increase for lower heads.

Random uncertainty

The random uncertainty was determined by taking repeated measurements of a single operating point. A head of 19.5 m with a rotational speed of 1500 rpm was used as a control point. This operating point was repeated at the beginning, in the middle, and at the end of the sequence of tests on the Mark 1 runner. Each time, measurement of the control point was repeated 4 times leading to 12 individual repeated runs. Using the method in [223], the random uncertainty in the efficiency can be determined. Table 7.5 lists the normalised efficiencies of the individual runs and the parameters used to calculate standard deviation.

Table 7.5 - Normalised efficiencies of the control point data

No.	$\boldsymbol{Y_r}$	$\boldsymbol{Y_r - \bar{Y}}$	$\boldsymbol{(Y_r - \bar{Y})^2}$
1	0.994311	-0.005688741	3.23618E-05
2	0.994835	-0.005164603	2.66731E-05
3	0.995097	-0.004902697	2.40364E-05
4	0.996239	-0.003761292	1.41473E-05
5	0.998109	-0.001891323	3.5771E-06
6	0.999932	-6.8125E-05	4.64101E-09
7	1.000002	1.53104E-06	2.34408E-12
8	1.001104	0.001103579	1.21789E-06
9	1.002511	0.002511371	6.30698E-06
10	1.004924	0.004924353	2.42493E-05
11	1.005123	0.005123416	2.62494E-05
12	1.007813	0.00781253	6.10356E-05
n = 12	$\bar{Y} = \sum \frac{Y_r}{n} = 1$		$\sum (Y_r - \bar{Y})^2 = 0.000187498$

The standard deviation, S_Y , is calculated using Bessel's correction:

$$S_Y = \sqrt{\frac{\sum(Y_r - \bar{Y})^2}{n-1}} = 0.00447 \tag{7.3}$$

The range of values within which the true value of the quantity is expected to lie, with 95% confidence is:

$$\bar{Y} \pm \frac{t \cdot S_Y}{\sqrt{n}} \tag{7.4}$$

From [223], for n = 12, the student's t-value = 2.201. Therefore, the maximum possible random uncertainty can be calculated as:

$$\delta_r = \frac{t \cdot S_Y}{\sqrt{n}} = 0.28\% \tag{7.5}$$

Total uncertainty

The total uncertainty, δ_t , combines the random and systematic uncertainties and can be calculated using the following equation:

$$\delta_t = \sqrt{{\delta_s}^2 + {\delta_r}^2} \tag{7.6}$$

The total uncertainty in the efficiency, δ_t , is ± 1.42%. It should be noted that within the total uncertainty, the systematic uncertainty of the torque transducer is by far the largest contributor.

7.3.2 Testing plan

Due to the timing of the manufacture of the Mark 1 and Mark 2 runner, the testing occurred in two phases. In the first phase, the Imported and Mark 1 runner were tested. When testing the runners, the experimental set up was intended to replicate the modelling simulation in CFD. To compare the runners, it was intended to test them both at the same heads across the manufacturer's suggested operating range of the Imported runner, from 15 m to 25 m. Table 7.6 lists the planned sequence of 'core' experimental runs. Additionally, to consider the applicability of the Turgo at low heads which has been considered within the literature [52], the Mark 1 runner was tested at 3, 4, and 5 m head. Table 7.7 lists the additional low head experimental testing conducted.

Table 7.6 - Register of 'core' experimental tests for the Imported and Mark 1 runners.

Head (m)	**Rotational speed (rpm)**										
	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
15	●	●	●	●	●	●	●	●	●	●	●
17.5	●	●	●	●	●	●	●	●	●	●	●
20	●	●	●	●	●	●	●	●	●	●	●
22.5	●	●	●	●	●	●	●	●	●	●	●
25	●	●	●	●	●	●	●	●	●	●	●

Table 7.7 - Register of additional 'low head' experimental tests for the Mark 1 runner.

Head (m)	**Rotational speed (rpm)**							
	400	500	600	700	800	900	1000	1100
3	●	●	●	●	●	●	●	●
4	●	●	●	●	●	●	●	●
5	●	●	●	●	●	●	●	●

7.3.3 Testing procedure

Figure 7.4 shows the procedure for testing at a single head setting. During testing, it was necessary to allow the induction motor’s VFD to cool for approximately 20 minutes between each run to avoid overheating.

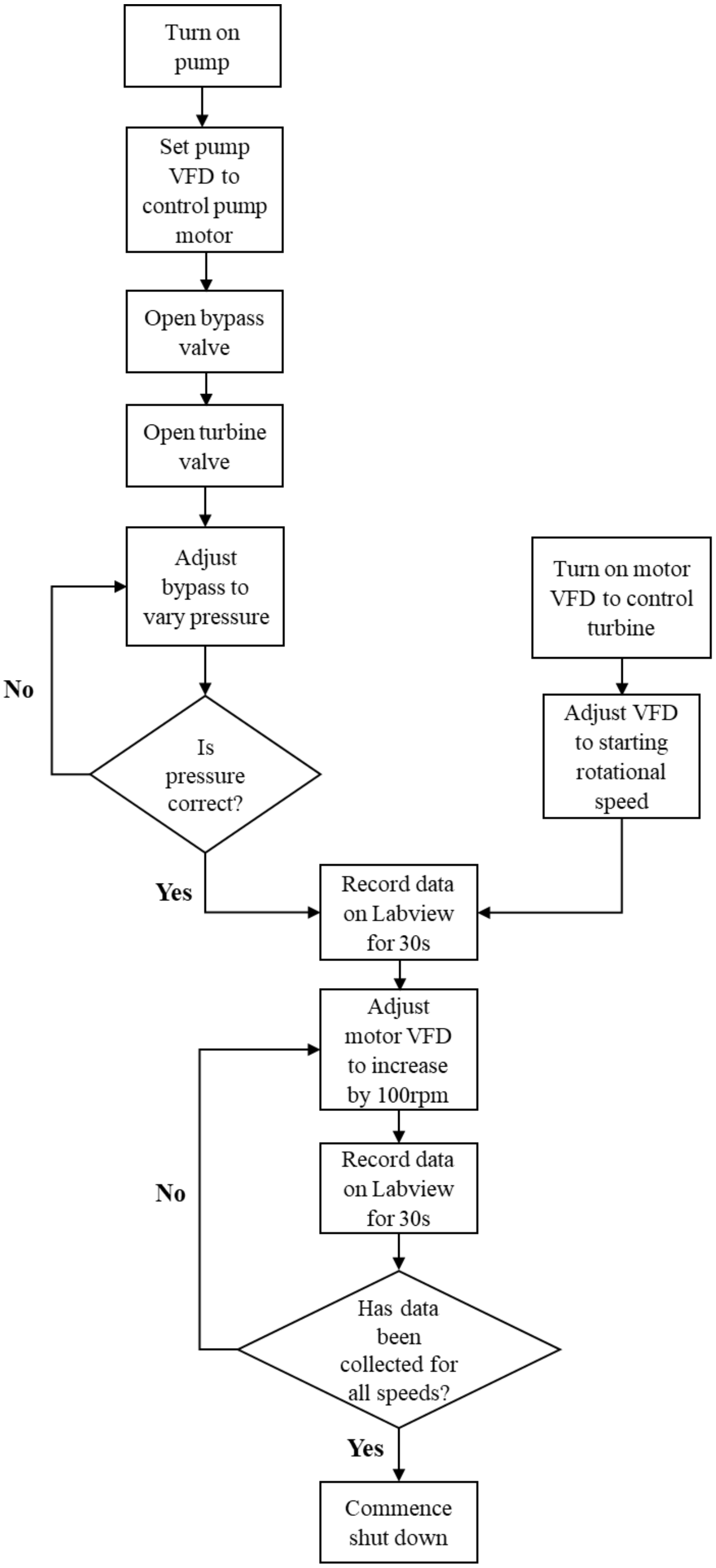


Figure 7.4 - Flow diagram of the testing procedure.

7.4 Phase 1 of testing

7.4.1 Results

Figure 7.5 shows efficiency against rotational speed for the Imported runner. It can be seen that the highest efficiency occurs at the lowest head, 15m. As the head increases, the peak efficiency values reduce. It appears that for the 3 highest heads, the efficiencies all peak at a similar value. In every case, as the head increases, the rotational speed at which the peak occurs also increases. The highest peak efficiency occurs at 1500rpm, the rated speed of the induction motor, meaning that the motor would also be operating efficiently at this rotational speed.

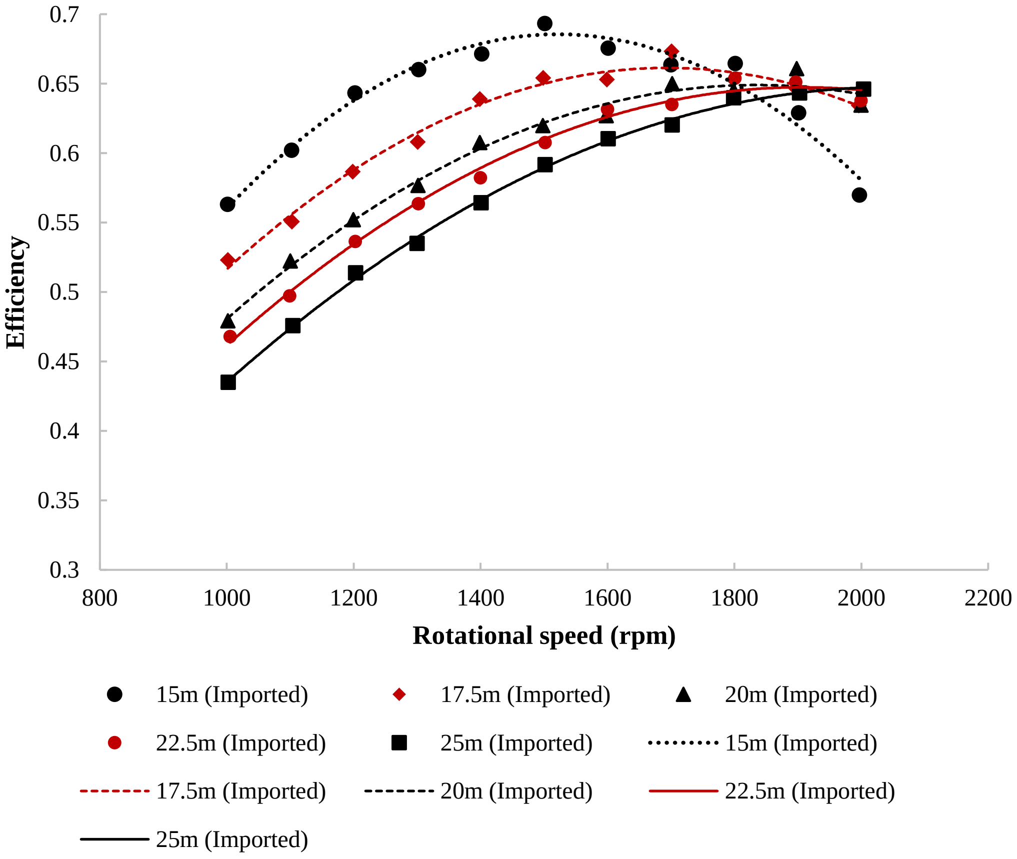


Figure 7.5 - Efficiency against rotational speed at a range of heads for the Imported runner.

Figure 7.6 plots efficiency against rotational speed for the Mark 1 runner. Similar to the Imported runner, the highest efficiency again occurs at the lowest head of 15 m. For the higher heads (e.g., 22.5 m and 25 m), the turbine did not reach its peak efficiency within the tested speed range. For the Mark 1 runner, the best efficiency point (BEP) at each head occurs at a higher rotational speed when compared with the equivalent head for the Imported runner. This trend can be represented by considering the speed ratio, the ratio of the turbine speed to the jet velocity [72].

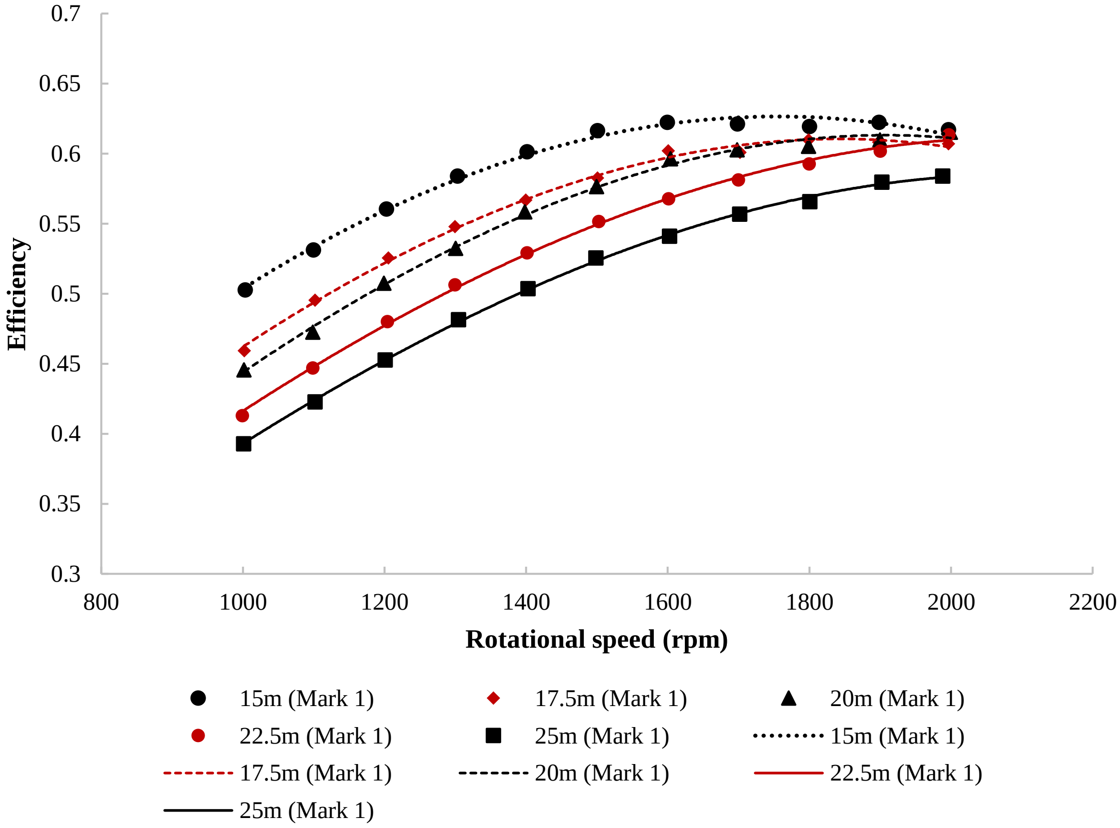


Figure 7.6 - Efficiency against rotational speed at a range of heads for the Mark 1 runner

Figure 7.7 plots the efficiency against the speed ratio for the Imported and Mark 1 runner. In this figure, the plotted points are for both runners at heads of 15, 20, and 25 m. The line of best fit represents the general relationship between speed ratio, irrespective of head. It provides a good fit to the data (Imported, $R^2 = 0.9377$, and Mark 1, $R^2 = 0.9667$). The figure shows that from a speed ratio of 0.25 to approximately 0.6, the Imported runner delivers higher efficiency. For the Imported runner, the peak efficiency point occurs at a speed ratio of approximately 0.5. For the Mark 1 runner, this peak occurs at a speed ratio of approximately 0.56. The flatter curve for the Mark 1 runner suggests that, despite lower peak efficiency, there is less variation in efficiency close to the peak.

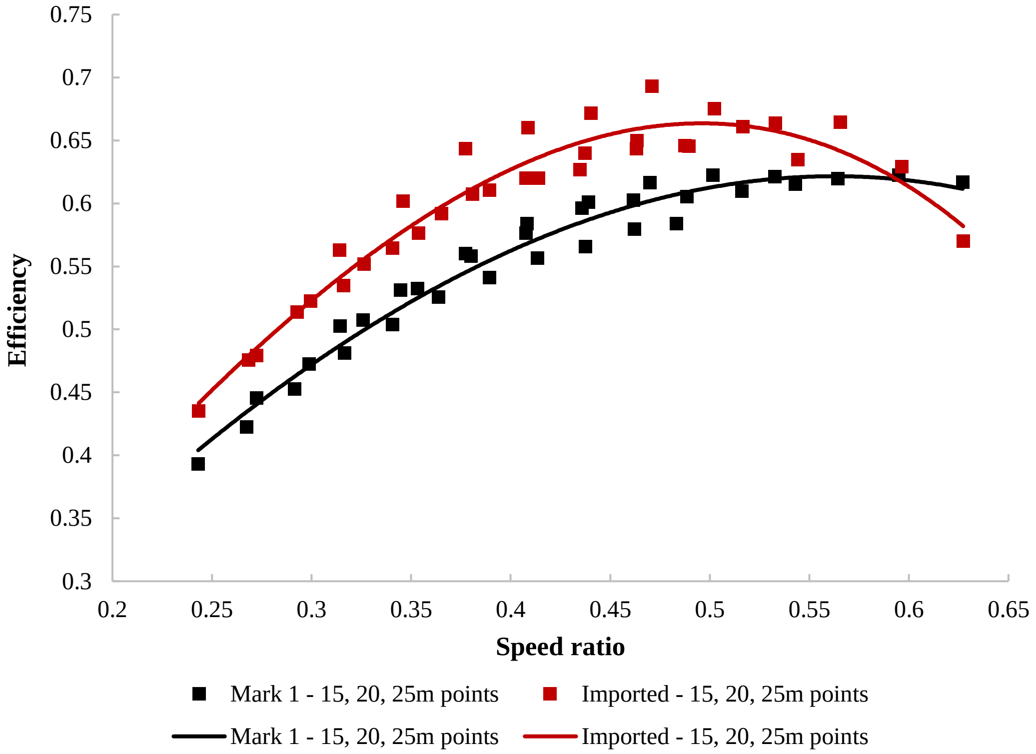


Figure 7.7 - Efficiency against speed ratio for the Imported and Mark 1 runners at heads of 15, 20, and 25m.

The experimental resting rig was also used briefly to explore the performance of the Mark 1 runner at low heads. It should be noted that due to the lower torques at low heads, the total systematic uncertainty will be higher than the value calculated earlier. Figure 7.8 plots efficiency against rotational speed for the Mark 1 runner at heads of 3, 4, and 5 m. In relation to Figure 7.6, it can be seen that the trend of increasing peak efficiency at lower heads is continued at these low heads. The peak efficiency for 3m head is 77%, far exceeding the best efficiency achieved within the core testing range. The trend of peak efficiency at lower heads occurring at lower rotational speeds also continues.

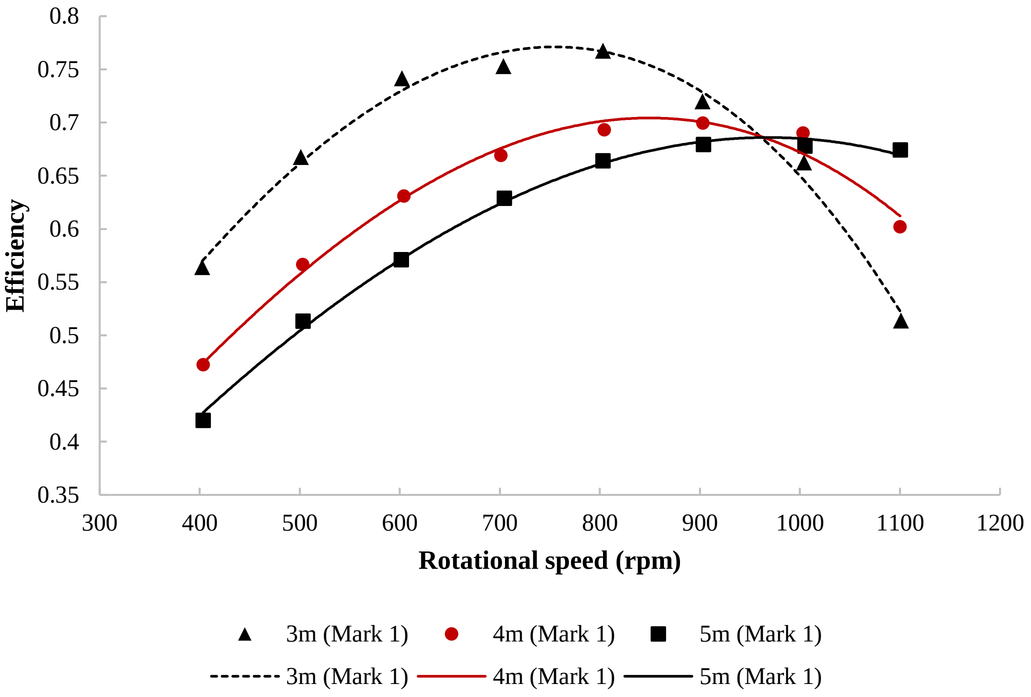


Figure 7.8 - Efficiency against rated speed at a range of low heads for the Mark 1 runner.

The results of these lower head runs can be used to consider the relationship between speed ratio and efficiency for a greater variation in head. Figure 7.9 plots efficiency against speed ratio for 3, 4, 5, 15, 20, and 25 m head for the Mark 1 runner. The lines of best fit follow a similar trend with the peak efficiencies for each head occurring at speed ratios between 0.5 and 0.55. As the head decreases, the peak efficiency increases.

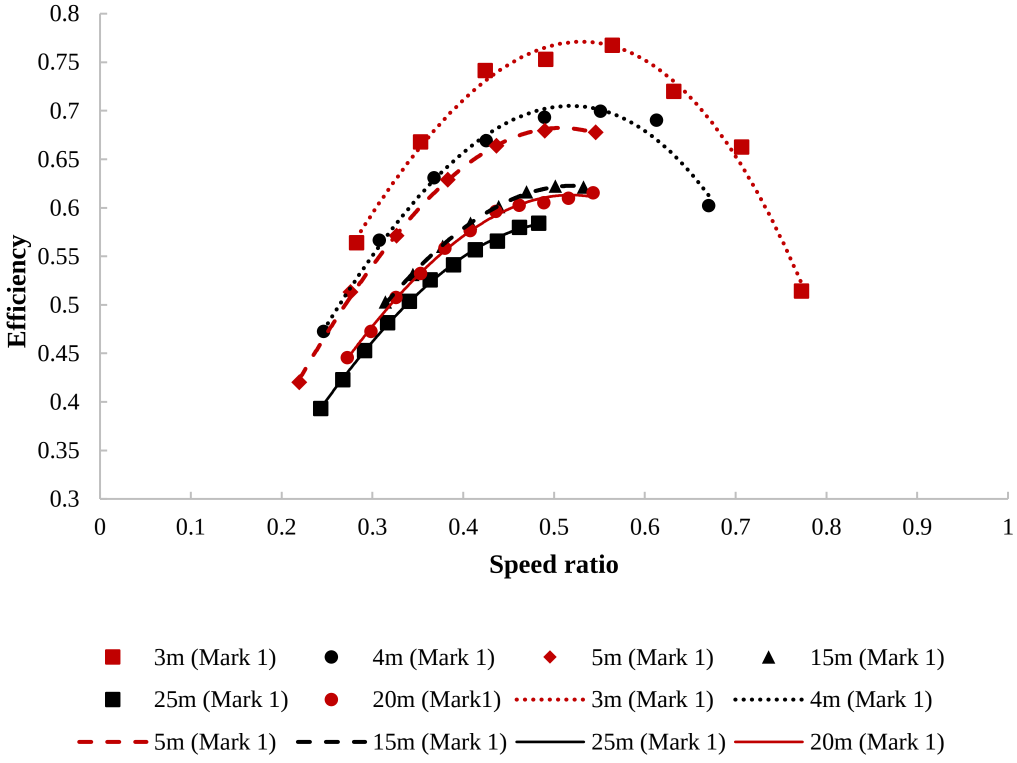


Figure 7.9 - Efficiency against speed ratio for the Mark 1 runner at low heads.

7.4.2 Discussion

The results of the first phase of laboratory testing demonstrated that across the range of heads from 15 to 25m, the Imported runner delivered higher efficiencies than the Mark 1 runner. In addition, at all of these heads, the Mark 1 runner's BEP occurred at higher rotational speeds. Consequently, for a specific head at a specific speed, the Mark 1 runner generated less torque and thus less power. Therefore, to explain these results there is value in considering the torque generated by the two runners. As in the development of the Mark 1 runner using CFD, examination of torque results can be used to determine factors affecting efficiency. During testing, the torque transducer recorded 2,000 points per second. This resolution made it possible to plot multiple torque values for each individual revolution of the runner. From the core experimental range (15 to 25m), using the BEP data at 15m and 1500rpm for both the Imported and Mark 1 runner, it is possible to plot the torque values over the course of full revolutions made by each runner. The data (that spans 3 revolutions) is extracted from the approximate midpoint in the testing run, after 15 seconds had elapsed. Figure 7.10 plots torque against the number of revolutions for the Imported runner, whilst Figure 7.11 plots the equivalent data for the Mark 1 runner.

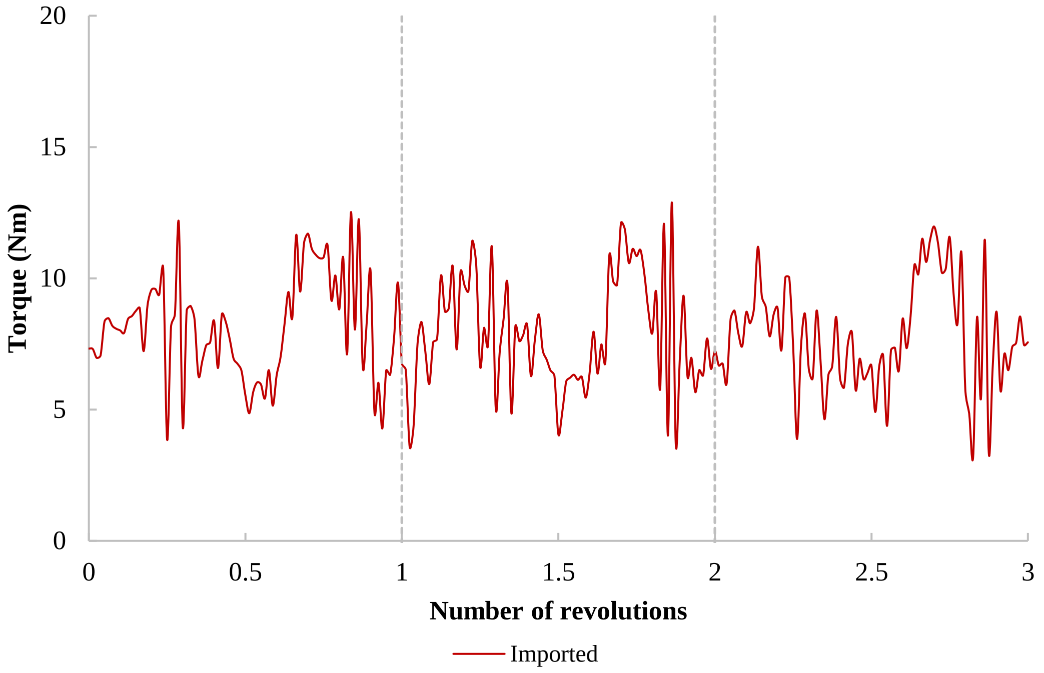


Figure 7.10 - Torque against number of revolutions for the Imported runner at 1500rpm and at 15m head.

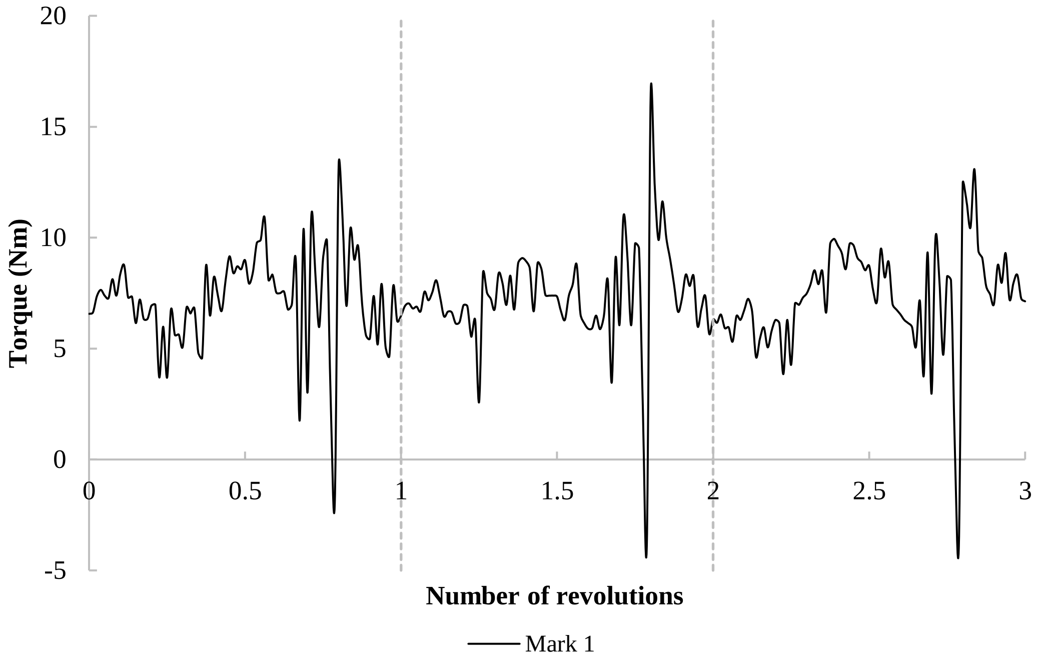


Figure 7.11 - Torque against number of revolutions for the Mark 1 runner at 1500rpm and at 15m head.

In these figures, the dashed grey lines represent the end of one complete revolution of a runner. For the Imported runner, whilst there is significant oscillation, it is possible to perceive general patterns. The torque oscillates around approximately 8 Nm. Within each period, there tends to be a peak in torque before a descent to a minimum after half a revolution. Subsequently, after rising again, there is an abrupt and steep change which spans the entire range of the torque values (from maximum to minimum). For the Mark 1 runner, there is also a repeating trend within each period. For the first half of each revolution, there is oscillation around approximately 7 Nm. In the second half of each period, the oscillations increase in magnitude. For every rotation shown, the torque descends to a minimum negative value. In comparing these two graphs, it appears for both runners, there is a portion of each revolution where the torque becomes more unstable. However, for the Mark 1 runner, the magnitude of instability is greater, leading to negative torque values. As a result, the average torque over a single period is affected. In the CFD simulations, torque curves for the passage of 2 blades demonstrated regions where there was interference between the flow exiting a blade and the trailing runner. From the experimental results, it is not possible to definitively determine the cause of spikes in the torque reading. However, as in CFD, the changes in torque can be attributed to the interaction between the water flow and the runner blades. As shown in Figure 7.11, the negative spikes in torque occur at approximately the same position within each rotation. Therefore, they may indicate a specific geometric deficiency with a particular blade, or incorrect positioning of this blade relative to the others. The results suggest that without the large negative spike, there would have been much less difference in the efficiency of the two runners.

Evaluation of the speed ratio for the 2 runners can be used to consider their performance independent of head. Compared to the Imported runner, Figure 7.7 shows that peak efficiencies for the Mark 1 runner occur at a higher speed ratio. As shown in Equation 6.5, the ideal speed ratio for a Turgo turbine (with blade inclination angle of 22.5°) is 0.46. In CFD simulations, the model of the Imported runner had an optimum speed ratio of 0.5 (see Figure 6.26). In experimental testing, the speed ratio for this runner is closer to 0.49. However, for the Mark 1 runner, the average optimum speed ratio is around 0.55. The difference in optimum speed ratio indicates that for the Imported runner, the blade speed is approximately half the jet speed, whilst for the Mark 1, the optimum occurs when the blade speed is greater. This suggests that the geometry of the Mark 1 runner is behaving atypically compared to previous experimental results. In the typical optimum range (between 0.46 and 0.5), the geometry of the Mark 1 generates insufficient torque to deliver the highest efficiency. At higher speed ratios, the relative torque generation is higher resulting in a flatter speed ratio to efficiency curve compared to the Imported runner, and testing in [72]. In [72], where speed ratio is plotted against efficiency for a number of heads, it is found that the peak efficiency remains relatively constant irrespective of the head. The results shown in Figure 7.9 indicate that this is not true for the Mark 1 runner. As the head decreases, there is a clear increase in efficiency whilst the speed ratio remains approximately constant. Potential explanations for this may depend on several geometric relationships which previous literature has identified as important: the PCD to nozzle diameter ratio (*D/d*), the nozzle diameter to blade width ratio (*d/w*), and the nozzle diameter to blade spacing ratio (*d/s*). Compared to [52] and [228] where best efficiencies were achieved with *D/d* of 7.5 and 10.13 respectively, both the Mark 1 and the Imported runner have a much lower ratio of 3.26. In [76], Gaiser et al. suggests that a low *D/d* is effective in delivering high rotational speeds but when reduced too low, flow limitations may occur. The same authors identify blade width to nozzle diameter as an important factor; if too low, turbulence and re-circulation of the flow are disruptive. In [52], best efficiency was achieved with 1.75 *w/d*, whilst in [74], Anagnostopoulos suggests 1.45 *w/d* should be used in the design of a Turgo blade but without justification. For the Mark 1, *w/d* is equal to 1.94. The relationship between performance and blade spacing (or number of blades) is discussed less in the literature. In [76], Gaiser et al. identify it as an important factor suggesting that it should exceed 0.45. In experimental testing, these authors find an optimum *d/s* of 0.94 but also state that it will depend on site characteristics. In most cases, the number of blades exceeds 10 with at least 20 typical [72, 76, 228]. However, Williamson et al. achieve high efficiencies at low heads using only 9 blades [52].

In comparison to other experimental testing set ups, the ratio of blade width to nozzle diameter of the Mark 1 is larger but similar in magnitude. However, there is a greater difference when nozzle diameter to PCD ratio is considered. The Mark 1 has a proportionally larger nozzle diameter compared with other runners. When evaluating these two ratios together, it implies that whilst the Mark 1 blade is similar in proportion to the other experimental blades, it is positioned at a much smaller PCD. The advantage of this is that it is able to run at a high rotational speed (for a comparatively low head) meaning that it can directly drive an induction motor. The drawback of this is that the flow rate is concentrated into a compact region of operation. Evaluating the blade spacing emphasises this.

Using an expression from [76] where, the nozzle diameter to blade spacing ratio is defined as:

$$\frac{d}{s} = \frac{d}{\frac{1}{Z}\pi D} \tag{7.7}$$

where *Z* is the number of blades and *D* is the pitch circle diameter. It is possible to compare this ratio for the Mark 1 with other turbines. The range of *d/s* in other literature is from 0.17 to 0.91 [76], whilst for the Mark 1 it is 1.366. The lower the value, the more voluminous the runner is in relation to jet diameter. The ratio indicates that despite the relatively low number of blades (14), there is little space between them in relation to the jet diameter. The consequence is that it is likely that there is significant interference between flow leaving a blade and the trailing one. This may explain why the lower head values achieve higher efficiencies. As the head decreases, the fixed nozzle means that the flow rate does too. When there is a smaller volume of water, the fluid film leaving the blade is likely to be thinner decreasing the interaction with the trailing blade. As the nozzle and PCD are equivalent for the Imported and Mark 1 runner, the *d/s* ratio is equal for both runners. However, the thicker blade profile of the Mark 1 runner means that the free volume between blade surfaces is less increasing the probability of interference. These results suggest that using the same blade design at a larger PCD may lead to increased efficiency due to greater blade spacing. However, it should be considered that changing the PCD will also affect the operational speed.

The results from CFD were able to provide further explanation of the experimental testing results. In Chapter 6, Figure 6.27 was used to show the difference in fluid velocities that resulted from a change in runner position. The figure shows that as the jet impacts the rotating runner, a portion of the flow will impact directly onto the runner's leading edge. This flow will be redirected upwards and do no useful work. Furthermore, due to the runner's orientation (with a vertical shaft), any portion of this reflected flow that does not clear the outer edge of the runner, will have to flow back through the runner. As such, during its passage through the runner it will interfere with flow that is passing directly through, increasing turbulence within the blades. Another finding from CFD was the prevalence of flow interaction between blades (as shown in Figure 6.34). Throughout the optimisation process, adaptations were made to minimise interference between flow leaving a blade and the trailing blade. Avoiding this reduced the generation of negative torque. The effect of both of these phenomena - impact on the leading edge and interference with the trailing blade - is likely to be greater for thicker blades. This analysis of the CFD results indicates the particular modes whereby the thicker blades of the Mark 1 runner affected its efficiency. These findings supported the decision to manufacture the Mark 2 runner. In particular, they emphasised the importance of minimising the thickness of the blade, both in general and specifically at its leading edge.

In existing literature, regression analysis has been used to predict hydraulic performance of small-scale Turgo turbines [76, 228]. In these examples, it was used to consider their performance in relation to a number of variables such as nozzle diameter, number of nozzles, and jet impact location. With the data from experimental testing, it is possible to use a similar approach. In this case, regression analysis has been used to consider the relationship between measured quantities and the hydraulic efficiency. In Figure 7.5 and Figure 7.6, where efficiency is plotted against rotational speed, the closest trend to the data was fitted using a third-order relationship. However, it is known that efficiency is also a function of head and flow rate. To incorporate head, it is possible to use speed ratio (x) as it is a function of both head and rotational speed. Consequently, it was assumed that the speed ratio accounted for the third order terms, and that a first order flow rate term was also significant. Table 7.8 shows the regression analysis where a third order relationship involving x, x^2, x^3, and Q is assumed for all of the recorded data for both runners from 15 to 25m. In the table, the P-value indicates the significance of the term. The lower its value, the more important the term is.

Table 7.8 - Third order regression analysis for the Mark 1 and Imported runners

	Mark 1				**Imported**			
	x^3	**x^2**	**x**	**Q**	**x^3**	**x^2**	**x**	**Q**
Coefficients	0.364	-2.74	2.68	-6.64	-1.54	-1.78	2.83	-8.54
P-value	0.102	3.16E-16	8.57E-37	8.62E-14	4.45E-07	5.43E-08	2.39E-46	3.08E-15
R^2	0.999				0.999			

Table 7.8 demonstrates that use of these variables provides a very good fit in relation to the output efficiency. However, between the two runners, there is a difference in the significance of the cubed speed ratio term. For the Mark 1 runner, comparison between the P-values for all of the variables indicate that it is unimportant. For the Imported runner, the P-value for the x^3 term is smaller but remains the largest of all of the coefficients. Between the two runners, there is also a difference in the sign of its coefficient. Due to the large P-

value for the x^3 term, it was decided to remove it and consider only the x^2, x, and Q terms. Table 7.8 shows the resulting second order regression analysis for the Mark 1 and Imported runners.

Table 7.9 - Second order regression analysis for the Mark 1 and Imported runners

	Mark 1			**Imported**		
	x^2	**x**	**Q**	**x^2**	**x**	**Q**
Coefficients	-2.37	2.57	-6.09	-3.38	3.31	-11.2
P-value	3.34E-42	1.22E-49	1.41E-14	2.05E-64	1.15E-72	8.5E-23
R^2	0.999			0.999		

With the revised terms, the quality of fit the is maintained as the R^2 values is the same (to 3 significant figures). The signs of all of the coefficients are the same for both runners. The results suggest that an estimate of efficiency can be derived using the following equation:

$$\eta = \alpha x^2 + \beta x + \gamma Q \tag{7.8}$$

In this equation, it is assumed that α, β, and γ are constant terms that depend on experimental parameters. The derivation of the regression coefficients used testing results where the runner (and therefore its geometry) was the only changed variable between the two data sets. Where possible, all other testing parameters were held constant, including jet aim position and nozzle diameter. Therefore, in this case, α, β, and γ can all be assumed to have some relationship to the runner geometry. To test the accuracy of the regression analysis in predicting efficiency, it is possible to apply the coefficients to compare prediction with the low head experimental results. Figure 7.12 plots efficiency against rotational speed for the Mark 1 runner comparing the low head experimental results to the results predicted using Equation 7.8 and the coefficients in Table 7.9.

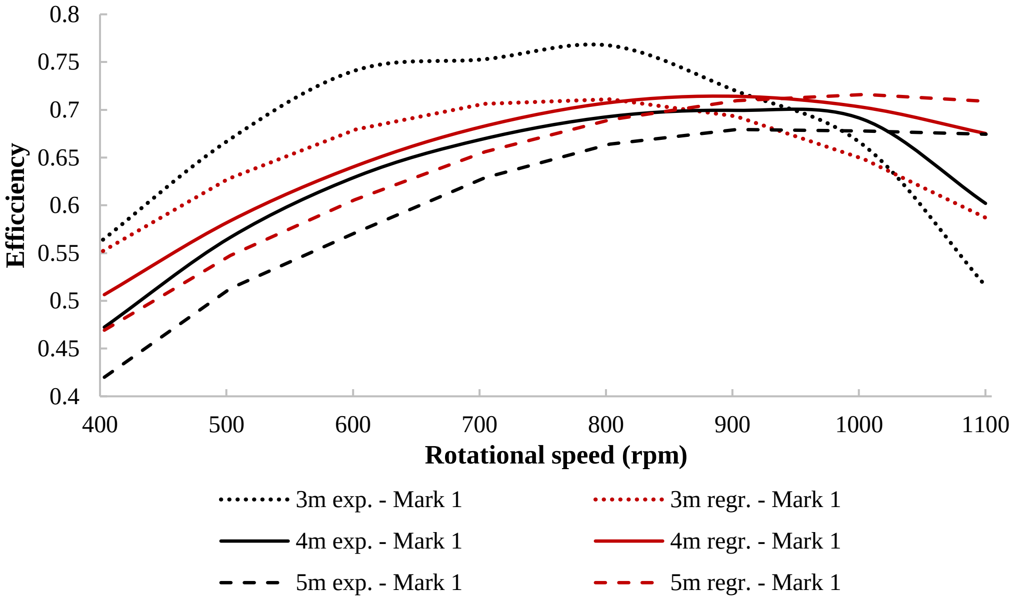


Figure 7.12 - Efficiency against rotational speed comparing experimental to predicted results.

In Figure 7.12 experimental results are shown with black lines and regression predictions in red. An equivalent line style indicates that results are for the same head. All of the predicted results capture the trend seen in experimental testing where low head results achieved higher efficiency than those in the 15 to 25m range. However, in the experimental results, 3m achieved a significantly higher efficiency than 4 or 5m. In the predicted results, it appears that for all of the heads, the efficiencies peak at a similar value. The largest difference occurs for 3m head at the BEP, where there is a difference greater than 5% between the experimental and the predicted results. The application of the regression analysis shows that there is value in being able to use a set of experimental data to check performance under different operating conditions. In this example, it was used to consider performance with different heads and flow rates. However, it should be noted that this method was only used to consider changes made with the same fixed nozzle. It would be advantageous to understand performance using a spear nozzle where the flow rate can be varied. Further experimental testing is required to apply the regression analysis when the jet diameter can be varied. This could be used to investigate the physical provenance of the coefficients (α, β, and γ). If their relation to physical properties was known, it may be possible to accurately predict variation in turbine performance in relation to changes in turbine geometry.

7.5 Phase 2 of testing

Following the first phase of testing in which the Imported and Mark 1 runners were tested, the Mark 2 runner was manufactured. In the intervening period between the two phases of testing, the torque transducer was used on another test rig. Following re-assembly of the Turgo experimental test rig, initial testing was conducted to check the functionality of the reinstalled torque transducer. It was found that both the speed sensor and torque transducer were producing significant spurious errors. To examine this, the Mark 1 runner was tested at a head and rotational speed for which data had been recorded previously. Figure 7.13 plots rotational speed against time for the Mark 1 runner showing data from both the first and second phase of testing. It can be seen that in the first phase, the reading of rotational speed is largely stable. In the second phase, there are periodic zero readings and between these frequent oscillations larger than 50rpm.

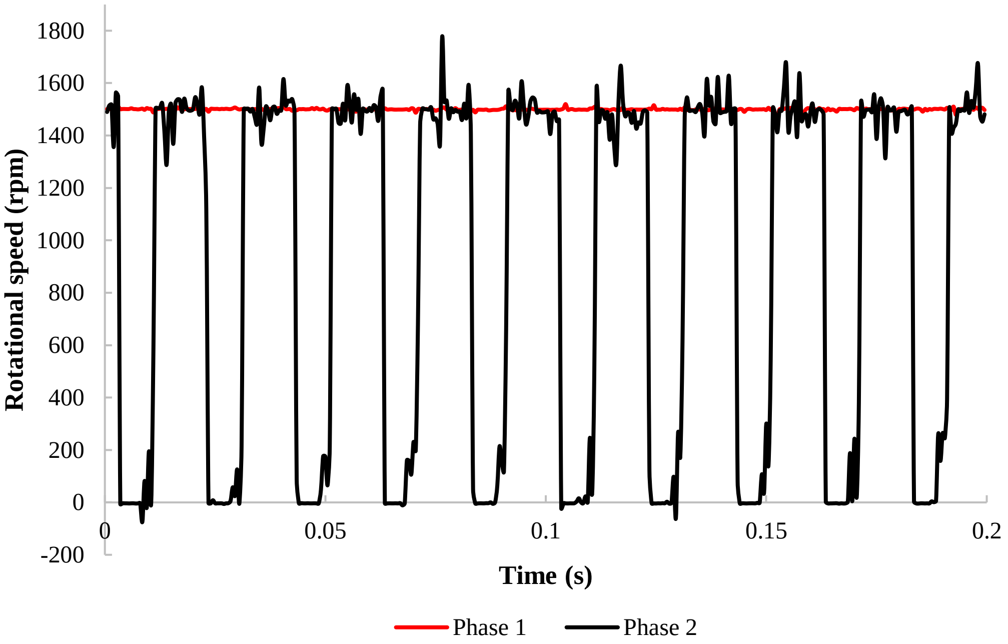


Figure 7.13 - Rotational speed against time for the Mark 1 runner at a head of 15m and nominal rotational speed of 1500rpm.

The measurement of torque provided the largest uncertainty in the first phase of testing. Figure 7.14 is a histogram that plots the frequency of torque readings over a 30 second period at a head of 15m and a rotational speed of 1500rpm in the first phase of testing. It can be seen that the results are approximately uniformly distributed with a positive skew, and with a similar proportion of erroneous low (<1Nm) and high (>13Nm) readings. Figure 7.15 is a histogram that plots the frequency of torque readings (using the same runner) at the same head and rotational speed during the second phase of testing. In this figure, it is obvious that a large proportion (greater than a third) of the readings were erroneous (<0.3Nm). Typically, the incorrect torque values corresponded to the periodic zero errors that occurred in the recorded data from the speed sensor.

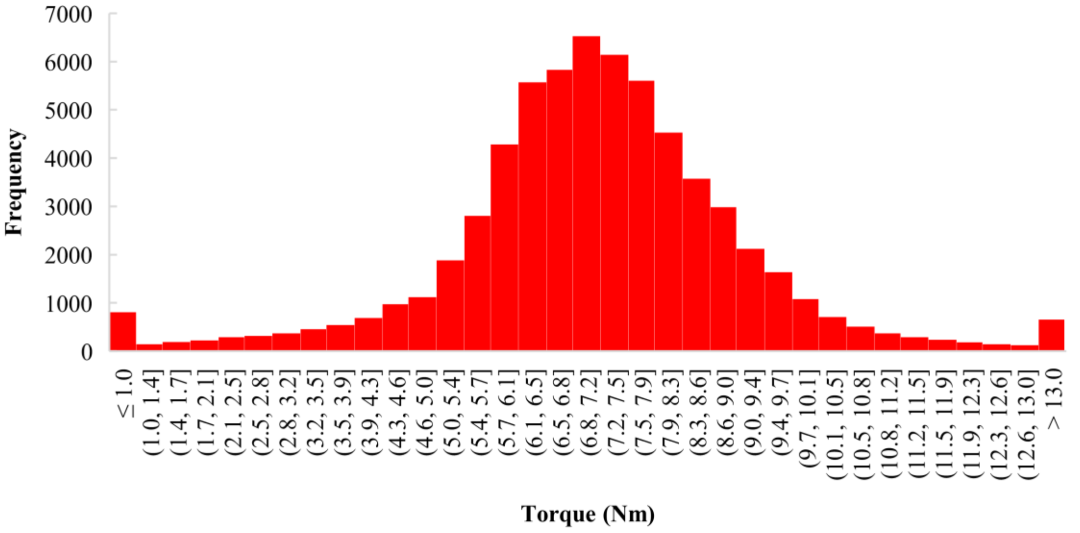


Figure 7.14 - A histogram to show the frequency of torque readings at a head of 15m and a rotational speed of 1500rpm in Phase 1 of testing.

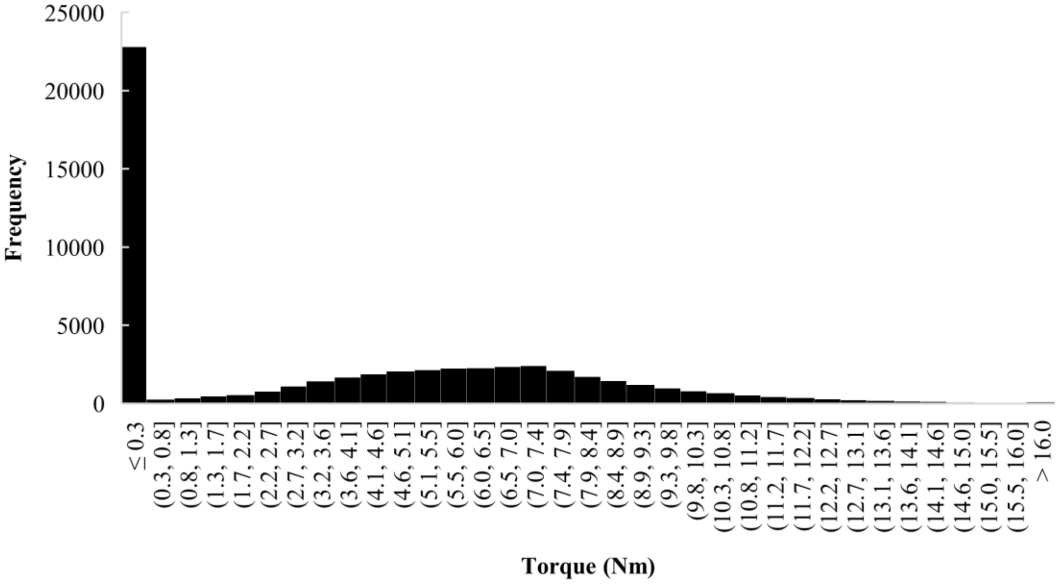


Figure 7.15 - A histogram to show the frequency of torque readings at a head of 15m and a rotational speed of 1500rpm in Phase 2 of testing.

Efforts were made to the clean the data by removing the spurious errors. However, as shown in Figure 7.13, amongst the remaining data there were still large fluctuations in the recorded values. Processing the data using the same approach as in the first phase led to highly erratic results with a very weak agreement to the expected trends established during the first phase of testing. All instrumentation was removed, checked, and re-installed, however, the zero errors and large fluctuations continued to occur. Possible explanations for the errors include equipment damage, shaft misalignment and resonant frequencies. Due to project time constraints, it was not possible to find solutions to these problems and test the Mark 2 runner experimentally.

7.6 Site installation

Alongside experimental testing, it is useful to evaluate efficiency and reliability in the field. A site was selected in Naubise, Dhading for the following reasons:

- **Proximity to Kathmandu.** The site can be reached in less than 2 hours by vehicle from Kathmandu.
- **Contact person in the local area.** An employee of NYSE lived in the local area, was willing to act as an intermediary with the local community and possessed the necessary experience to operate the plant.
- **Site characteristics.** There was an available head of 20m and flow rate in excess of 20L/s.
- **Existing civil structure.** The flow rate could be extracted from a pre-existing canal that supplies water to a traditional mill.

The pre-existing civil structure at the site was upgraded to improve the annual flow reliability. Figure 7.16 shows newly constructed civil structures at the site. The de-silting bay minimises the entry of silt, sand, and rocks into the system. The forebay tank provides capacity for the system to deal with small variations in the flow rate.

Figure 7.16 - (a) de-silting bay and (b) forebay tank at the pilot site. Numbered labels indicate: 1 – intake, 2 – de-silting bay, 3 – canal, and 4 – forebay tank. Photo credit, Prem Karki.

A powerhouse was constructed to provide protection to the turbine, generator, and control system. Figure 7.17 shows the powerhouse under construction at the pilot site. On the right side of this image, the PVC penstock pipe can be seen.

Figure 7.17 - Powerhouse under construction at the pilot site. Photo credit, Prem Karki.

Figure 7.18 shows the turbine the turbine-generator set, ballast tank, and control panel installed in the powerhouse. The control panel contains an ELC which ensures that the power generated by the turbine is either used locally or diverted to the ballast tank. This ensures that the turbine's rotational speed can be maintained at the generator's rated speed of 1500 rpm. The generator installed in the field was the induction motor provided with the Imported turbine. At the pico-hydro scale, it is common to use an induction motor as a generator (IMAG) due to their high availability, relatively low cost and robust design [229]. The IMAG was used with a 'C-2C' connection allowing the three-phase motor to generate a single-phase supply [208].

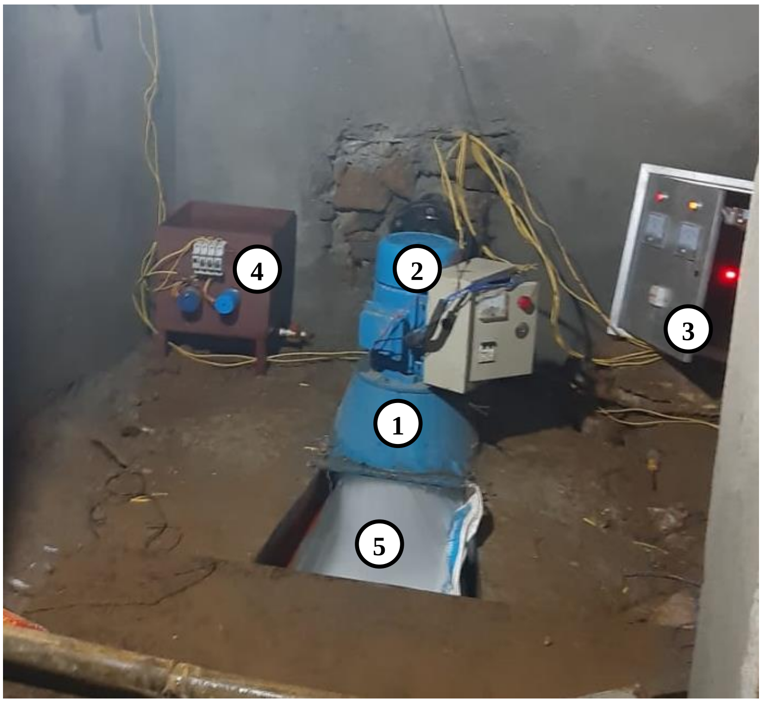


Figure 7.18 - Turbine-generator set, ballast tank and control panel inside the powerhouse. Numbered labels indicate: 1 – turbine casing, 2 – generator, 3 – control panel including ELC, 4 – ballast tank, and 5 – tailrace. Photo credit, Prem Karki.

7.6.1 Field testing

Following installation, the turbine-generator set could be tested in the field. This phase of testing provided an opportunity to compare between the Imported, Mark 1, and Mark 2 runners. However, it should be noted that the accuracy of field-testing results was considerably lower than those collected in the laboratory. Environmental variation, quality of the testing equipment and increased opportunity for human error all contributed to this. In addition, due to its timing the author could not be present at the site during field testing. The author developed a testing procedure based on [200] which detailed the experimental process and the configuration of each runner. In particular, this included the thicknesses of spacers required to ensure that the 3 runners were tested in approximately the same position. As per the testing procedure, the system was tested by diverting all of the power generated to the ballast load. Through measurement of the pressure and the flow rate, it was possible to estimate the input power. A root-mean-square (RMS) meter could be used to measure the ballast voltage, current, and power. Table 7.10 lists the measurements and the method used in field testing, Figure 7.19 shows the methods used for the measurement of head and flow rate. All 3 runners were tested on the same day meaning the environmental conditions were broadly similar. Figure 7.20 shows the process used for field testing.

Table 7.10 – Measurements taken and methods used during field testing.

Measurement	Method	Equipment required	Range	Estimated uncertainty
Flow rate	Height of water measured using a ruler with a rectangular weir in the tailrace, as shown in Figure 7.19(a).	Ruler	0 to 0.3 m	± 5 mm (human error in measurement due to turbulence in tailrace).
Pressure	Reading of pressure taken whilst turbine is in operation, as shown in Figure 7.19(b).	Analogue pressure gauge	0 to 7 kg/cm^2	± 0.1 kg/cm^2 (human error due to reading from gauge).
Output power	True RMS digital multimeter connected across the ballast load.	UNI-T UT243 Multimeter	0 to 600 kW	± 3% [230].

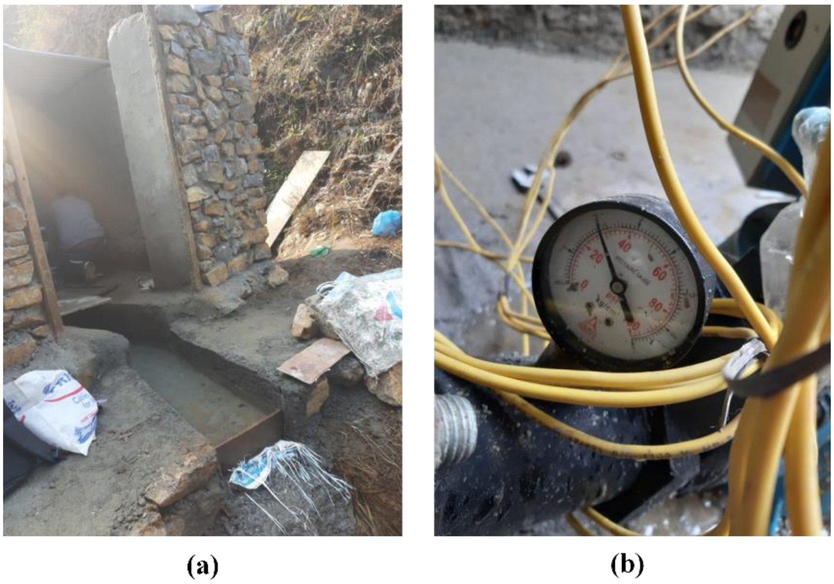


Figure 7.19 - (a) Rectangular weir arrangement and (b) analogue pressure gauge. Photo credit, Prem Karki.

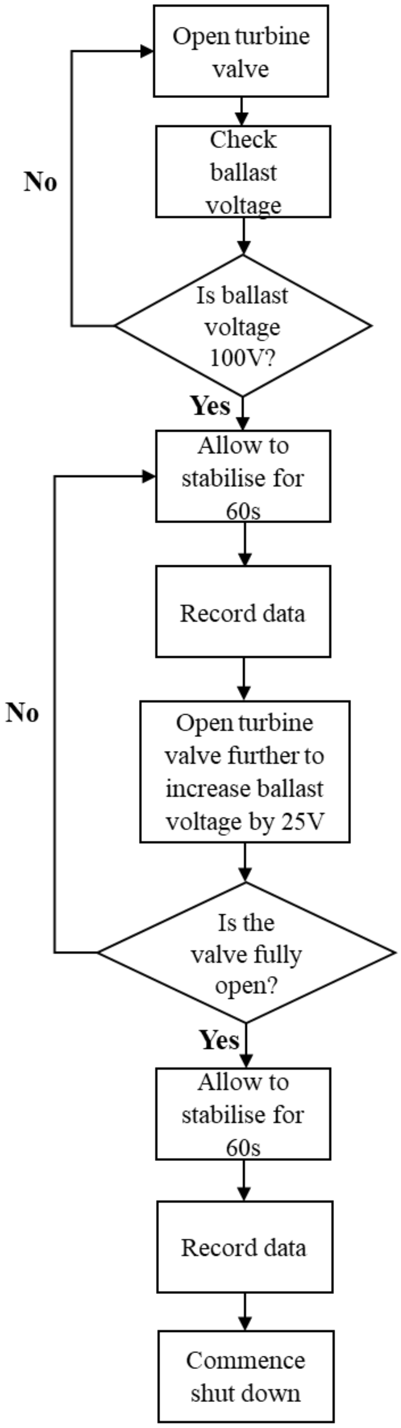


Figure 7.20 - Flow chart showing the testing procedure at the pilot site.

The process used during site testing ensured that the flow rate from the nozzle and the power generated were increased gradually. As the valve is opened further, the voltage across the ballast load increases until it reaches a maximum value. The ELC ensures that the maximum voltage across the ballast is approximately 230 V. Figure 7.21 plots the power output against the ballast voltage for the three different runners. The vertical dashed lines represent the highest value of ballast voltage for each runner, i.e., the ballast voltage when the shut off valve was fully open. The horizontal dashed lines indicate the maximum power output achieved with the valve fully open. It can be seen that the Mark 2 runner achieves the highest output power, followed by the Mark 1, and then the Imported runner. With the valve fully open, all of the runners were operating under conditions that can be compared to experimental testing. Table 7.11 presents the average recorded values from the weir and pressure gauge and the resulting estimated values of flow rate and head. The estimated flow rate from the weir is calculated according to the method presented in [81]. The estimated head is calculated from the pressure gauge reading assuming density of water to be 997 kg/m^3 and acceleration due to gravity to be 9.81 m/s^2. Using Equation 7.1, these values can be combined to estimate the potential available power. Table 7.12 presents the estimated 'water-to-wire' efficiency of the 3 runners.

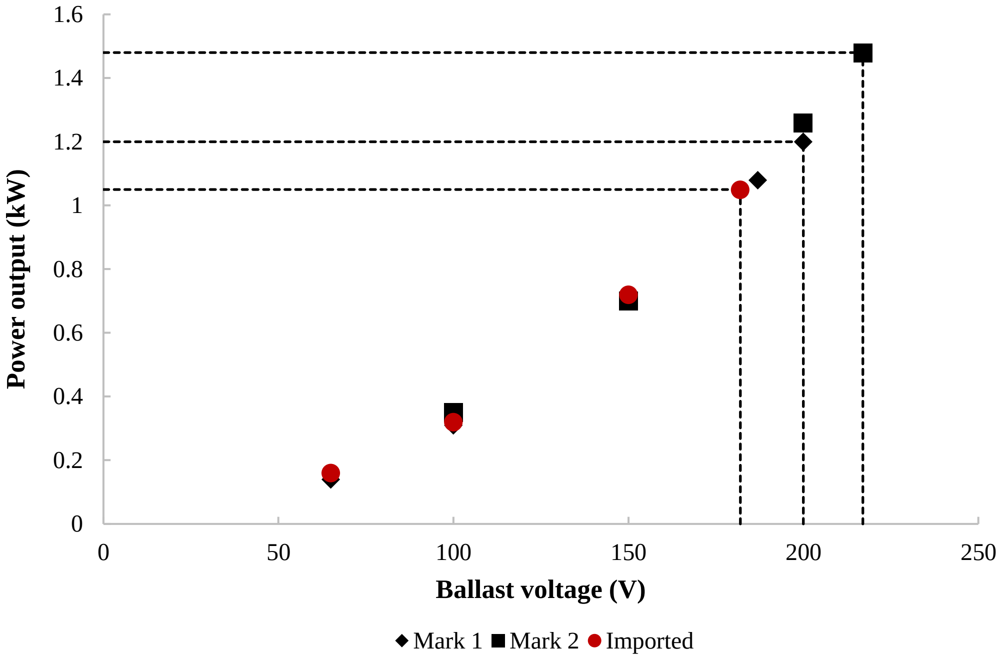


Figure 7.21 - Power output against ballast voltage for the three runners tested at the pilot site.

Table 7.11 - Open nozzle conditions.

Height above weir (mm)	Pressure gauge (kg/cm^2)	Estimated flow rate (m^3/s)	Estimated head (m)	Potential available power (W)
80	2.067	0.0156	20.61	3069

Table 7.12 - Estimated peak power efficiency of the Imported, Mark 1, and Mark 2 runners.

Runner	Power generated (kW)	Average available power (kW)	Estimated 'water-to-wire' efficiency	Percentage difference relative to the Imported runner
Imported	1.05	3.07	34.2%	-
Mark 1	1.20	3.07	39.1%	14.3%
Mark 2	1.48	3.07	48.2%	41%

The estimated 'water-to-wire' efficiencies have significant uncertainties and therefore are most useful in comparison to each other. The results clearly suggest that for broadly equivalent operating conditions, the Mark 2 runner achieved the highest efficiency. For the Mark 2 runner where the generator is operating closest to its rated voltage, it is reasonable to estimate the turbine's hydraulic efficiency. The peak rated power for the Mark 2 runner was approximately 1.5 kW (50% of the induction motor's rated load). In [208], Smith provides approximate efficiencies for a 2.2 kW IMAG under a numbering of loading conditions. For an IMAG operating at 50% rated load, Smith gives an approximate efficiency of 74.2%. Using this value, it is possible to derive an estimated hydraulic efficiency of 65.0%. It should be noted that the information used to derive the induction motor efficiency is for a different machine at a different rated power, however, the value for hydraulic efficiency appears realistic when compared to the results of laboratory testing. Repeating the method for the other runners is unreliable due to their operation further from the induction motor's rated voltage. Given the results of experimental testing, it was not an expected result that the Mark 1 runner would generate more power than the Imported runner. The reason for this was unknown and difficult to ascertain. The runners were installed with spacers to replicate the runner heights used in experimental testing. In the field, the runner was mounted directly onto the generator shaft rather than on a shaft connected to the torque transducer. It is possible that inaccuracies in the measurement for runner height between these two configurations was significant in affecting the efficiency. As mentioned previously, the author was not present during field testing. First-hand observation would have helped in the identification and prevention of spurious errors within the testing process.

7.7 Summary

In this chapter, the methodology, procedure and results of experimental testing have been presented. The testing rig and methodology led to results with a reasonable uncertainty in the middle of the core testing range (±1.46%) and produced efficiency-rotational speed curves that are typical for impulse turbines. The testing confirmed that the Imported runner was able to achieve the manufacturer's expected efficiency of approximately 70%. The Mark 1 runner was less efficient and tended to operate with a higher speed ratio. It is believed that manufacturing defects discussed in Chapter 6 affected the performance by increasing flow interference. The Mark 2 runner could not be tested on the experimental rig due to a problem with the torque transducer. Field testing was completed and indicated that the Mark 2 runner produced the most power at the highest efficiency. Whilst the same approach was repeated during field testing for each runner, the variation in environmental conditions, and the likelihood of random errors hinder the reliability of the results. Ideally, the Mark 2 runner should be tested on the same experimental rig under the same conditions as the Imported and Mark 1 runner.

In summary:

- The Imported runner was able to achieve the manufacturer's expected efficiency of approximately 70%.
- The Mark 1 runner's peak efficiency was lower (62%) and compared to the Imported runner, it tended to operate at a higher speed ratio.
- Field testing was completed and suggested that the Mark 2 runner produced the most power at the highest efficiency.

Chapter 8

Towards an open-source Turgo turbine design

8.1 Introduction

In the preceding chapters, the application of the DFL methodology led to a detailed understanding of the installation environment, project process, and the capability of manufacturers. This understanding of local context was used to inform the proposed design solution for a Turgo turbine runner. In this chapter, the actions taken are considered in relation to the DFL methodology and the experiences used to derive supporting principles. The ongoing use of the design and further design improvement depends upon its further replication. Consequently, this chapter explores the opportunity to make the design 'open-source' using the testing results to identify its application range, considering the potential to develop a complete scalable design, and proposing routes to replication for Nepal and elsewhere.

8.2 DFL: the Turgo turbine runner case study

In this section, the development of the Turgo turbine runner and its testing (presented in Chapter 6 and Chapter 7) is considered in relation to the DFL methodology. The work undertaken thus far is analysed in relation to the 3 key phases, whilst reflections on the process are used to derive further principles to aid future applications of the DFL methodology.

8.2.1 The process

As shown previously, the process of DFL is considered to include three phases. In Figure 8.1, activities that have been undertaken are grouped according to their contribution to each phase. It can be seen that the preparatory work undertaken in Chapters 4, 5 and 6 have all contributed to an understanding of the local context. Subsequently, this knowledge was used to design solutions for local manufacture. Finally, the manufactured prototype was tested and installed in the field.

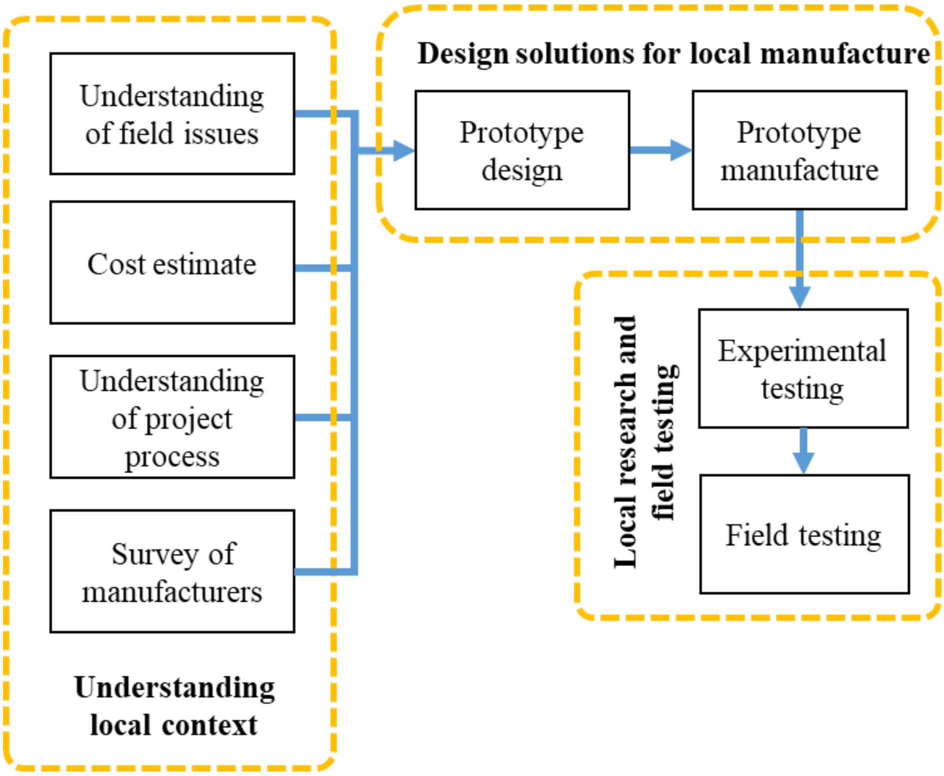


Figure 8.1 - Completed activities considered in relation to DFL.

The experiences of the study of operational plants resulted in an improved understanding of micro-hydropower in the context of Nepal. At the operational plants, a number of technical issues were identified including poor civil structures and issues in alignment of rotating components. These experiences supported the use of the Turgo turbine due to its resistance to abrasion and ability to be used in a directly driven arrangement. Alongside technical considerations, the assessment considered the social and economic aspects of the sustainability of the plants. A proposed design solution could not directly address these social issues, but they remained important in developing a contextual understanding. The analysis of the project process led to a greater awareness of the 'landscape' that projects are developed within, and the effect that this can have. It was established that there was a connection between the observed technical issues and the project process. By evaluating the project process, the occurrence of technical issues could be attributed to unclear designation of responsibilities and a lack of quality checks. The manufacturing capability survey provided a detailed understanding of the available processes and materials in Nepal. This ensured that proposed design solutions were feasible within the local context. The cost survey established an understanding of the baseline cost for hydropower technology in Nepal, allowing the cost of proposed solutions to be compared.

The proposed design solution used casting as the primary process in the manufacture of the runner blades. Based on the results of the manufacturer’s survey, it had been established that this process was familiar to manufacturers and appropriate for the local context. During manufacture, the selected material and process were unable to achieve the intended dimensions. As alternative material choices for casting had been identified, the material choice and design were changed. As this stage in the manufacturing process was repeated, it was possible to introduce a new quality assurance process. During the manufacture of the Mark 2 runner, templates were used to check the conformance to the expected dimensions during the finishing process.

Experimental testing was conducted in the country of use and used to demonstrate the efficiency of the newly manufactured runner. This helped to build familiarity with the technology amongst a wider range of engineering professionals within Nepal. The challenges faced during manufacture were, to an extent, confirmed during experimental testing, although it would have been advantageous to verify the performance of the Mark 2 runner. The prototype was installed in the field for ongoing monitoring. The installation used water extracted from a natural source and with electronic equipment (ELC and ballast tank) typical for this type of installation. However, the community located near to the installation site were already electrified from another source. Consequently, the use case was different from the expected application where a turbine is the only source of electricity.

8.2.2 Contribution to the Design for Localisation methodology

In comparison, to the original case study (see Section 3.2.1) and the others considered in Section 3.2.2, the Turgo turbine runner has yet to undergo prolonged field testing. Currently with a single installation operational for only a short period of time, there is a limited scope of field experience, both in quantity and duration. As such, there has not yet been the opportunity for lessons from the field to influence design changes. It should also be noted that the turbine runner represents only a single sub-system of the complete Turgo turbine.

However, the experiences of the project can still be usefully applied to inform the DFL methodology. Experiences derived from its application are valuable. They can be used to inform design changes for the Turgo turbine runner (as seen in the changes from the Mark 1 to the Mark 2) and inform subsequent use of DFL in other contexts. These supporting principles have all been formulated based on experiences and knowledge gained during the activities presented in Figure 8.1:

- **The construction and implementation of a technology occurs due to the actions of multiple stakeholders, the importance and interrelation of individual actions should be considered.**
  The development of a technology may be shaped by activities that occur within a project process. Whilst these may be difficult to directly design for, if they are understood, mitigating actions can be devised and implemented.

- **Where process limitations are not well known, there is value in learning-by-doing.**
  For some manufacturing operations, the limitations in the local environment may not be known. Through attempting something new, it may be possible to understand what these limits are, allowing them to be used in future design.

- **Materials and their selection are not always understood locally.**
  Local manufacturers may apply material selection based on experience and ‘rules of thumb’. For some applications this may be appropriate, but rigour should be applied where possible.

- **New manufacturing technologies can be used alongside existing ones.**
  Access to the internet is increasing both awareness and availability of new manufacturing technologies (e.g., additive manufacturing). Although these may be unfamiliar to local workshops, it may be possible to combine them with established technologies.

- **‘Familiar’ processes may require additional quality assurance when used in the production of new products.**
  When a manufacturing process is consistently repeated with an identical (or near identical) design, the application of the same process with a new design may present unexpected challenges. Design changes should be supported by quality assurance processes that are focused on preventing the development of these errors.

- **Design information should not be communicated verbally.**
  In some instances of local manufacture, the cultural context may mean design information is communicated verbally or through other informal methods. To avoid this, appropriate means of sharing design information should be identified.

- **Introduce jigs and guides wherever they are needed.**
  For workshops that produce a limited product range, new design solutions may pose challenges (e.g., work piece alignment and tolerance) during the manufacturing process. Communication with manufacturers is valuable in understanding these challenges and potential methods to reduce or remove them.

8.2.3 Continuing design improvement

In this work, the stages of the DFL methodology were followed, leading to a design for a Turgo turbine runner. Whilst successfully manufactured in Nepal, field testing of this runner design was limited. In Chapter 3, when the DFL methodology was proposed, a key supporting principle was that the DFL process may be non-linear. In the PT case study, challenges observed during field testing led to subsequent design changes. Similarly, in the development of the T-series Crossflow and the RHL turbines, designs were refined iteratively over a number of years based on experiences in the field. These experiences suggest that iterative design improvement forms a key part of the DFL methodology. Every installation and its local context provide experiences that can be used to drive design improvement.

As a result of this, the remainder of this chapter is focused on how further replication of the Turgo design could be driven using an open-source approach. Figure 8.2 shows the desired feedback loop for continuing the DFL methodology. An open-source Turgo turbine design would lead to local manufacture by new companies and an increased number of field installations. Each of these installations provides valuable experiences aiding the understanding of the local context. In turn, this can be applied to enable re-design that is focused on overcoming challenges from the field. An open-source approach allows these changes to be shared and incorporated where locally appropriate.

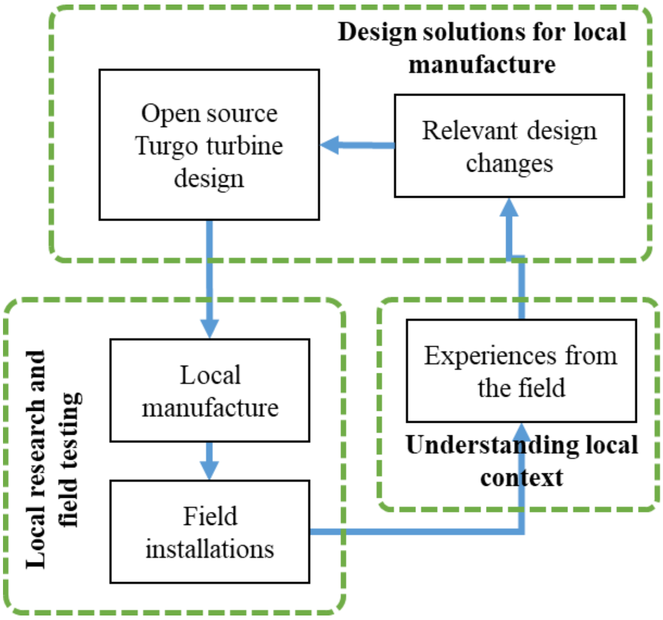


Figure 8.2 - Feedback loop for continuing the DFL methodology.

8.3 Development of an open-source design

In this research, the application of the DFL methodology resulted in the manufacture of two Turgo turbine runners. These runner designs are appropriate for the Nepali context, however, there are additional sub-systems where the DFL methodology requires application. As most of these components are (common to Pelton turbines and therefore) already manufactured in Nepal, and – in comparison to the turbine runner – their design is largely uncomplicated, they will not be considered here. Instead, there is greater value in contemplating how further replication of a complete Turgo turbine design could be motivated. If achieved, further replication would have a number of useful outcomes. Firstly, the DFL methodology can continue. The manufacture and installation of new Turgo turbines results in experiences that can be used to refine the design. Secondly, these new installations result could result in increased electricity generation for off-grid communities. Finally, if Turgo turbine replication is successful in Nepal, it may indicate a pathway for the introduction of other turbine types. The creation of a locally manufactured Francis turbine has been a long-held aim of Kathmandu University [231].

To achieve the objective of further replication of a complete Turgo turbine design, there are three interrelated challenges to overcome:

1. How to scale existing testing results to find alternative application ranges for the runner design?
2. How to create a complete turbine design that can be scaled alongside the runner?
3. How can all of the required design information be transferred to manufacturing companies (and other users) in both Nepal and elsewhere?

In this section, the scaling process will be presented for the Turgo turbine. Using the developed design and considering the engineering design limitations in the local context, the application range is calculated. Further, potential ranges for the finite blade sizes are also calculated. Subsequently, a methodology to make the design available ‘open-source’ in Nepal and elsewhere is proposed.

8.3.1 Scaling of the Turgo turbine design

For hydro-turbines in general, a turbine runner design is intended to operate at a particular rated head and flow rate. Whilst a turbine runner remains functional as the head and flow rate vary, there is a limit to the range of a single design. Consequently, for most turbine designs there is a recommended operational envelope. Outside of this, cost, efficiency, or reliability may prompt the use of a different design. From the testing results of a turbine, it is possible to predict the performance of a geometrically similar machine [221]. This process is achieved using laws of hydraulic similarity, otherwise known as non-dimensional (or dimensionless) parameters. For large scale hydropower plants where testing is unfeasible, it enables accurate prediction of performance based on a model [57, 232]. Using non-dimensional parameters, it is possible to find site characteristics, a rotational speed, and a scaling factor that determine rated operating conditions for a dimensionally similar turbine. This process allows the size of a turbine to be changed, and the resulting turbine performance predicted.

For 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.

$$C_Q = \frac{Q}{\omega D^3} \tag{8.1}$$

$$C_H = \frac{gH}{\omega^2 D^2} \tag{8.2}$$

$$C_P = \frac{P}{\rho \omega^3 D^5} \tag{8.3}$$

$$C_\omega = \frac{{C_P}^{0.5}}{{C_H}^{1.25}} = \frac{\omega P^{0.5}}{\rho^{0.5} (gH)^{1.25}} \tag{8.4}$$

In these equations, Q is the flow rate, ω is the rotational speed in rad/s, D is a length dimension (typically the PCD), g is the acceleration due to gravity, and H is the head. Specific speed is a dimensionless parameter associated with the maximum efficiency of dimensionally similar turbines [221]. Thus, if the performance of a turbine is known for a certain set of parameters, the specific speed of a dimensionally similar turbine will be equal. Consequently, for different types of turbine, there exists typical ranges of specific speed which indicate whether the turbine is appropriate for the particular site conditions. Table 8.1 shows ranges of specific speed for common turbine types.

Table 8.1 - Specific speeds for common turbine types, adapted from [221].

Turbine type	Specific speed
Pelton	0.094 – 0.15
Francis	0.32 – 2.3
Kaplan	1.9 – 5

The values that are used to evaluate these dimensionless groups are typically those that occur at the best efficiency point (BEP) of a physical turbine type. For the Turgo runner design, the values used are those derived from the CFD simulation which were the expected maximum efficiency results. Table 8.2 shows the BEP values from the CFD simulation.

Table 8.2 - BEP values from CFD simulation.

Parameter	Units	Original
H, head	m	14.7
Q, flow rate	m^3/s	0.0126
n, number of jets	-	1
d_j, diameter of jet	m	0.0312
a, scaling ratio	-	-
D, pitch circle diameter	m	0.1
N, rotational speed	rpm	1500
ω, rotational speed	rad/s	157
P, power	W	1475
C_ω, specific speed	-	1.02

In Table 8.2 - BEP values from CFD simulation.Table 8.2, it can be seen that the values are used to calculate a specific speed of 1.02. In comparison to the ranges presented in Table 8.1, this specific speed is higher than for the Pelton turbine. Physically, this result means that for equivalent values of head, flow rate, rotational speed, and power output, a Pelton turbine would require a larger diameter runner.

Turbines can be scaled by equating their dimensionless groups. As such, the ratios of key parameters for two turbines can be derived. From a set of experimental results for one turbine, this approach allows the design to be scaled depending on a desired output [233, 234]. Typically, the turbine selection depends on the head and flow rate of the chosen site. The following equations demonstrate an approach that can be used for the scaling of the Turgo turbine. For a given head and flow rate, the velocity of the jet of water that leaves the nozzle will be:

$$v = c_v\sqrt{2gH} \tag{8.5}$$

where c_v is the discharge coefficient. The required jet diameter for a given flow rate is:

$$d_j = \sqrt{\frac{4Q}{n\pi v}} \tag{8.6}$$

where n is the number of jets. For similar turbines, a length scaling ratio (indicated by a) will relate key dimensions.

Therefore, for 2 similar turbines indicated with subscripts 1 and 2:

$$a = \frac{d_{j,2}}{d_{j,1}} \tag{8.7}$$

The length scaling ratio can be used to scale the PCD similarly:

$$D_2 = aD_1 \tag{8.8}$$

For the two turbine types, X_R can be used to indicate the ratio between the original (indicated by subscript 1) and scaled turbine (indicated by subscript 2) for a particular parameter, X.

$$X_R = \frac{X_2}{X_1} \tag{8.9}$$

Using this relationship, Equations 8.1, 8.2, 8.3, 8.4 can be rearranged to:

$$\omega_R = \frac{{H_R}^{1.25}}{{P_R}^{0.5}} \tag{8.10}$$

$${D_R}^5 = \frac{{P_R}^{0.5}}{{H_R}^{0.75}} \tag{8.11}$$

$$Q_R = \frac{P_R}{H_R} \tag{8.12}$$

$$\omega_R = \frac{\sqrt{H_R}}{D_R} \tag{8.13}$$

Henceforth, N will be used for the rotational speed with the units in revolutions per minute. Equation 8.13 can be rearranged to:

$$N_2 = N_1 \frac{D_1}{D_2} \sqrt{\frac{H_2}{H_1}} \tag{8.14}$$

Similarly, Equation 8.12 can be used to calculate the output power. However, it should be considered that where there are multiple jets, the flow is split equally between the number of nozzles. Therefore, when relating turbines with multiple jets through non-dimensional numbers, the flow is divided by the number of jets.

$$P_2 = P_1 \frac{H_2}{H_1} \frac{Q_2}{nQ_1} \tag{8.15}$$

The scaling process results in a specific PCD and jet diameter for any combination of head and flow rate. In practice, particularly within the micro-hydro range, it is not cost effective to use a different PCD for each individual project. Furthermore, whilst the Turgo can be used at a wide range of heads (as seen in Chapter 7 and [52]), there will be some sites where the characteristics make another turbine type more appropriate. In Nepal, the survey of manufacturers demonstrated the typical approach taken for the selection, design, and manufacture of the Pelton turbine. Typically, a scaling spreadsheet is used that indicates an ‘ideal’ PCD and jet diameter. In practice, manufacturers own Pelton bucket moulds in a finite number of sizes. Based on experience and calculation, the manufacturers select a bucket mould (corresponding to a particular PCD) from the range that they have and determine the appropriate jet diameter. For Pelton turbines, manufacturers may have moulds for bucket PCDs from 100 to 400 mm in 25 mm or 50 mm increments [54]. In Nepal, micro-hydropower Pelton turbines rarely exceed 500 mm as above this size it is likely the Pelton turbine is not the most appropriate choice [54].

Similarly, the scaled rotational speed may also indicate that the selected turbine type is inappropriate. Typically, due to their availability and cost, the generators used at micro-hydropower sites are 4-pole machines with a rated speed of 1500 rpm [81]. In Chapter 4, this was true of every generator observed during the site study. Whilst other electrical machines are available, the familiarity and cost of 4-pole machines has made them the most prevalent in the market. To allow operation of these generators with a wider range of rotational speeds, belt drives are used. Existing literature suggests that for the full micro-hydropower range, a maximum step-up ratio of 3:1 can be used [54, 65]. This is based on the increased cost of transmission equipment (e.g., thicker shafts and larger bearings) for operation at low rotational speeds (< 500 rpm). Generators can be directly driven by hydro-turbines which reduces transmission losses and improves reliability due to fewer components [81]. It is suggested that a 1500rpm rated generator could be directly driven by a turbine with rated speed of -15% to +10% (of 1500 rpm) with only a small loss in the overall efficiency (1 to 2%) [54]. For higher rotational speeds, it should be considered that the runaway speed of an impulse turbine is approximately twice the rated speed [54]. Consequently, although it should only occur occasionally, rated speeds above 1500 rpm are usually avoided as the resulting vibration at runaway speed is likely to damage the turbine [54].

These experiences in the field and an understanding of the approach used for Pelton turbines in Nepal can be used to inform a practical application of scaling for the Turgo turbine. Table 8.3 lists the assumptions made in the scaling process.

Table 8.3 - Assumptions in the scaling process.

No.	Assumption
1	Turgo blades that correspond to particular PCDs are available within a range of 0.1 m to 0.4 m, at discrete intervals of 0.025 m. Blades will be selected from the nearest available size.
2	The lower limit of the turbine's rated speed is 500 rpm. This assumes that a flat belt with a ratio of 3:1 will be used to step up the rotational speed to match a generator's rated speed of 1500 rpm.
3	The upper limit of the turbine's rated speed is 1650 rpm. This assumes that the turbine can be operated at 10% less than its rated speed to directly drive the generator.
4	The scaling process will consider the Turgo turbine in a single and double jet arrangement only. Larger number of jets (e.g., 3 or 4) increase the complexity of the design significantly.

Using these assumptions and Equations 8.1 to 8.15, the rotational speed, PCD, and rated power can be calculated for any head and flow rate. Figure 8.3 plots the potential site characteristics for the range of PCD sizes. The red dashed lines indicate the interval between each PCD, i.e., when a line is crossed, a larger or smaller PCD (±0.025 m) is used. The continuous red lines indicate the lower and upper limit of the turbine's rated speed, i.e., outside of these lines, the turbine rotates too slowly or quickly to be used in combination with a 1500 rpm generator. The grey dashed lines indicate lines of constant power for 10 kW, 50 kW and 100 kW, i.e., a head and flow rate that lies on the grey line will generate that much power. Each area bounded by a combination of continuous and dashed lines indicates the ranges of head and flow rate where a particular PCD is appropriate. To facilitate identification of the relevant sizes, the regions that correspond to PCDs of 0.2m, 0.3m, and 0.4m are indicated. In the figure, it can be seen that as the PCD increases, the applicable area increases. Consequently, blades for larger PCDs will accommodate a larger range of sites.

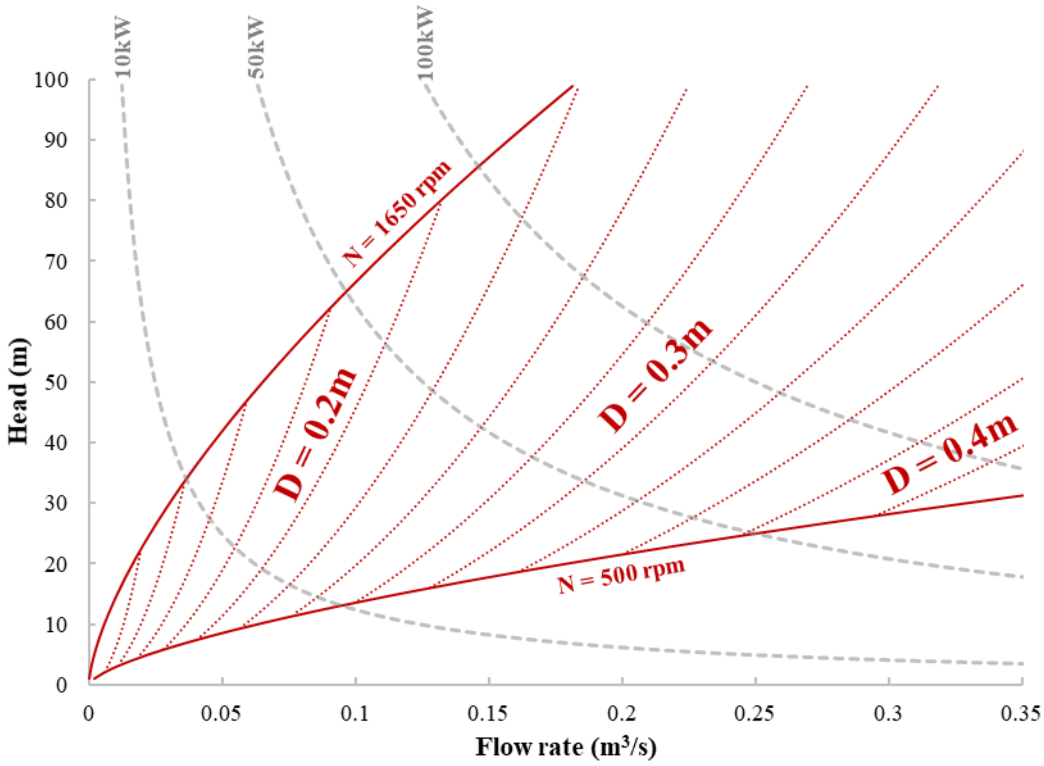


Figure 8.3 - Operating range of the scaled Turgo turbine at a number of PCDs.

Figure 8.4 plots the operating range for the Turgo turbine in both single and double jet arrangements. The formatting is similar to Figure 8.3, however, the dashed blue lines indicate boundaries for a double jet rather than a single jet Turgo. The labels include subscripts of ‘1 jet’ and ‘2 jet’ to indicate which arrangement they are referring to. It can be seen that in the 2 jet arrangement, lower heads can be achieved within the lower limit of rotational speed. Meanwhile, for an equivalent flow rate the 2 jet upper limit of speed occurs at a lower head. The labelled areas show that the same PCD blade can be used to service sites with different heads and flow rates depending on the number of jets.

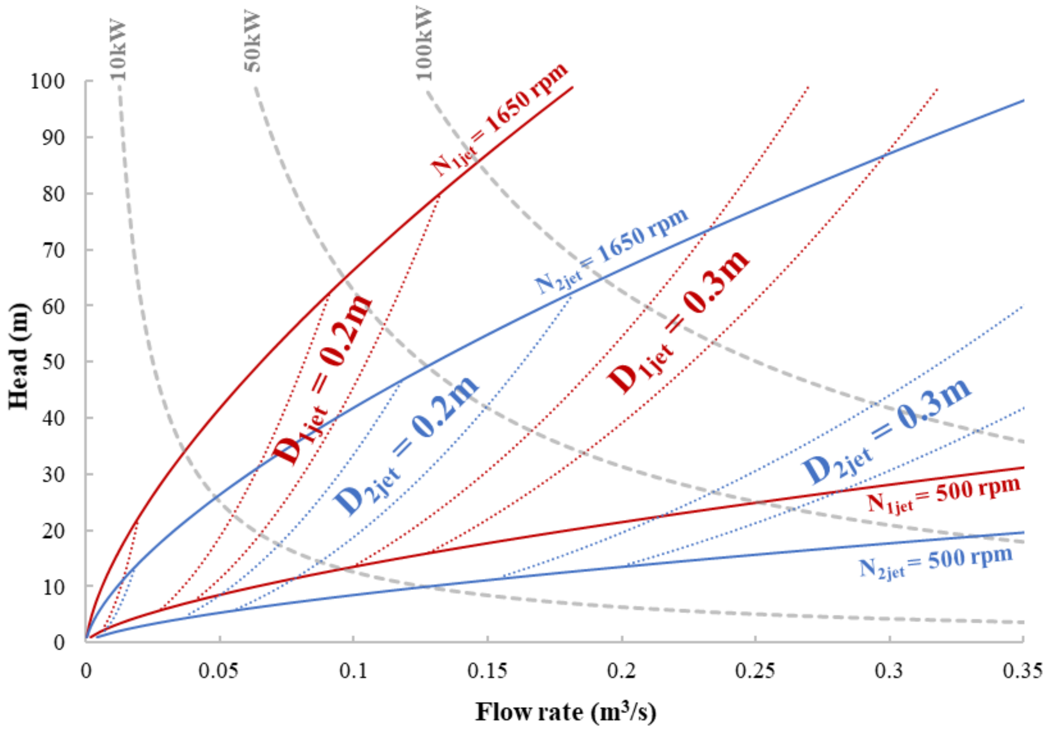


Figure 8.4 - Operating range for the scaled Turgo turbine in 1 and 2 jet arrangements.

A motivation (identified in Section 2.3.4) in exploring the Turgo turbine was its applicability to sites with characteristics at the intersection of Pelton and Crossflow turbines. To explore this, the same list of site characteristics of Pelton and Crossflow sites identified earlier in Section 2.3.4 was used in conjunction with the scaling data. Figure 8.5 plots the operating range for a single jet scaled Turgo turbine in relation to existing Pelton and Crossflow sites. The markers on the figure indicate the head and flow rate of these sites. The boundary lines for different PCDs have been removed, i.e., the area between the red lines indicates the range of Turgo turbines that can be used irrespective of the PCD selected. It can be seen that within the red lines, the majority of markers present are for Crossflow sites. Close to the upper speed limit, there are several Pelton sites that fall within the area between the lines. At lower heads, there are also a large number of Crossflow sites that fall outside the range of the Turgo.

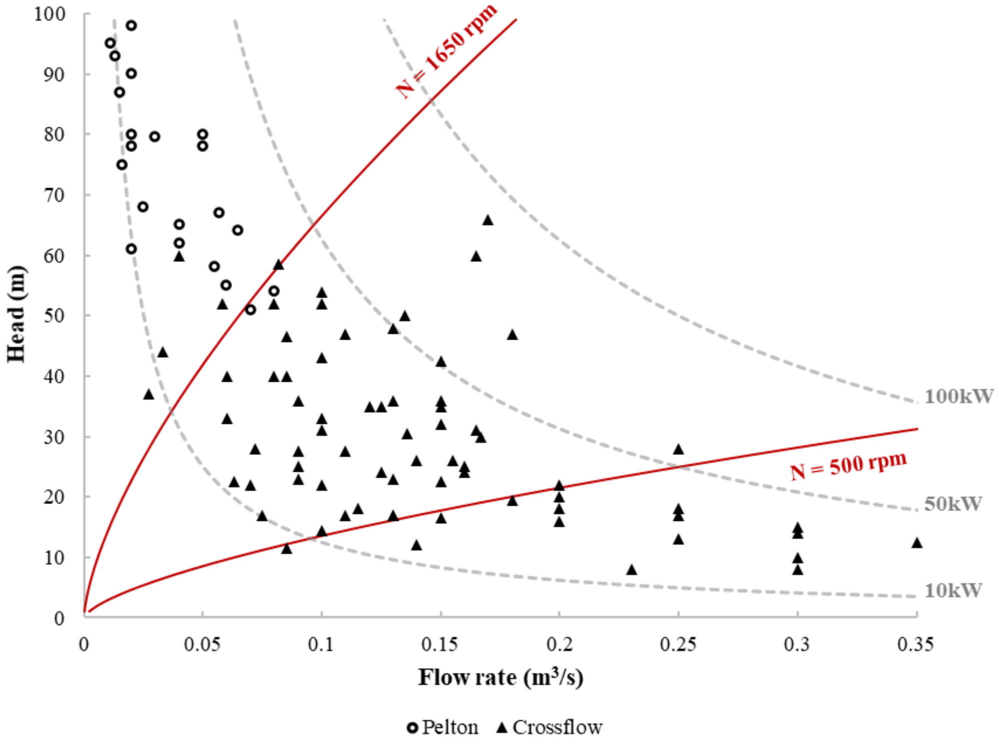


Figure 8.5 - Operating range of the scaled Turgo turbine in relation to existing Pelton and Crossflow sites in Nepal.

Given the objective of targeting the boundary between Pelton and Crossflow sites, it could be advantageous to target a larger number of Pelton sites at this boundary. The Pelton turbines constructed for lower heads tend to have large diameters making them expensive. Turgo turbines in this region would be more compact. To consider how to change the operational range of the Turgo turbine, it is possible to use the scaling equations assuming that the BEP had occurred at a head of 25 m rather 14.7 m. Figure 8.6 shows the operating range of the scaled Turgo turbine using this assumption. In this case, the area between the blue lines incorporates a larger proportion of the Pelton sites. It suggests that the scaling process can be used to target particular operational envelopes.

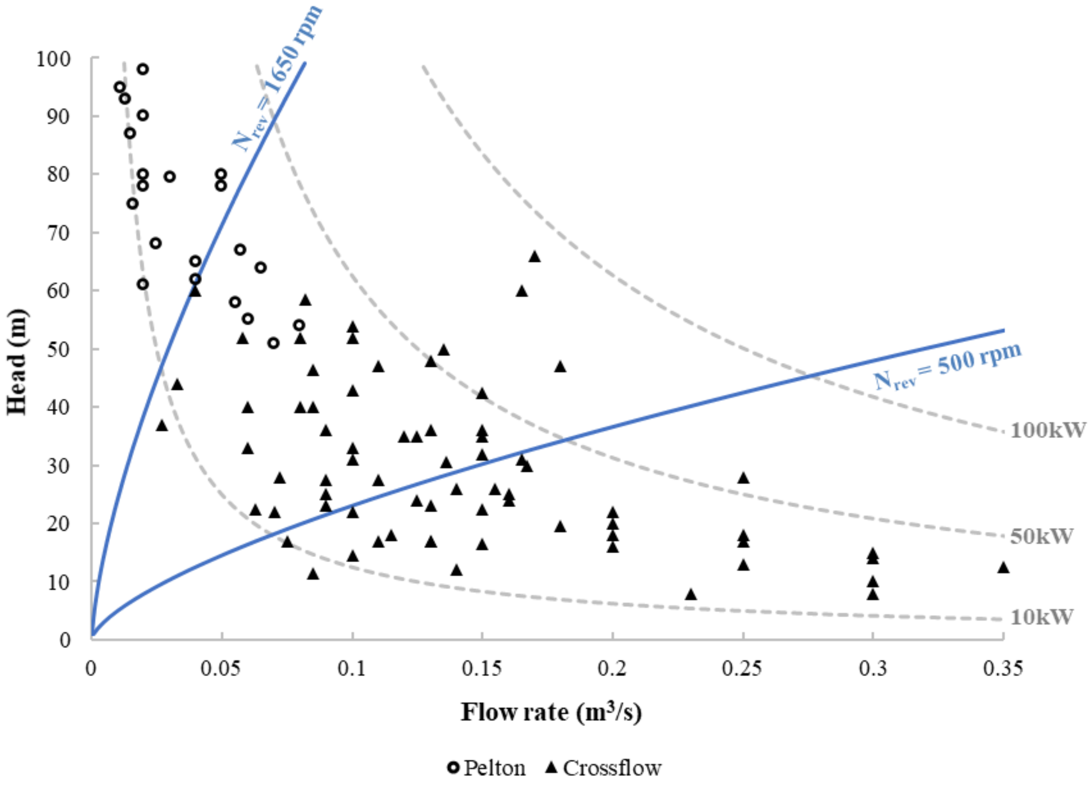


Figure 8.6 - Operating range of the scaled Turgo turbine assuming BEP at 25m, in relation to existing Pelton and Crossflow sites in Nepal.

In this section, an approach to scaling has been demonstrated. This approach can be used for any set of input values meaning that in the future, subsequent experimental testing results could be used for scaling, rather than using values from CFD. The scaling process was conducted with a finite number of runner sizes with the intervals for these runner sizes selected on an arbitrary basis. In practice, an analysis of cost and reliability will be required to identify the optimum range of discrete runner sizes. The results of the cost survey presented in Section 6.4 can be useful in comparing the cost of scaled Turgo designs to Pelton and Crossflow turbines in Nepal.

8.3.2 Design development

The dimensionless scaling of the Turgo runner demonstrates (numerically) that a finite number of scaled runner designs could be used to cover a potential operating range. Alongside the runner, the design of other components is also dependent upon the site characteristics. The head and flow rate drive calculations which determine the appropriate dimensions of components. Figure 8.7 shows the sequence of activities which could be used to design an impulse (Pelton or Turgo) turbine. The process begins with known site characteristics: head and flow rate. If hydrodynamic testing results are available for a similar turbine, it is possible to use non-dimensional scaling to determine the appropriate size of the runner and jet diameter, which inform the engineering design of multiple components. Where testing results are unavailable, the runner design is derived from site characteristics alone. For either case, engineering design is required for all of the sub-systems shown in the blue dashed box. For each of these components, design considerations include the strength, reliability, and required dimensions. Between components, interfaces need to be determined. Engineering design will also include the selection of bought-out components that are constituent in these sub-systems.

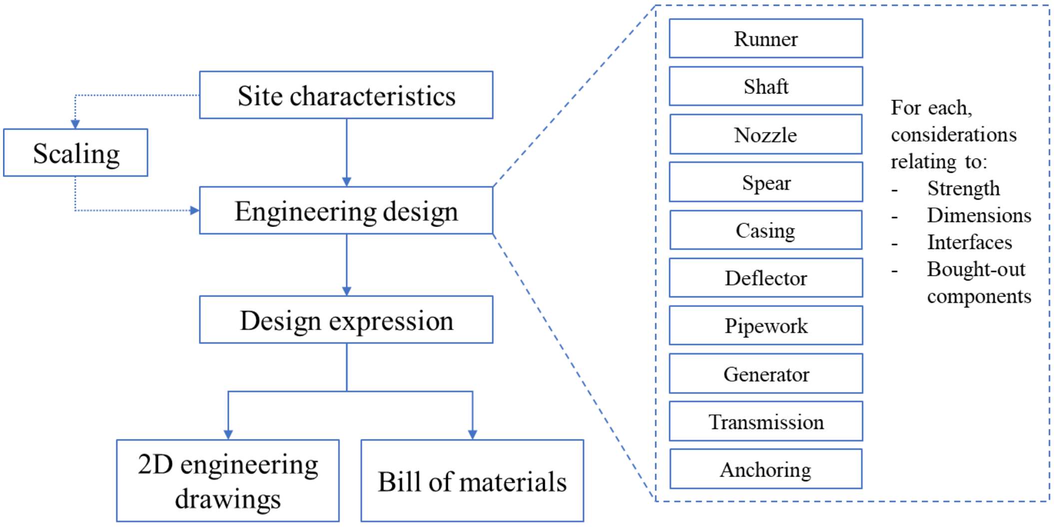


Figure 8.7 - Design process for an impulse turbine.

Using the Pelton turbine as an example, published guidelines exist to aid the engineering design of specific components. These are particularly useful for runner design where hydrodynamic results from a model turbine are unavailable. In [54], Thake provides a calculation (based on head and flow rate) to determine the runner PCD. Key dimensions of the turbine are then calculated using this value. Figure 8.8 shows the design of the bucket stem where the dimensions shown are determined in relation to "% PCD". Similarly, in [57], Nechleba provides a calculation for jet diameter which is then used to dimension other components. Figure 8.9 shows the bucket design with dimensions provided in relation to jet diameter, d_0.

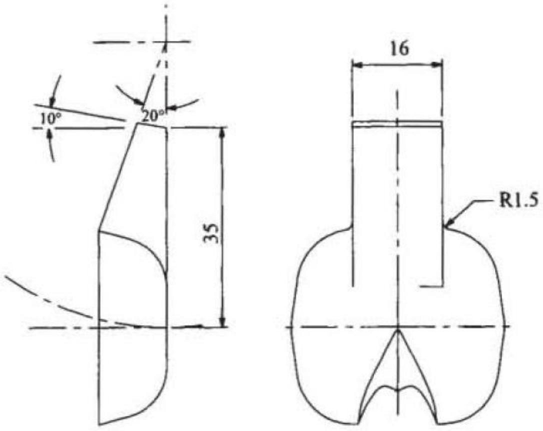


Figure 8.8 - Thake's design of a Pelton bucket stem. Image from [54].

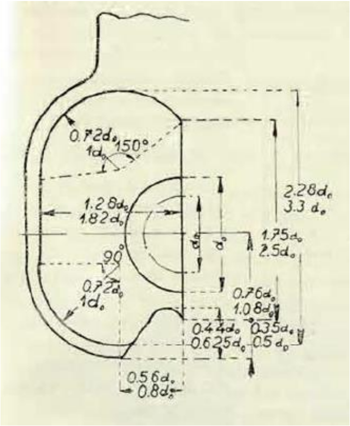


Figure 8.9 - Nechleba's design of a Pelton bucket. Image from [57].

These two examples show how site characteristics determine the development of a turbine design. Even with these guidelines, the responsibility remains with a designer to convert the numerical information into physical design information. Traditionally, design expression was in the form of drawings produced by hand. This was a time-consuming process where some replication of engineering drawings was possible (using tracing paper) but without any automation. More recently, CAD has allowed the faster production of engineering drawings and extended the opportunity for replication and increased automation. In Nepal, the interviews indicated that for the Pelton turbine, manufacturers used a spreadsheet to determine key engineering parameters and then adapted 2D CAD models accordingly. Subsequently, the CAD models were developed into engineering drawings.

Despite the use of CAD and spreadsheets, the complete design process used in Nepal remains time-consuming. To increase the availability of the Turgo turbine design, it is advantageous to minimise the most time-consuming design processes: engineering design, CAD design development, and the production of 2D drawings and a bill of materials. The properties of commercially available software (CAD and spreadsheet packages) allow the integration of these processes. Using CAD and spreadsheet software, it is possible to create a parametric 3D design. With relevant calculations for each sub-system, alongside integrated logic determining the selection of bought-out components, a complete system model can adapt to user inputs.

To demonstrate this, an indicative 3D CAD model has been developed. Figure 8.10 shows the CAD model of the lower half of the Turgo turbine. The model includes the core components of the runner, shaft, lower casing, nozzle, and spear. In addition, a pair of plummer block bearings are shown for reference. The key omissions are the spear actuation mechanism, jet deflector, pipework, transmission system, fasteners, and anchoring.

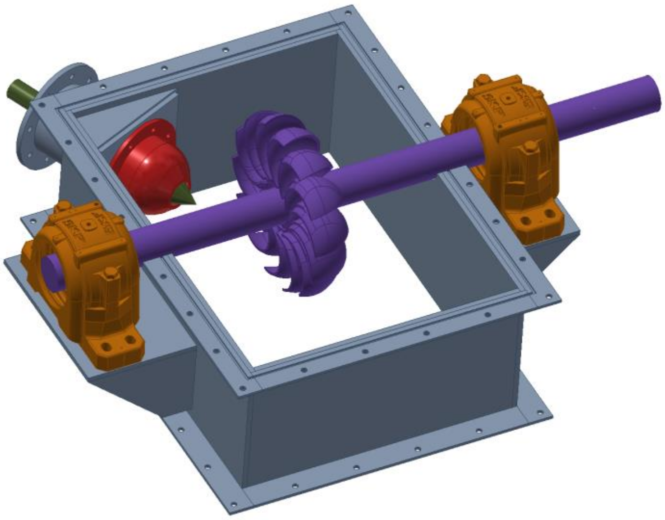


Figure 8.10 - Indicative CAD model of the Turgo turbine.

The potential of parametric design is explained using the nozzle as an example. The nozzle's function is to accelerate the flow of water and direct a jet of the correct diameter at the runner. It is assumed, as was found in Chapter 6 for Pelton nozzles, that the body is machined from bar stock, fabricated with a flange before final machining and finishing processes. Figure 8.11 shows the location of the nozzle and identifies its major dimensions. Table 8.4 lists these major dimensions and identifies a non-exhaustive list of key design considerations.

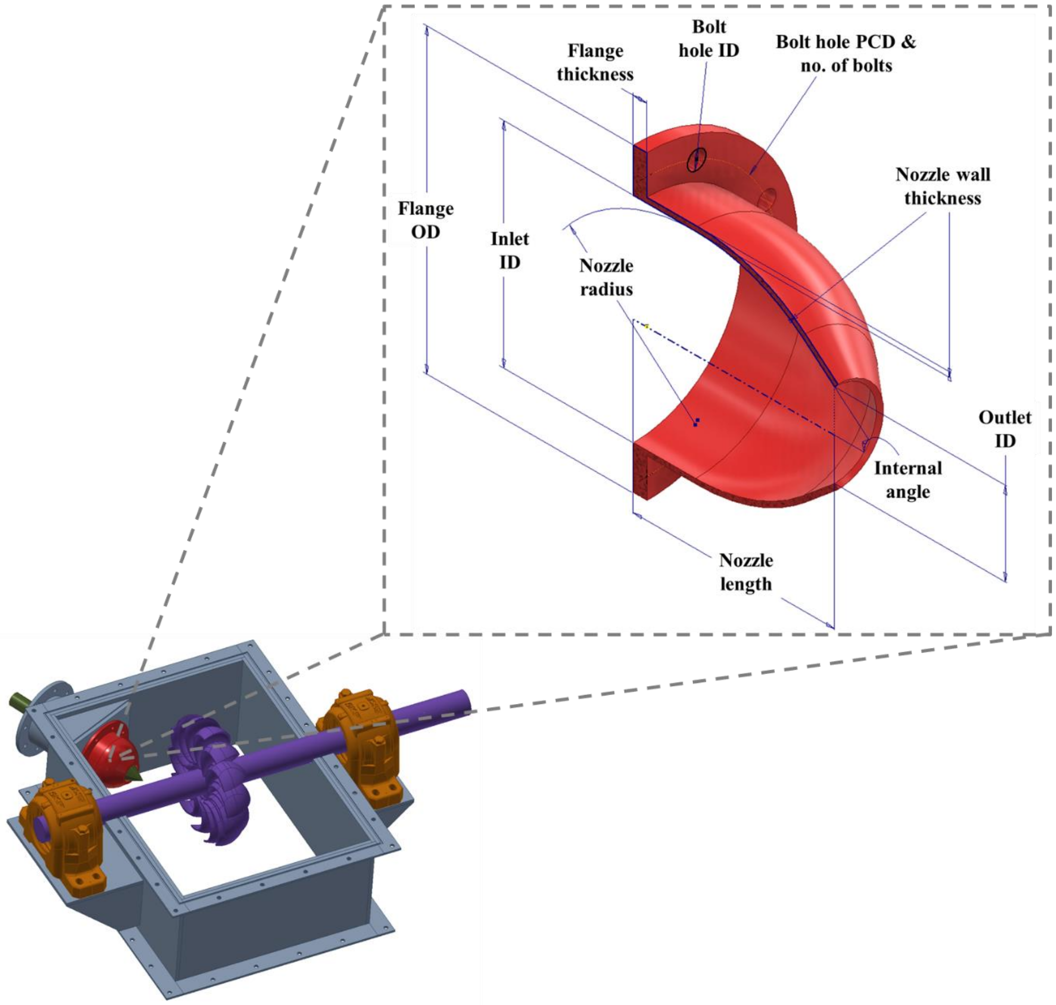


Figure 8.11 - Key design parameters for the nozzle.

Table 8.4 - Engineering design consideration in the parameterised nozzle design.

Dimension	Engineering design considerations

Flange outside	• Static pressure • Water hammer • Standard available flanges • Interface with casing
Flange thickness	• Standard available flanges • Static pressure • Water hammer • Standard fasteners
Inlet inside diameter	• Empirically proven constant from literature • Bar stock dimensions • Machining time
Nozzle wall thickness	• Static pressure • Water hammer • Bar stock dimensions • Machining time
Nozzle length	• Dimensions of spear valve • Interface with casing dimensions • Cost of bar stock
Outlet inside diameter	• Jet diameter
Internal angle	• Empirically proven constant from literature
Bolt pitch circle diameter	• Static pressure • Water hammer • Standard available flanges
Number of holes	• Static pressure • Water hammer • Standard available flanges
Hole diameter	• Standard fasteners

Within CAD, the labelled dimensions are the parameters that control this part. In the table, there are various types of design consideration. Many are direct engineering calculations. For example, considering the nozzle wall thickness, the hydrostatic head exerts a pressure which the thickness of material must safely sustain. Other design considerations depend upon the interaction of the nozzle with other components and standard parts. For example, considering nozzle length, it can be seen in Figure 8.11 that there is a limitation on the length to prevent fouling of the runner on the nozzle. Some design considerations are empirical constants recommended within hydropower literature, e.g. a nozzle internal angle is often recommended [54]. The most complex design considerations are those related to cost and material availability. These require the integration of local knowledge and compared to the other considerations – calculations and interfaces – would require most programming. Whilst feasible within the parametric arrangement, their consideration may be more effective when done ‘manually’. However, to consider the nozzle, the following example demonstrates hypothetically how they could be evaluated. Bar stock is more common in certain sizes, a potential trade-off could exist between ordering an (expensive) less common size that results in less machining time or using a (cheaper) commonly available diameter that requires more machining time. The cost of bar stock and price of machining are numerical values that are known or can be estimated. Therefore, it is feasible that an optimum design that satisfies dimensional and reliability requirements, at the lowest cost, could be automatically determined.

For every component, it is possible to generate a parametric model. As indicated for the nozzle, between components there are numerical relationships that exist. All of the engineering design including calculation, relationships between components, dimensions of standard parts can be contained in a single spreadsheet and linked to the design parameters for every component. Consequently, it is possible to conduct the calculations and propagate these results to the relevant design parameters. The development of a parametric model permits a number of advantages. Firstly, once the model exists, site characteristic information can be used to instantaneously develop a 3D model with correctly scaled dimensions. Secondly, the calculation spreadsheet can be used to drive the nature of the design. For example, the selection of factors of safety can be changed as desired. Finally, if a design improvement is identified, it can be incorporated into the ‘master’ model.

8.3.3 Information transfer

This section will consider how a scalable Turgo design could be made available in Nepal and elsewhere, using an open-source approach. In Section 8.3.2, it was explained that CAD software could be used to develop a 3D parametric model that changes in response to user inputs. Whilst this 3D model contains all of the design information required for manufacture, provision of the model is not necessarily the most appropriate method of information transfer. Effective means of transferring the information depends on the local context. The purpose of this section is to consider two cases where an open-source Turgo design could be used: in Nepal for the micro-hydropower industry and globally, for micro-hydropower companies and the ‘open-source hardware’ community. For the Nepal case, lessons from this research are used to suggest potential actions of stakeholders and regulatory measures that could support supportive the use of the open-source design.

There is value in returning to consider the 3 case studies outlined in Section 3.2.2 and the manner in which these turbines designs have been transferred (or shared) and subsequently replicated. In each of these case studies, the estimated production of more than 1,000 of each turbine design suggests successful modes of information transfer which could provide lessons for an open-source approach. For the Remote Hydrolight and T-series, design information was (and still is) available as 2D technical drawings. On the ground in Afghanistan, the original transferral of the RHL design to new workshops was carried out in person. Owen Schumacher, Anders Austegard [142] and their team, visited automotive workshops and constructed turbines co-operatively ensuring that important steps during manufacture were clearly communicated. This method was employed on the ground as it had been identified that understanding of engineering drawings was limited. Subsequently, to increase availability of the design, technical drawings and supporting documentation were made available online [235] and can be downloaded free of cost. It is believed that this has led to the design being used in other locations outside of Afghanistan [142]. The development of the T-series turbine took place in Nepal, initially at a single manufacturer [64]. After the establishment of the T-series, several books were published describing the sizing of turbines [64] and their fabrication [236]. However, Entec own the rights to the design and sell the drawing package (and licences to manufacture) to companies worldwide. In Nepal, the drawing package for the T-15 turbine was purchased by the AEPC and distributed amongst micro-hydropower manufacturers [222]. Elsewhere, Entec have conducted training to support manufacturers in the production of T-15 turbines. To use the drawing package, a calculation using the site parameters determines a width for the runner, with other dimensions varying accordingly [222]. Compared to the other examples, there is less literature which describes the transfer of the Peltric set design. After KMI had proven the concept of a small Pelton turbine with an integrated generator and control system, other manufacturers followed and developed their own versions. From the interviews with representatives from manufacturing companies (as shown in Chapter 5), it is likely that close inter-personal relationships meant that the design concept was communicated informally rather than using engineering drawings. These examples are not described specifically in relevant literature as open-source technologies, however, they can still provide applicable lessons. In particular, the two examples from Nepal show how design information has been shared and replicated, using different methods. For the Peltric set, it appears that this took place informally via direct contact between companies. For the T-15 turbine, intervention by the AEPC resulted in distribution of the design. Common to both cases is a willingness by companies to use new designs when their efficacy has been demonstrated, either informally (in recommendation between manufacturing companies) or formally (through government level support). These experiences suggest that similar mechanisms could be supportive to the use of an open-source Turgo design in Nepal.

As explored in Chapter 5, the subsidy-based project process determines many milestones within the development of micro-hydropower projects in Nepal. This contextual understanding is useful in evaluating how an open-source design could be used. Within tendering documentation, it was found that the technology type was usually specified. Therefore, for the Turgo turbine, the technology needs to be recognised as a viable option by the AEPC, RSCs and the consulting companies who conduct detailed feasibility studies. These stakeholders require the necessary information to determine the site conditions where a Turgo turbine is a superior choice to the other turbine types. The technology must be approved by the AEPC to ensure that under the correct circumstances, a subsidy will be provided. Manufacturing companies must be capable of producing the turbine in accordance with the design. Alongside the transfer of the design information, training and on-going support for manufacturing companies will also be necessary. The subsidy delivery mechanism provides additional opportunities to manage the risk of deviation from the Turgo design. Delivery of the subsidy should depend on the power output testing but additionally upon a factory acceptance test which determines the manufactured product adheres to the specifications of the design. The description of these measures provides an indication of how the Turgo design could be used and regulated in Nepal in practice.

In the examples considered previously, the communication of design information depended on a combination of 2D engineering drawings and face-to-face interaction. These in-person interactions were useful where there was uncertainty in local capacity, when pertinent design details required reinforcement or when particular manufacturing techniques needed to be learnt. Since the development periods of these case studies, there have been significant changes in technology and access to it. An open-source approach today can incorporate these technological developments. In 2017, World Bank Data indicated that 21% of the population had internet access in Nepal [237]. Meanwhile, at all of the manufacturing companies interviewed in Chapter 5, CAD software was used. More recently, additive manufacturing has enabled rapid prototyping and is available at Kathmandu University and elsewhere [238]. In Nepal, micro-hydropower is well understood across society and supported through government subsidy. Amongst established companies, there are many years of experience which informs approaches to the design, manufacturing, and implementation of projects. These changes to technology access and the landscape of micro-hydropower in Nepal have a significant impact on the way in which designs can be communicated, developed, manufactured, and experiential knowledge exchanged. Efforts to improve the availability of the Turgo turbine in Nepal can take advantage of these changes.

In Nepal, the target audience for design transmittal is micro-hydropower manufacturers. At these companies, it is assumed that the available equipment is typical for a micro-hydropower manufacturer in Nepal (e.g., similar to NYSE), that there is internet access, ability to use a spreadsheet program, open .pdf files, and to open and edit .dwg files. As found earlier, the production of the Pelton turbine depends upon using a design spreadsheet and adapting 2D CAD files accordingly. For the Crossflow turbine, design information is extracted from the Entec T-15 drawings and is usually adapted on CAD. For these two turbine types, manufacturers possess all of the design information that they require to build the turbine.

For the Turgo turbine, the design information needs to be transferred in a way that is usable by these manufacturing companies. To explain this, it is assumed that there is complete parametric model for the Turgo turbine (as explained in Section 8.3.2). In Nepal, as use of 3D CAD software is not widespread, provision of the complete parametric model is not an effective method of information transfer. Instead, it is advantageous to provide 2D engineering drawings as .pdf and .dwg as these formats are widely used. Thus, it is necessary to develop engineering drawings from the 3D parametric model. These complete sets of engineering drawings should correspond to each of the runner PCD sizes. A complete engineering drawing package, including drawings and bill of materials, is required for each runner PCD size. For the micro-hydropower manufacturers, a spreadsheet-based tool could be used to input site characteristics and determine whether a Turgo turbine is feasible. If so, the spreadsheet would inform the designer of the correct PCD runner and thus the drawing package that should be used. For the blade profile, 2D engineering drawings cannot be used to fully capture the complex blade dimensions. Therefore, 3D printing remains the most effective means of information transfer. Availability of 3D printing at Kathmandu University and Nepal Communitere Makerspace [239] could allow manufacturers to procure the 3D designs they require. Alternatively, a library of physical designs could be held in country. In the longer term, individual ownership of the specific blade designs (as with the Pelton) would allow most timely production.

Globally, for the open-source community and micro-hydropower manufacturers elsewhere, to transfer the design it is appropriate to make the 3D parametric CAD model available alongside the design packages for the specific runner sizes. This information will allow manufacture of the Turgo turbine design in locations where manufacturing facilities are similar to Nepal, and there is capacity to procure a 3D printed mould. Given the increasing availability of additive manufacturing, it is hoped that this could motivate other companies to produce the Turgo turbine design. In the context of Nepal, it is known that the institutional stakeholders can provide some regulation of the use of the design. Elsewhere, it should be considered that wider replication increases the possibility of incorrect or inaccurate use of the design. There are a number of general measures that should be taken to avoid this. A commonly cited example of successful open-source hardware are small-scale wind turbines [25, 128, 240], and specifically the Piggot wind turbine [241]. Despite differences between small-scale wind and hydropower, open-source designs in both should adhere to specific requirements. This is particularly important in terms of user safety and the functionality of the technology. In [241], Piggot states that the guidelines he provides are followed at the user's own risk, and provides common failure modes and mitigating actions. Alongside the design itself, supporting information on operation and maintenance is also important [240]. For wider use of an open-source Turgo design, it is necessary that users are provided with all of the relevant design information, a detailed explanation of the risks involved, and comprehensive information on how to manufacture and use the technology. With the correct available information to ensure safe replication, sharing of the design enables interrogation, adaptation, and re-use of the design. This provides an additional opportunity for continuation of DFL. Using the internet, individual experiences in production and use of the Turgo turbine design can be recorded and shared leading to subsequent design progression.

8.4 Summary

In this chapter, it was shown that the development of the Turgo turbine runner has followed the stages of the DFL methodology outlined in Chapter 3. The approach led to the identification of several supporting principles that can be used in future applications of DFL. To continue the DFL process for the Turgo turbine, further replication of the design is required. An open-source approach was proposed as a way to increase uptake of the design. It was demonstrated that existing results can be used to scale the runner. A number of different runner sizes can be used to cover the range of sites with feasible characteristics. The creation of a complete parametric model that adapts depending on numerical inputs was proposed. Finally, it was shown that this scalable model can be used to provide all of the required design information for Nepal and elsewhere.

In summary:

- The development of the Turgo turbine runner followed the DFL methodology and resulted in the derivation of a number of supporting principles.
- An open-source approach can be used to promote replication of the design and the integration of subsequent improvements.
- Using non-dimensional scaling, a model was developed that allowed determination of appropriate runner dimensions in relation to head and flow rate.
- For the context of Nepal, it was identified that discrete design packages related to specific blade sizes was the most feasible method of information transfer.

Chapter 9

Conclusions and future work

9.1 Discussion

The motivation for this work was improving the reliability and sustainability of small-scale energy projects, specifically micro-hydropower in Nepal. To explore this, a design methodology was proposed and applied to the development of a Turgo turbine runner design, appropriate for manufacture and use in Nepal. Research activities (that were constituent in the design methodology) were diverse, leading to a range of outcomes that can be considered significant both independently, and collectively.

The review of literature identified opportunities to improve the reliability and sustainability of community owned and operated mini-grid systems. Existing research indicated that the complex socio-technical nature of these systems was a challenge to sustainable operation. Micro-hydropower in Nepal was identified as a particular example of this, with additional technical challenges related to its locally manufactured equipment. To explore this, a technology rarely produced in Nepal, the Turgo turbine, was identified as a case study that could be used to consider how to successfully develop locally manufactured technology, where reliability and sustainability of its ongoing use were key objectives. Based on an existing case study, Design for Localisation was proposed as a design methodology focused on developing solutions appropriate for a local context in terms of use and manufacture. Three key stages were proposed from a detailed case study and supported by evidence in supporting literature. The design methodology was used to inform a research methodology to fulfil the research objectives.

A field-based study was used to understand the factors affecting sustainable operation of MHPs in Nepal. Based on evaluation of existing literature regarding the assessment of small-scale energy projects, technical reliability, financial viability, and community engagement were identified as key factors. A field study using a mixed-methods approach was devised to address these areas, and was conducted at 24 MHPs in Nepal. The findings demonstrated that at the operational stage, the interaction between community and technology makes achieving sustainability complex. There was strong evidence that inherent features of each MHP can make a site more or less likely to be sustainable. This understanding of the local context can be useful when considering new projects and in identifying existing projects where sustainability may be weak. The significance of this finding is not limited to micro-hydropower, for other small-scale energy projects inherent site features may also be significant. It was also found that amongst the MHP sub-systems, there were both social and technical problems that began in earlier project phases. This finding (which can also be applied in other contexts) is useful in demonstrating that early prevention of operational issues may be possible.

The identification of the importance of the project process and the ‘landscape’ that it takes place in, led to a detailed examination of the project timeline, the involved stakeholders, and their actions. The objective was to understand how issues identified during the field study (and in other literature) develop during the project process and identify opportunities to prevent their occurrence. A variety of methods were used to collect information including a detailed review of government documentation, an interview with a government official, and interviews with representatives from manufacturing companies. Consequently, it was possible to categorise the involved stakeholders and identify their actions throughout the project timeline. From the field study and other literature, a comprehensive list of potential operational strengths and weaknesses was developed. Based on the timeline and actions of the stakeholders, it was possible to understand how these strengths and weaknesses develop. It was found that there were opportunities to address sustainability issues through quality assurance and capacity building. The subsidy driven process in Nepal provides an opportunity to ensure that required standards are met. These findings could be applied by the AEPC in Nepal. More broadly, they indicate that the development of community energy projects which involve institutional, industrial, and community-based stakeholders require careful consideration. Although project completion may be readily achievable, sustainable operation of projects requires greater coordination of stakeholder actions.

In line with the stages of the DFL methodology, the field study and project process evaluation were successful in improving understanding of the local context in Nepal. However, to progress to the development of appropriate design solutions required an awareness of local manufacturing capacity, and the availability of materials and processes. To do so, a survey was conducted with representatives of 8 micro-hydropower manufacturing companies in Nepal. Detailed analysis of the production process for Pelton and Crossflow runners identified numerous opportunities for increased quality assurance. The survey led to identification of the range of processes and materials that could be used in the manufacture of the Turgo turbine. Alongside manufacturing capability, a cost survey was used to establish baseline costs for Pelton and Crossflow turbines in Nepal. It found that the penstock, turbine, and generator were the most expensive sub-systems. The collected data was used to develop numerical expressions for the prediction of the cost of Pelton and Crossflow installations (excluding civil structures). They could be used in Nepal to identify approximate expected costs for hydropower equipment, and to compare costs of small-scale hydropower equipment worldwide.

The improved understanding of manufacturing capability was applied to the design of a locally appropriate Turgo turbine runner. CFD was used as a tool to aid design improvement. Unlike its conventional use, restrictions derived from the local context were used to bound the design progression. As such, the design development was focused on driving an improvement in efficiency with a relatively small number of simulations. The design process used a 3D CAD representation of an Imported Turgo turbine runner as the baseline design. Its development depended on using a DOE approach to identify major dimensional changes (e.g., height, width, and depth) followed by incremental improvements driven by parametric control of the blade profile. Analysis of the torque results and flow visualisation were used to aid design decisions. Initially, through varying the offset, the efficiency of the original design was significantly improved from 55.4% to 69.0%. Subsequent changes resulted in an eventual improvement to 82.5%. Compared to the use of CFD in large scale multi-variable parametric design improvement, the approach used relatively little computing power. However, it depended upon analysis of visual and numerical data to inform design changes. At stages during this process, design changes were made which did not result in improvements in efficiency. Initial improvements in efficiency came most quickly. Consequently, it is suggested as an appropriate method for making changes from low (~ 60%) to medium efficiency (> 70%) when access to significant computing power is unavailable. Continual improvement to high efficiencies (> 80%) in this manner is likely to be an inefficient approach. Analysis of experimental results in the literature indicate that there may be opportunities to improve efficiency through the variation of geometric relations between the nozzle diameter and (i) PCD, (ii) blade width, and (iii) number of blades.

Working with a local manufacturing partner, the digital model was developed into a locally appropriate Turgo runner design. Initially, based on the manufacturing capability survey and the preference of the local partner, the runner blades were cast in steel and welded to a central hub. To transfer the blade’s design information, additive manufacturing was used;

a 3D printed design was used to produce a mould for the casting process. Due to communication issues around the material required for shrinkage, the cast steel blades were considerably thicker than the intended design. Consequently, an alternative design was developed using blades cast in brass, bolted onto a hub. The manufacturing process revealed unexpected challenges relating to communication and its effect on the manufacturing process. In general, the use of additive manufacturing and the internet was found to be a successful means of transferring design information and could be used in applications outside hydropower.

As part of the DFL methodology, local testing was identified as a key stage. A testing rig was developed that allowed the performance of the Imported and manufactured runners to be compared through the variation of head, flow rate, and rotational speed. During testing, the pitch circle diameter and nozzle diameter were held constant. In experimental testing, it was found that the Imported runner achieved the manufacturer's expected efficiency of approximately 70%. The Mark 1 runner was less efficient and tended to operate with a higher speed ratio. However, it was found that the efficiency of the Mark 1 runner improved at low head. It is believed that the relationship between nozzle diameter and PCD was significant. At lower heads, thinner fluid films resulted in less interference with the trailing blades. The results of testing were used to identify regression coefficients that could be used to predict performance. A second order expression involving terms related to speed ratio and flow rate was derived. A second phase of testing with the brass runner was attempted. However, erratic results from the torque transducer prevented the collection of this data. A field-testing site was developed close to Kathmandu. At this site, flow from the tailrace of an existing MHP was used to power the Turgo turbine. The turbine was integrated with an ELC and ballast load. Basic testing was used to compare the performance of the Imported, Mark 1 and Mark 2 runners in environmental conditions. Although unreliable and with significant margin for error, the testing suggested that the Mark 2 runner was the most efficient of all of the runners. The experiences of testing in the laboratory and in the field highlighted several challenges of local testing in Nepal. Procurement times for equipment were very long with multiple unexpected delays. In addition, when the torque transducer broke, there was no local capacity for repair.

By following the stages of the DFL methodology, a locally appropriate Turgo turbine runner was designed, manufactured, and tested. The process identified a number of principles that were supportive to the methodology and could be applied in other contexts. For the Turgo turbine, further replication and subsequent iterative improvements depend upon the availability of the design. The creation of an open-source design was posited as the most effective route. Using non-dimensional scaling, a model was developed that allowed determination of appropriate runner dimensions in relation to head and flow rate. Constraints were applied based on locally available generators and transmission arrangements. The development of a parametric turbine design, integrated with a spreadsheet, was proposed as a means to rapidly produce the design information appropriate for any viable site. For the context of Nepal, it was identified that discrete design packages related to specific blade sizes (available as 3D printed moulds) was the most feasible method of transferring design information. Elsewhere, complete CAD models could be used to replicate the design, extending the opportunity for further installations leading to subsequent design changes and improvements.

In this thesis, the application of the DFL methodology has been successful in the development of a locally appropriate Turgo runner. The stages of the methodology and supporting principles were followed. Whilst not prescriptive in its nature, the methodology promotes stages of good practice to be followed. The approach taken in this thesis was exhaustive and extensive (to fulfil other research objectives), going beyond what is reasonable within a design process, and exploring issues that conventional engineering design may not be able to address. However, it is believed that for engineers intending to apply the DFL process, developing a basic understanding of local context through interview should be considered a minimum objective. The subsequent stage of understanding local manufacturing capacity is very important. The approach taken here was again exhaustive but necessary given that manufacturing capability was unknown and was described largely anecdotally in the literature. The developed design solutions were appropriate for local manufacture, although their development indicated numerous challenges to overcome. As identified, the DFL methodology may depend on iterative stages of design development. In the application of the methodology, local testing was the most significant weakness. Currently, a precise efficiency for the Mark 2 runner remains unknown. However, the installation in the field provides an opportunity for the reliability of the runner design to be evaluated. Consequently, it can provide useful experiences to inform subsequent design change.

9.2 Key research outcomes

The key research outcomes are described in relation to the research objectives:

1. **To understand the factors that affect the sustainability of plants.**

A field-based study was devised to evaluate technical reliability, financial viability, and community engagement. These three areas were identified from available literature as important and interrelated. The study used a mixed-methods approach to gather a diverse range of information. For micro-hydropower in Nepal, the findings indicated specific technical issues that develop at a range of stages. Findings that could be applied more widely to other community-based energy projects were that inherent features of a project location, and events internal and external to the plant were important in determining sustainability.

2. **To evaluate the development of threats to sustainability within the project process.**

The project process which depended on the actions of multiple stakeholders was evaluated through a review of government documentation and semi-structured interviews with a government official and manufacturing companies. Using the findings from the field study, the development of operational strengths and weaknesses was characterised for the project process. Consequently, it was possible to identify opportunities within the project process to prevent operational weaknesses and reinforce strengths.

3. **Evaluate the approach and capability of micro-hydropower manufacturers.**

To understand the capability of micro-hydropower manufacturing companies, a survey was devised. The survey used predominantly closed question generating a combination of quantitative and qualitative data. The information demonstrated the experience of manufacturing companies, available processes and materials, and the typical approach taken during the production of key components. The collected data was useful in understanding opportunities to introduce greater quality assurance during the production of hydropower equipment. For the proposal of new design solutions, the information regarding capacity could be used to ensure that designs are locally appropriate.

4. Develop a new locally appropriate turbine runner design.

The knowledge regarding local capacity was used to specify a manufacturing process and relevant design restrictions. CFD was used as a tool to facilitate improvement in the efficiency of a Turgo blade design. Working in collaboration with a local manufacturing company, a CAD model was developed into a complete runner design. CAD, additive manufacturing, and the internet were used to transfer the blade design and produce a mould for casting. Due to problems in manufacturing, 2 versions of the runner design were developed. The locally manufactured runners were tested in the laboratory and the field.

5. Apply a design methodology that enables the development of locally appropriate design solutions.

Design for Localisation was proposed as a design methodology to adapt an existing design for local manufacture and use in a new context. After establishment and validation based on existing case studies, the design methodology was applied in this thesis. The key stages and principles of the methodology were followed and resulted in the Turgo runner design. An open-source design methodology, dependent on hydrodynamic scaling, a parametric CAD model and the use of additive manufacturing, was proposed as a route to further replication of the design.

9.3 Future work

Derived from the research, the following are areas for future work:

- The field-based methodology (devised and presented in Chapter 4) can be adapted and applied to evaluate the sustainability of other off-grid renewable energy technologies, e.g., wind and solar.
- Analysis of project processes for subsidy-based community owned energy technologies could be used to understand innovative approaches used elsewhere that drive project sustainability.
- To understand opportunities to improve financial viability of MHPs, a power consumption and tariff level model could be used. Whole system modelling of the power used by consumers and productive end uses could help to establish appropriate tariff levels that are equitable for all consumers and ensure income for the plant.
- Focusing specifically on Pelton and Crossflow turbines, further opportunities can be identified to implement quality assurance methods into the design and manufacturing process.
- Laboratory-based experimental testing of the Mark 2 runner is required to determine its efficiency. Validation of the results of simulation in CFD can provide confidence that scaled versions of the turbine will deliver the expected efficiency.
- In other fields, further case studies supportive to the Design for Localisation methodology can be derived. These can be used to identify further supporting principles for its application.
- The installed Turgo turbine requires ongoing monitoring and regular inspection. Experiences from the field should be documented as they will be useful in subsequent installations and informing potential design changes.
- In Chapter 8, it was shown that multiple Turgo runner sizes can be used to cover a range of site characteristics. Based on considerations of cost and reliability, the intervals of these runner sizes should be determined.
- Using the discrete runner sizes, a selection of complete Turgo designs appropriate for manufacture in Nepal can be developed. The results of the cost survey can be applied to determine whether complete designs are competitive with existing technology in Nepal.

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Appendices

Appendix A

Interview questionnaires

A.1 Site assessment interviews

A.1.1 Survey with plant operator survey

DQ1	Gender?	Male	Female
DQ2	Age?	15 to 25	
		26 to 36	
		37 to 45	
		46 to 55	
		56 or more	
DQ3	What is your education attainment level?	Does not know how to read	
		Can read and write	
		Incomplete elementary school	
		Completed elementary school	
		Completed high school	
		Incomplete high school	
		Completed course	
DQ4	How long have you been working as the plant operator?		

Q1	Are you the only plant operator?	Yes	No (go to Q1a)
Q1a	How is the job shared?		
Q2	Did anyone have this job before you?	Yes	No (go to Q2a)
Q2a	Why did they leave the job?		
Q3	Did you attend plant operator training?	Yes	No
Q4	Do you have a training manual from plant operator training or any other instructional documentation that you follow?	Yes, please specify	No

Q5	What is your salary?				
Q6	Is it a good job and why?	Extremely good			
		Good			
		Not good or bad			
		Bad			
		Extremely bad			
	Why?				
Q7	Do you have any other work?	Yes, please specify	No		
Q8	Does the plant operate for the same number hour each day?	Yes, how many?	No (Go to Q8a)		
Q8a	If different, please enter number of hours in morning, afternoon and night for each day of the week?	Day	M	A	N
		Mo			
		Tu			
		We			
		Th			
		Fr			
		Sa			
		Su			
Q9	How many hours do you spend working at the MHP plant every day? (*Either in the powerhouse or on the civil works*)				
Q10	Do you follow a maintenance schedule?	Yes (go to Q10a)	No		
Q10a	Do you have it in the powerhouse?	Yes	No		
Q11	Do you keep a logbook?	Yes (go to Q11a)	No		
Q11a	Do you have it in the powerhouse?	Yes	No		
Q12	Were you given tools after commissioning?	Yes (go to Q12a)	No		
Q12a	Do you have them in the powerhouse?	Yes	No		
Q13	Do you keep spare parts?	Yes (go to 13a)	No		
Q13a	If yes, what? (Tick all that apply)	Belt			
		O-ring material			
		Gasket material			
		Grease			
		Bearings			

		Fuses	
		Paint	
		Oil	
		Others, please specify.	
Q14	Where do you buy these spare parts? Specify for all mentioned in previous question		
Q15	What parts of the system have broken in the last year? (Tick all that apply)	Civil components	
		Valves	
		Turbine runner	
		Bearing	
		Turbine shaft	
		Generator bearing	
		Belt	
		ELC	
		Ballast load	
		Other electrical	
		Other, please specify?	
Q16	**If working**: In the last year, what part caused the biggest problem? E.g., longest time the turbine wasn’t working. **If broken:** what is the current problem with turbine?	Civil components	
		Valves	
		Turbine runner	
		Turbine bearing	
		Turbine shaft	
		Generator bearing	
		Belt	
		ELC	
		Ballast load	
		Other electrical	
		Other, please specify?	
Q17	**If working:** Due to the biggest problem in the last year, how long was the system not working? **If broken:** How long has the system not been working?		
Q18	**If working:** who found the problem? **If broken:** Has the problem been found? If yes, by who?		

	Please specify company name and or/profession, location, approximate travel time, how they were contacted		
Q19	**If working:** Who repaired the problem? **If broken:** Who will repair the problem? *Please specify company name and or/profession, location, approximate travel time*	Plant operator	
		Original turbine Manufacturer	
		Different turbine manufacturer	
		A non-specialist workshop	
		Other, please specify.	
Q20	Do you stop the turbine to do planned maintenance?	Yes (go to Q20a)	No
Q20a	How often?		
Q21	If there is a cover, do you ever remove it to inspect the turbine?	Yes (go to Q21a)	No
Q21a	How often?		
Q22	Do you know how to remove the cover?	Yes	No
Q23	How often do you check temperature of the bearings?		
Q24	How often do you listen to bearings?		
Q25	How often do you grease bearings?		
Q26	How often do you flush silt from the forebay tank?		
Q27	How often do you flush silt from the silt tank?		
Q28	How often do you clean the trash rack?		
Q29	How often do you write down energy meter values?		
Q30	How often do you write down current, voltage and frequency?		
Q31	If you find a problem with the turbine that you cannot fix yourself, what do you do?		

A.1.2 Semi-structured interview with a management representative

DQ1	Gender?	Male	Female
DQ2	Age?	15 to 25	
		26 to 36	
		37 to 45	
		46 to 55	
		56 or more	
DQ3	What is your education attainment level?	Does not know how to read	
		Can read and write	
		Incomplete elementary school	
		Completed elementary school	
		Completed high school	
		Incomplete high school	
		Completed course	
DQ4	How long have you been involved in managing the MHP plant?		

The following questions will be asked, where applicable the interviewee will be given the opportunity to expand on their answer:

Q1	How is the MHP plant owned? Do you think this structure works well? E.g., private, co-operative or community owned	
Q2	How many households are connected?	
Q3	Is there a connection fee for new consumers? If yes, how much?	
Q4	What is the payment structure used and how much do consumers pay? E.g., consumption based, fixed amount per household, fixed amount per appliance	
Q5	How often do consumers pay?	
Q6	How is the money collected?	
Q7	Do all consumers pay regularly?	
Q8	What happens if a consumer misses a payment?	
Q9	What non-residential facilities/businesses/productive end uses are connected to the hydropower?	Hospital/health clinic
		Post office
		School
		Community centre
		Local government offices
		Flour mill/grain milling
		Bakery
		Furniture making
		Grocery shop
		Barber shop
		Tea shop
		Other (please specify all)
Q8	What is the payment structure for productive end uses and what do they pay?	

Q9	Approximately, how much money is collected per month?
Q10	Do you keep accounts of the plant?
Q11	What is the plant operator’s salary?
Q12	Is there money budgeted for routine maintenance and purchasing spares?
Q13	Where is the nearest place to buy spare parts?
Q14	Is there good community interest in the MHP plant?
Q15	If there is a problem with the turbine that the plant operator is unable to repair, what happens next?
Q16	When there have been technical problems, has there been enough money to pay for repairs?
Q17	Do you know if there is spare capacity that could be used by household consumers or productive end uses? If yes, how much?
Q18	Are there any social and political issues that have been caused by the MHP plant?

A.1.3 Semi-structured interview with a consumer

DQ1	Gender?	Male	Female
DQ2	Age?	15 to 25	
		26 to 36	
		37 to 45	
		46 to 55	
		56 or more	
DQ3	What is your education attainment level?	Does not know how to read	
		Can read and write	
		Incomplete elementary school	
		Completed elementary school	
		Completed high school	
		Incomplete high school	
		Completed course	
DQ4	How long have you been receiving electricity from the MHP plant?		

The following questions will be asked, where applicable the interviewee will be given the opportunity to expand on their answer:

Q1	How much do you pay for the electricity?
Q2	Do you think this is a good price?
Q3	Would you pay more money to use more electricity?
Q4	What happens if you miss a payment?
Q5	How often is the supply bad? Is this at particular times? E.g., no electricity when you want it, not enough electricity for some appliances, dim lights etc.
Q6	Are you told when there is an issue with the supply?

Q7	What do you use electricity for?	
Q8	What do you use for lighting when there is no electricity? And what is the cost of this?	
Q9	What is electricity used for in the village? (Tick all that apply)	Lighting
		Mobile phone charging
		Television
		Radio
		Computer
		Heater
		Rice cooker
		Fridge
		Other, please specify all
Q10	Has the MHP plant make your life easier? If yes, how? e.g., spend less money on lighting, light in the evenings, new opportunities	
Q11	Would you prefer grid electricity?	

A.2 Project process interviews

A.2.1 Interview with a representative from a manufacturing company

Q1	Do you think plant operators are well trained?	
Q2	What is the most common turbine fault once a turbine is in operation? Why do you think this problem occurs?	
Q3	If you are told of a problem with a turbine in the field, what is the process that leads to its repair?	
Q4	After a feasibility study is complete, what happens before manufacture begins? E.g., turbine selection, design, production drawings	
Q5	Is there a baseline design that you use? How is this adapted?	
Q6	How are the following made? E.g., process, material including grade (if known), finish, coating?	Pelton runner
		Crossflow runner
		Nozzle
		Spear
		Penstock
Q7	Have you experienced problems with communities building civil works? How do you mitigate against these problems?	
Q8	When ordering material and components from India and China, do you consult with other manufacturers in the local area to order in bulk to reduce costs?	

Appendix B

Site assessment procedure

General information	**TAKE GPS OF POSITION OF:** • **NEAREST ROAD HEAD** • **APPROXIMATE VILLAGE CENTRE** • **POWERHOUSE** **NOTE THE FOLLOWING:** • **DATE AND TIME OF ASSESSMENT** • **APPROXIMATE WALKING TIME FROM NEAREST ROAD HEAD TO THE POWERHOUSE** • **APPROXIMATE WALKING TIME FROM THE VILLAGE TO THE POWERHOUSE** • **WHO IS PRESENT DURING THE ASSESSMENT**

Intake and weir	Intake is clean, free from erosion with no obvious cracks visible. Moving parts appear oiled and free to move.	5
	Some dirt, debris and a small amount erosion is visible. Cracks may be present, but they are small. Any obvious leaking is minor.	3
	Intake is heavily contaminated with obvious signs of erosion. Cracks are significant and/or leakage is obvious.	1
	Key points for installation quality: • Is the sluice gate oiled? • Is the weir well supported? E.g., width of gabions equivalent to water depth • Is there provision to exclude large floating debris? • Is there a gate or stop logs to close scheme for maintenance? • Is there a sluice gate? And is it in an effective position to flush deposited sediments?	

Channel	Channel is clean, free from erosion with no obvious cracks visible. Obvious effort to minimise entry of debris into channel e.g., banks around channel are swept and overhanging vegetation cut back.	5
	Some dirt, debris and a small amount erosion is visible. Cracks may be present, but they are small and any obvious leaking is minor. Some effort to minimise entry of debris into channel.	3
	Channel is heavily contaminated with obvious signs of erosion. Cracks are significant and/or leakage is obvious. No obvious effort to minimise entry of debris into channel.	1
	Key points for installation quality: • How is the canal lined? • How fast is the flow? • How steep are the slopes on either side of the channel? Is there vegetation on these slopes?	

Forebay tank	Forebay tank and trash rack are clean, free from erosion with no obvious cracks visible. Minimal silt build-up. Trash rack is clean.	5
	Some dirt, debris and a small amount erosion is visible. Cracks may be present, but they are small. Any obvious leaking is minor. Some silt is obvious in bottom of bay.	3
	Forebay and trash rack is heavily contaminated with obvious signs of erosion. Cracks are significant and/or leakage is obvious. Significant build-up of silt in the bottom of bay.	1
	Key points for installation quality: • How large is the trash rack bar spacing? What direction do the bars go in? • Can the trash rack be easily removed? • Is there a service area for the trash rack? • Is the shape good for settling silt? E.g., length of transition should be about 3 times the width of headrace • Is there a flushing gate? Is it in an effective position to flush deposited sediments?	

Penstock	Clean with good quality of paintwork (or well covered if PVC), free from rust with no obvious leaks visible. Bolts are all tight.	5
	A little dirty with tired paintwork (or some exposed areas if PVC) and possible visible rust. Any obvious leaking is minor. Some bolts may be a little loose.	3
	Very dirty with obvious rust (or exposed areas if PVC). Leakage is obvious. Bolts are loose and or/missing.	1
	Key points for installation quality: • Is the penstock made from PVC, steel or other? • Are there regularly spaced sliding blocks with straps? • Are there expansion joints after anchor blocks? • Is there a thrust block before powerhouse? • Do all the blocks and/or supports have solid foundations? • Do drainage routes takes water away from supports?	

Tailrace	Tailrace is clean, free from erosion with no obvious cracks visible. Water is effectively returned to the river.	5
	Some dirt, debris and a small amount erosion is visible. Cracks may be present, but they are small.	3
	Tailrace has debris in it and obvious signs of erosion. Cracks are significant.	1
	Key points for installation quality: • How is the water being returned to the river? • Is there an effective method to slow the flow before it returns to the river? • Is there reasonable access into the tail race if required?	

Internal pipework and valves	Clean with good quality of paintwork, free from rust with no obvious leaks visible. Bolts are all tight.	5
	A little dirty with tired paintwork and possible visible rust. Any obvious leaking is minor. Some bolts are a little loose.	3
	Very dirty with obvious rust. Leakage is obvious. Bolts are loose and or/missing.	1
	READING OF STATIC PRESSURE Key points for installation quality: • Do any valves freely turn?	

Powerhouse	A solid structure which is well looked after and a good place to work. Clean and organised.	5
	There are some signs of deterioration but it still a safe place for the equipment. Some dust and dirt.	3
	Powerhouse has signs of deterioration since its construction e.g., leaking roof, broken door etc. There is lots of dust and/or oil on the floor of the powerhouse.	1
	Key points for installation quality: • Is there a lock on the door? • Does the layout provide enough space to work in? • Is there sufficient lighting for work? • Is the access good? • Is their good protection from flooding?	

Turbine	Clean with good quality of paintwork. All drive components are clean and free from grease. Belt is tight and has cover. Casing bolts are tight. Sounds correct.	5
	Some dirt and grease. Paintwork is tired. Belt and drive components are showing signs of wear.	3
	Very dirty with grease on shafts and belts. Belt is not covered. Potential leaking from casing and loose bolts. Abnormal sound at bearing and they appear to be running hot?	1
	LISTEN WITH SCREW DRIVER TO BEARINGS Key points for installation quality: • Is there a manual control system? • Can the positions of components be easily adjusted on the base frame? • Are washers and bolts correctly sized? • Are there shims in place? • Is the electro-mechanical machinery placed on adequate foundations? • Are there cracks in the turbine foundations? • Do components look properly aligned?	

Control panel, cabling and ballast load	Cable outers are in good condition. All connections look tight with cable shoes where necessary. Cables are all sensibly and safely routed. Ballast is well protected and ventilated.	5
	Some cables are looking worn and loose but no exposed wire. Some cable routing is potentially hazardous.	3
	Cables take dangerous routes. Wires are exposed. Cable shoes are missing in places. Fuses are also missing. Ballast is not properly protected.	1
	RECORD GENERATOR POWER, VOLTAGES, CURRENTS AND FREQUENCY Key points for installation quality: • Does the panel have a lock? • Are the contents of the panel well arranged? • Are the contents of the panel labelled? • Are cables to and from the panel sensibly routed? • Is the control panel earthed? • Is the ballast in a safe position? • Does the ballast receive good ventilation?	

Generator	Clean, with good quality of paintwork. No exposed moving parts or cables. All cabling is covered and safely leaves the generator.	5
	Some dust and dirt but in reasonable condition. Some cables exposed but risk is small.	3
	Dirty machine. Exposed moving parts and/or cables.	1
	LISTEN TO GENERATOR Key points for installation quality: • Is the generator well positioned to receive a good airflow? • Is cabling from the AVR securely protected? • Is the generator earthed?	

Appendix C

Survey of manufacturing and casting companies

C.1 Survey of manufacturing companies

No.	**Question**
Section 1: General Information	
1.1	Name of the Company
2.1	What is your position in the company?
2.2	To what level have you been educated?
2.3	Have you completed any other training? If yes, please specify
2.4	How many years of experience in micro-hydro do you have?
3.1	How long has the company been trading?
3.2	What services do the company provide?
3.3	What types of turbines does your company manufacture? More or less than 50 projects of each?
3.4	Do you produce as-built drawings?
3.5	Are these available at the site?
3.6	Do you deliver a full bill of materials including suppliers to site?
3.7	Do you do repairs of other manufacturers equipment?
Section 2: Components	
4.1	For a Pelton Turbine system, what are the most common faults (Rank in order of frequency)
4.2	For each fault, what action occurs?
4.3	For a Crossflow Turbine system, what are the most common faults (Rank in order of frequency)
4.4	For each fault, what action occurs?
4.5	Are any components tested? If so, how?
Component: Crossflow runner	
5.1	What materials can this part by made from?
5.2	If this part can be made from more than one material, what determines the choice of material?
5.3	Describe how you would make a Crossflow Runner.
5.4	Is the runner balanced?
5.5	For this part, are the same processes used for every project? e.g. 10 kW vs. 100 kW
5.6	Have you always manufactured crossflow runners in this way?
5.7	Have you developed any of your own jigs or methods to make the manufacturing easier?
Component: Pelton Runner	
6.1	What materials can this part by made from?

6.2	If this part can be made from more than one material, what determines the choice of material?
6.3	Describe how you would make a Pelton Runner
6.4	How is accuracy of buckets to the original design ensured?
6.5	Is the runner balanced?
6.6	How are the blades aligned with the jet?
6.7	For this part, are the same processes used for every project? E.g. 10 kW vs. 100 kW
6.8	Have you always manufactured Pelton runners in this way?
6.9	Have you developed any of your own jigs or methods to make the manufacturing easier?
Component: Generator	
7.1	What type of generator do you use for micro-hydro systems?
7.2	Is this the same for Pelton and Crossflow systems?
7.3	Is this the same for different sizes of system?
7.4	How do you determine what type of generator you use?
7.5	How do you determine which supplier you obtain from?
7.6	Where is your supplier based?
7.7	What is the typical lead time for this component?
7.8	When purchasing this component, how many are bought at a time?
Component: Turbine shaft	
8.1	What materials can this part by made from?
8.2	If this part can be made from more than one material, what determines the choice of material?
8.3	For this part, are the same processes used for every project? E.g. 10 kW vs. 100 kW
8.4	What is the typical lead time for this component?
8.5	When purchasing this component, how many are bought at a time?
8.6	How do you check bearing tolerances on the shaft?
Component: Pelton nozzle	
9.1	Is this part bought-in or manufactured on-site?
9.2	What materials can this part by made from?
9.3	If this part can be made from more than one material, what determines the choice of material?
9.4	Describe how this part is made.
9.5	For this part, are the same processes used for every project? E.g. 10 kW vs. 100 kW
Component: Pelton spear	
10.1	Is this part bought-in or manufactured on-site?
10.2	What materials can this part by made from?
10.3	If this part can be made from more than one material, what determines the choice of material?
10.4	Describe how this part is made.
10.5	For this part, are the same processes used for every project? E.g. 10 kW vs. 100 kW
Section 3: Processes	
11.1	Does casting occur in-house or off-site?
11.2	If off-site, where does casting take place?
11.3	How long does it take to order and procure cast components?

11.4	If known, what type of casting is used?
11.5	If known, what sort of tolerance is achievable through casting?
Tolerances	
12.1	In general, what is the tolerance/accuracy available for micro-hydro components?
12.2	What is the highest tolerance/accuracy achievable?
Welding	
13.1	What types of welding do you have?
13.2	What is the minimum sheet thickness for welding in mild steel?
13.3	What qualification do the company's welders have?
13.4	After welding, do you relieve internal stresses through heat treatment?
13.5	Are critical components pre-heated to reduce stress?
13.6	Do you have a welding sequence that welders follow?
13.7	Are welded parts tested?
Oxy-acetylene 'gas' cutting	
14.1	What is the maximum thickness of steel that can be cut?
14.2	What is the expected tolerance?
14.3	What method is used to cut accurately in a straight line?
14.4	Is any other form of sheet metal cutting available?
Roller bending and folding	
15.1	What is the largest width of sheet that can be rolled/folded?
15.2	What is the maximum thickness of sheet that can be rolled/folded?
Painting	
16.1	What types of painting do you use?
16.2	What is the painting specification for surfaces in contact with water?
16.3	Is sandblasting applied before painting?
Metrology	
17.1	What equipment do you use?
17.2	For each equipment used, what is the accuracy of the measuring equipment?
17.3	For each equipment used, what is the range that can be measured?

C.2 Survey of casting companies

No.	**Question**
1	What different types of casting are available?
2	Why are these types used?
3	What quality of sand is used and why?
4	What metals (and what grade) are available to cast?
5	Who supplies the metal material?
6	Who supplies the sand material?
7	What is the thinnest section that can be cast?
8	What is the maximum weight that can be cast?
9	Are cast pieces tested for internal quality?
10	If a manufacturer sends a metal Pelton bucket to be cast - what is the procedure? Do you make your own pattern first, and use this to cast the rest of the buckets?
11	What is the typical delivery time?
12	Do you ever cast a whole runner?

C.3 List of randomly generated sites

No.	**Flow (L/s)**	**Head (m)**	**Penstock length (m)**	**No.**	**Flow (L/s)**	**Head (m)**	**Penstock length (m)**
1	16	128	181	**60**	102	100	141
2	18	114	161	**61**	276	37	52
3	116	18	25	**62**	53	193	273
4	12	177	250	**63**	61	168	238
5	116	19	27	**64**	281	37	52
6	122	19	27	**65**	70	153	216
7	21	112	158	**66**	96	116	164
8	238	10	14	**67**	81	145	205
9	133	18	25	**68**	77	154	218
10	26	95	134	**69**	258	46	65
11	208	12	17	**70**	62	199	281
12	18	146	206	**71**	98	127	180
13	183	15	21	**72**	286	46	65
14	158	18	25	**73**	104	128	181
15	27	106	150	**74**	92	154	218
16	244	12	17	**75**	78	182	257
17	170	18	25	**76**	119	120	170
18	165	21	30	**77**	114	128	181
19	151	23	33	**78**	108	138	195
20	184	19	27	**79**	341	44	62
21	244	15	21	**80**	331	46	65
22	238	16	23	**81**	334	46	65
23	181	22	31	**82**	117	132	187
24	175	23	33	**83**	157	108	153
25	26	155	219	**84**	251	68	96
26	22	190	269	**85**	89	192	272
27	24	175	247	**86**	100	171	242
28	26	177	250	**87**	287	60	85
29	179	26	37	**88**	116	150	212
30	28	170	240	**89**	251	70	99
31	221	23	33	**90**	312	57	81
32	216	24	34	**91**	100	179	253
33	249	21	30	**92**	161	112	158
34	28	192	272	**93**	92	199	281
35	292	20	28	**94**	346	54	76
36	161	39	55	**95**	353	54	76
37	176	36	51	**96**	103	189	267
38	150	43	61	**97**	322	62	88
39	216	30	42	**98**	271	74	105
40	167	39	55	**99**	347	58	82
41	53	125	177	**100**	327	62	88
42	63	110	156				
43	169	42	59				
44	231	31	44				
45	251	29	41				
46	228	33	47				
47	210	36	51				
48	244	31	44				
49	213	36	51				
50	258	30	42				
51	244	32	45				
52	195	41	58				
53	187	43	61				
54	236	39	55				
55	243	39	55				
56	59	166	235				
57	82	121	171				
58	87	115	163				
59	257	39	55				

Appendix D

Design for the welded blade

D.1 Loading on a blade

To model the worst-case loading on a single blade, it was assumed that this would occur due to the force of the jet applied at 25m head. It was also assumed that this force was applied to a single blade, therefore, the blade was held in a constant position whilst this force was applied. Figure D.1 shows the loading on a single blade.

Figure D.1 – Loading on a single blade.

The force of the jet can be calculated using:

$$F_j = \dot{m}v = \rho A v^2 = \frac{\rho \pi {D_j}^2}{4} \qquad (D.1)$$

where m dot is mass flow rate, v is water velocity, ρ is water density, A is area of the jet, D_j is jet diameter, g is acceleration due to gravity and H is head. For a head of 25 m, jet diameter of 0.0307 m, and acceleration due to gravity of 9.81 m/s^2, this results in F_j = 363 N.

Due to the inclination angle of the jet of 22.5°, this jet force can be considered as an axial component of 139 N and a radial component of 335 N.

D.2 Bending moment calculation welded blade

The jet hits the blade close to its centre, this causes a bending moment in the stem [54]. As the runner rotates, each blade experiences a peak bending moment which falls to zero when the blade is not in contact with the jet. As such, this cyclical loading can result in a failure due to fatigue. To consider the welded runner, it is assumed that maximum bending stress occurs on the section of the stem located furthest from the applied load. Figure D.2 shows the approximate location of the highest load which occurs at the edge of a stem, the section through this point is identified as A-A. Figure D.3 shows the section view along A-A.

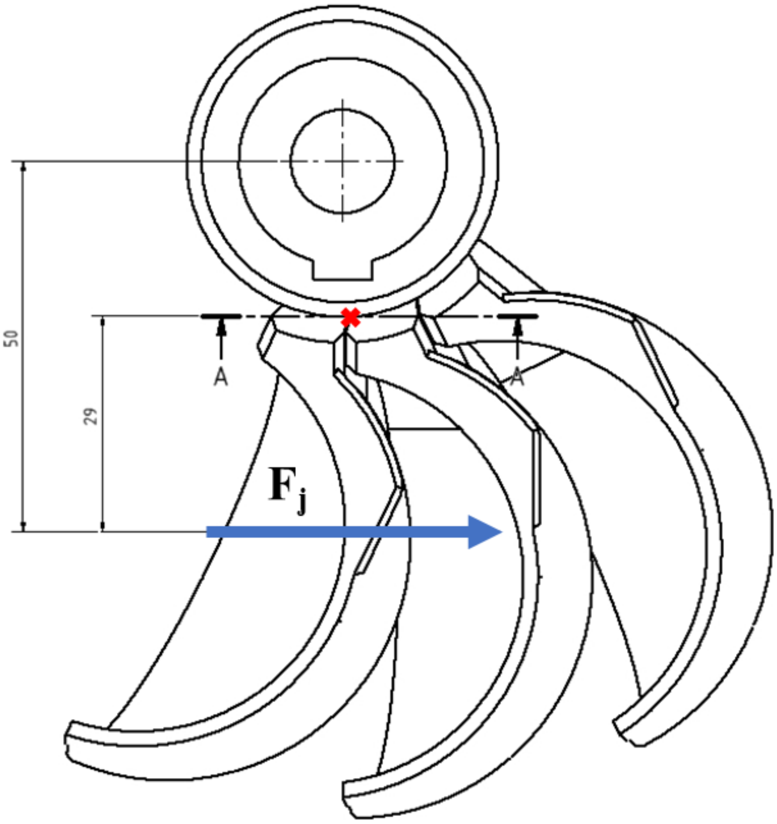

Figure D.2 - Jet force acting on the welded runner with point of maximum stress identified.

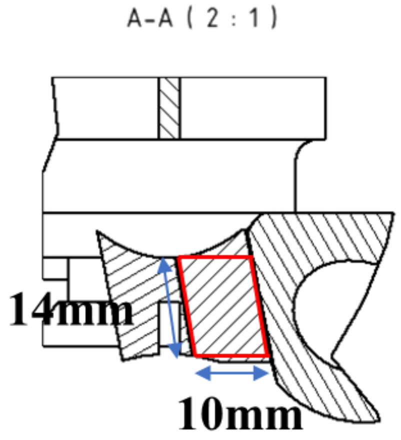

Figure D.3 - Section where maximum bending moment occurs for the welded runner.

Using the method described in [54], Table D.1 shows the parameters and results used to calculate the fatigue stress in the stem.

Table D.1 - Parameters and results in the welded blade bending moment calculation.

Parameter	Result
Width	$b = 10\ mm$
Height	$d = 14\ mm$
Length of the parallelogram overhang	$a = 2.5\ mm$
Distance to neutral fibre	$y = 5\ mm$
Second moment of area for a parallelogram [242]	$I = \frac{bd(b^2 + a^2)}{12} = 1239.58\ mm^4$
Stem section modulus	$Z = \frac{I}{y} = 247.92\ mm^3$
Moment arm from jet to section	$x = 29\ mm$
Radial component of the jet force	$F_r = 335\ N$
Moment	$M = F_{jet} \times a = 9{,}715\ Nmm$
Fatigue stress in stem	$\sigma_f = \frac{M}{Z} = 39.19\ N/mm^2$

In [54], Thake provides estimates of the maximum recommended fatigue design stress for Pelton buckets cast in a number of different materials. These estimates consider the applied cyclical stresses and the quality of the cast bucket. For cast steel, the average maximum fatigue design stress is 40 N/mm^2, therefore the stem design is acceptable.

D.3 Weld stress calculations

As well as the stem, it is also necessary to determine whether the welding on a single blade is sufficient to sustain the worst case loading on a single blade. It is assumed that this load was fully supported by the weld and that the runner ring (shown transparently in Figure D.1 provided) no additional support. The proposed welding arrangement used a v-notch weld on the top and a fillet weld on the underside of the blade. Figure D.4 shows the welding arrangement. For both welds, the throat length is assumed to be equal.

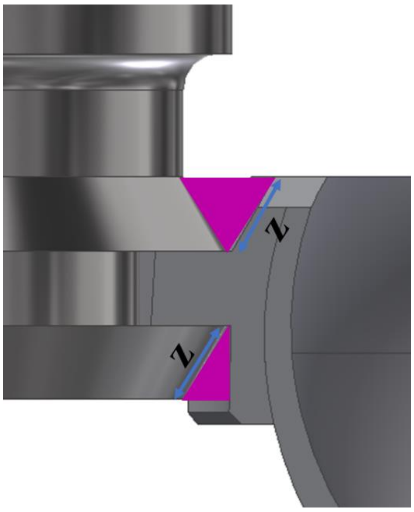

Figure D.4 - Proposed welding arrangement.

The loading can be resolved into horizontal and vertical components. For simplicity, both welds were modelled as identical fillet welds. Figure D.5 shows a diagram with the resolved components of the applied force, modelled welding arrangements and key dimensions.

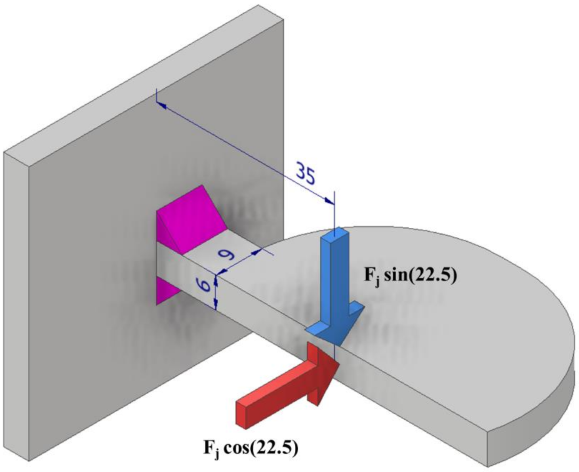

Figure D.5 - Diagram showing assumed loading and welding arrangement.

For simplicity and ease of calculation, each of the resolved components of the applied force was modelled as if applied vertically. Figure D.6 shows the horizontal component of the force modelled in a vertical position. Figure D.7 shows the dimensions of the welds.

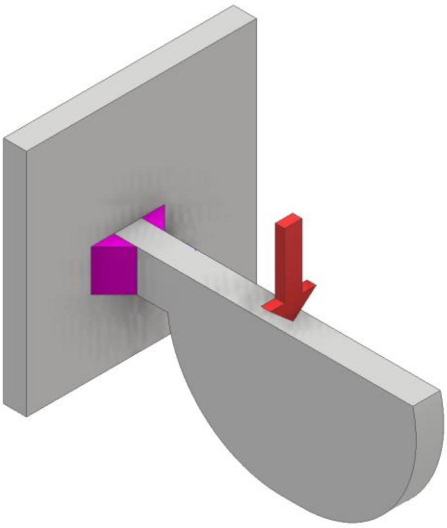

Figure D.6 - Horizontal component of force resolved into vertical position.

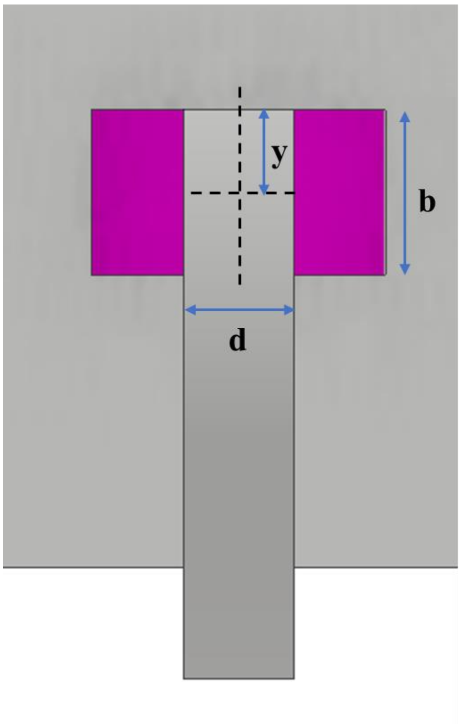

Figure D.7 - Dimensioning of the welds for horizontal component calculation.

Table D.2 lists the parameters, their values and where applicable the formulae that leads to their calculation. It is assumed that a 7018 electrode (mentioned as available in Nepal), where the design stress of approximately $p_w = 220N/mm^2$ [243].

Table D.2 - Parameters and results in the horizontal component calculation.

Parameter	Result
Length of weld	$b = 9\ mm$
Distance between weld	$d = 6\ mm$
Vertical distance from weld centroid	$y = 4.5\ mm$
Unit weld area	$A_u = 2d = 2\ \times 9 = 18\ mm^2$
Unit moment of inertia	$I_u = \frac{d^3}{6} = \frac{9^3}{6} = 121.5\ mm^4$
Applied force	$P =\ F_j \cos(22.5) =\ 335\ N$
Applied moment	$M = P \cdot y = 11{,}725\ Nmm$
Shear stress	$\tau_r = \frac{P}{A_u} = \frac{335}{18} = 18.6\ N/mm^2$
Bending stress	$\tau_s = \frac{M \cdot y}{I_u} = \frac{11725\ \times 4.5}{121.5} = 434\ N/mm^2$
Resultant stress	$\tau_r = \sqrt{{\tau_s}^2 + {\tau_b}^2} =\ \sqrt{18.6^2 + 434^2 =} 434\ N/mm^2$
Throat thickness	$a = \frac{\tau_r}{p_w} = \frac{434}{220} = 1.97$
Leg length	$z =\ a\sqrt{2} =\ 2.79\ mm$

The required leg length to meet the design stress is 2.79. For a leg length of 7 mm as is achievable, the factor of safety is 2.51.

The calculation is repeated for the horizontal component of the applied force. Figure D.8 shows the vertical component of the force. Figure D.9 shows the dimensions of the welds.

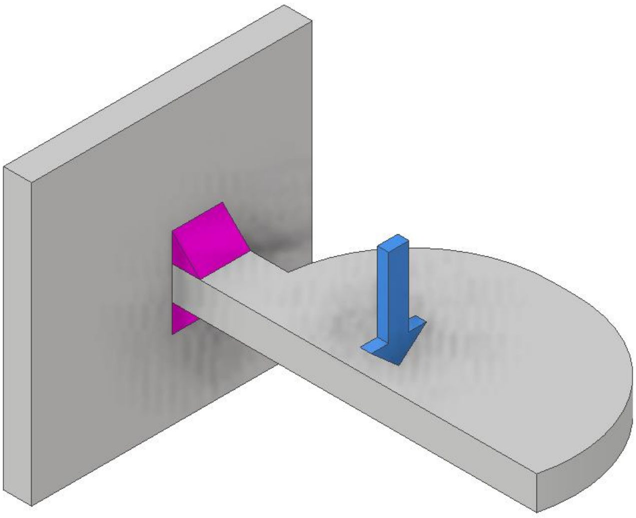

Figure D.8 - Vertical component of force.

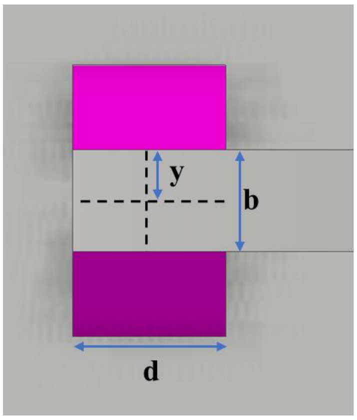

Figure D.9 - Dimensioning of the welds for vertical component calculation.

Table D.3 lists the parameters, their values and where applicable the formulae that leads to their calculation. Again, it is assumed that the design stress is for an Electrode E35 steel S275 is p_w = 220N/mm^2.

Table D.3 - Parameters and results in the vertical component calculation.

Parameter	Result
Distance between weld	$b = 6\,mm$
Length of weld	$d = 9\,mm$
Vertical distance from weld centroid	$y = 3\,mm$
Unit weld area	$A_u = 2d = 2 \times 9 = 18\,mm^2$
Unit moment of inertia	$I_u = \frac{bd^2}{2} = \frac{6 \times 9^2}{2} = 243\,mm^4$
Applied force	$P = F_j \sin(22.5) = 139\,N$
Applied moment	$M = P \cdot y = 4862\,Nmm$
Shear stress	$\tau_r = \frac{P}{A_u} = \frac{139}{18} = 7.22\,N/mm^2$
Bending stress	$\tau_s = \frac{M \cdot y}{I_u} = \frac{4862 \times 3}{243} = 60\,N/mm^2$
Resultant stress	$\tau_r = \sqrt{{\tau_s}^2 + {\tau_b}^2} = \sqrt{7.22^2 + 60^2} = 60.4 N/mm^2$
Throat thickness	$a = \frac{\tau_r}{p_w} = \frac{60.4}{220} = 0.274\,mm$
Leg length	$z = a\sqrt{2} = 0.388\,mm$

For leg length of 7 mm, the factor of safety is 18. The calculations indicate that for the worst-case loading, a weld with 7 mm leg length is acceptable.

Appendix E

Design for the bolted blade

E.1 Bending moment calculation for bolted blade

For the bolted blade, it is assumed that the same worst-case loading is applied as in the case of the welded blade. For the bolted blade, it is assumed that the greatest bending moment occurs at the point on the stem at a radius marginally larger than the radius of the runner hub. Figure E.1 shows the location of the jet force, the point of greatest bending moment (indicated by the red cross) and the section A-A that passes through this point. Figure E.2 shows the section A-A where the maximum bending stress occurs.

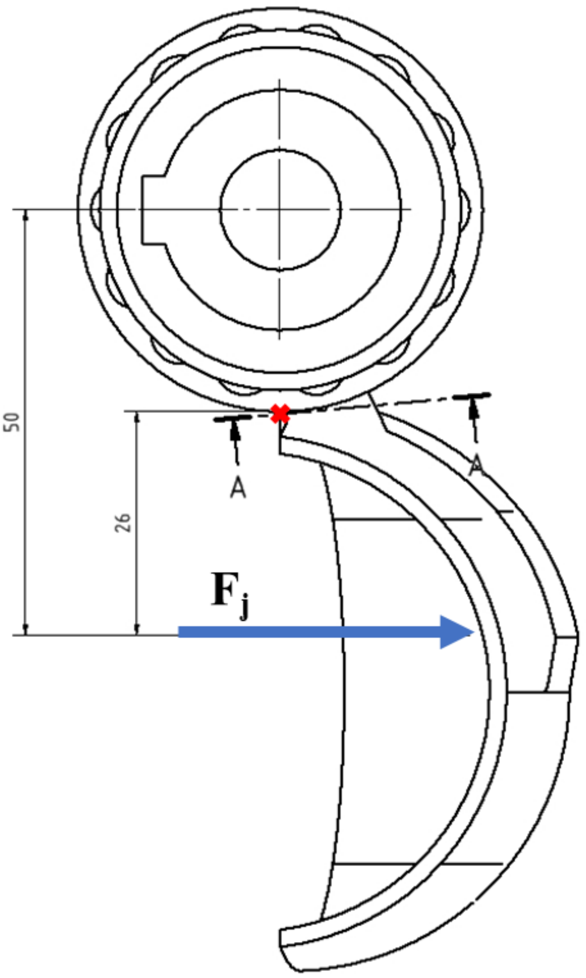

Figure E.1 - Jet force acting on the bolted runner with point of maximum stress identified.

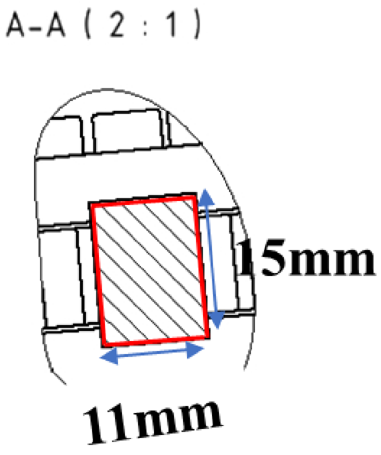

Figure E.2 - Section where maximum bending moment occurs for the bolted runner.

Table E.1 shows the parameters and results used to calculate the fatigue stress in the stem.

Table E.1 - Parameters and results in the bolted blade bending moment calculation.

Parameter	Result	
Width	$h = 11\ mm$	
Height	$b = 15\ mm$	
Distance to neutral fibre	$y = 5.5\ mm$	
Second moment of area [242]	$I = \frac{bh^3}{12} = 3093.75\ mm^4$	$(E.1)$
Stem section modulus	$Z = \frac{I}{y} = 562.5\ mm^3$	$(E.2)$
Moment arm from jet to section	$x = 26\ mm$	
Radial component of the jet force	$F_r = 335\ N$	
Moment	$M = F_{jet} \times a = 8{,}710\ Nmm$	$(E.3)$
Fatigue stress in stem	$\sigma_f = \frac{M}{Z} = 15.48\ N/mm^2$	$(E.4)$

In [54], Thake provides estimates of fatigue design tress for cast Pelton buckets. For brass, the fatigue design stress is 20 N/mm^2, therefore the stem design is acceptable.

E.2 Shear stress on the bolt

The horizontal component of the jet force exerts a shearing stress upon the M4 bolt that connects the blade to the hub. It is assumed that the entire horizontal component of jet force is exerted on the bolt. Acting in the opposite direction are reaction forces (equal to half the horizontal component of the jet force) exerted by the hub and hub cap upon the bolt. Figure E.3 identifies the location of these forces. The red dash line indicates the central axis of the bolt.

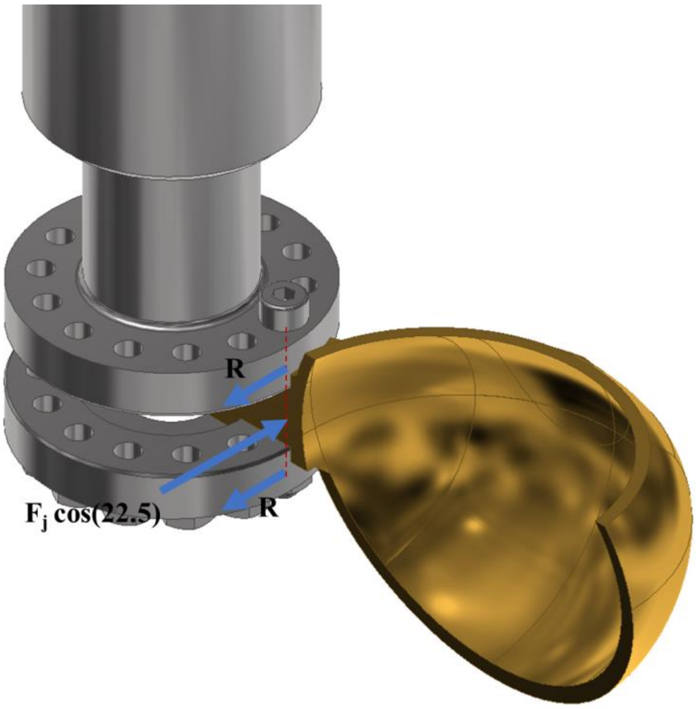

Figure E.3 - Shear stress on a single bolt due to the jet force.

It is assumed that the bolt is in double shear therefore the shear stress is given by [243]:

$$\sigma_s = \frac{2F_j\cos(22.5)}{\pi d^2} = \frac{2\times 335}{\pi\times 4^2} = 13.33\ N/mm^2 \qquad (E.5)$$

where F_j is the jet force given previously and d is the bolt diameter, nominally 4mm in this case.

With no tensile component, using Von Mises-Hencky theory [243] to predict the factor of safety leads to:

$$FoS = \frac{S_Y}{\left(3\tau_{xy}{}^2\right)^{0.5}} = \frac{700}{(3 \times 13.33^2)^{0.5}} = 30.3 \qquad (E.6)$$

where S_Y is the tensile strength of an A2-70 bolt [244], τ_{xy} is the shear stress calculated above. The result demonstrates that this bolt size is acceptable.

Appendix F

Experimental testing

F.1 Torque transducer calibration

The torque transducer was calibrated using masses of known weights. An experimental rig was used where the torque transducer was held in a fixed position and weights added at a known distance from the central axis. As weights were added, the voltage signal was measured. Weights were added up to approximately 50 Nm and then removed. Measurements of voltage signal were repeated as the weights were removed. Linear regression was used to determine the gradient and y-intercept (and their respective uncertainties) of the resulting relationship. They were:

- Gradient = 9.98 ± 0.00791
- Y-intercept = -3.954 ± 0.0256

The gradient and y-intercept can be used to predict the torque based on the voltage signal. In addition, the uncertainties in gradient and y-intercept allow the overall uncertainty in the prediction to be calculated. Table F.1 shows the values recorded during the calibration process.

In the core test range of 15 to 25m, the lowest recorded torque of 5.29 Nm occurred at head of 15m at a rotational speed of 2000 rpm whilst testing the Mark 1 runner. Based on the calibration data, the worst-case uncertainty is assumed to be the average of the uncertainties that correspond to the nearest measured torque. Th corresponding rows are highlighted in Table F.1. Therefore, the resulting worst-case uncertainty is 1.307%.

Table F.1 - Values recorded during torque transducer calibration.

Measured torque (Nm)	Average voltage signal (V)	Predicted torque (Nm)	Min. predicted torque (Nm)	Max. predicted torque (Nm)	Uncertainty (%)
2.5475	0.65	2.536	2.505	2.566	2.425
5.0139	0.9	5.032	4.999	5.064	1.301
7.3465	1.135	7.378	7.343	7.412	0.938
9.7674	1.38	9.824	9.787	9.860	0.744
12.2263	1.63	12.320	12.281	12.358	0.625
14.6561	1.875	14.766	14.725	14.806	0.548
17.1881	2.125	17.262	17.219	17.304	0.492
19.6819	2.375	19.758	19.713	19.802	0.450
22.1172	2.62	22.204	22.158	22.250	0.417
24.7572	2.88	24.800	24.751	24.848	0.390
27.2764	3.13	27.296	27.245	27.346	0.369
29.5369	3.36	29.592	29.540	29.644	0.353
31.9768	3.6	31.988	31.934	32.042	0.338
34.4458	3.85	34.484	34.428	34.540	0.325
36.7834	4.09	36.880	36.822	36.938	0.314
39.2067	4.33	39.276	39.217	39.336	0.305
41.7468	4.58	41.772	41.711	41.834	0.296
44.2859	4.84	44.368	44.304	44.432	0.288
46.6859	5.08	46.764	46.699	46.830	0.282
49.0726	5.32	49.161	49.093	49.228	0.276
46.6859	5.06	46.565	46.499	46.630	0.282
44.2859	4.82	44.169	44.105	44.232	0.289
41.7468	4.57	41.673	41.611	41.734	0.297
39.2067	4.32	39.177	39.117	39.236	0.305
36.7834	4.07	36.681	36.623	36.738	0.315
34.4458	3.84	34.384	34.328	34.440	0.326
31.9768	3.595	31.938	31.884	31.992	0.339
29.5369	3.345	29.442	29.390	29.494	0.354
27.2764	3.12	27.196	27.146	27.246	0.370
24.7572	2.87	24.700	24.652	24.748	0.391
22.1172	2.61	22.104	22.058	22.150	0.419
19.6819	2.365	19.658	19.614	19.702	0.451
17.1881	2.115	17.162	17.120	17.204	0.494
14.6561	1.86	14.616	14.576	14.657	0.552
12.2263	1.615	12.170	12.132	12.209	0.631
9.7674	1.37	9.724	9.688	9.761	0.750
7.3465	1.125	7.278	7.243	7.313	0.948
5.0139	0.895	4.982	4.949	5.014	1.312
2.5475	0.645	2.486	2.455	2.516	2.471

F.2 Bearing design

F.2.1 Loading

The testing rig required a bearing design to support the lower section of shaft (including the runner) taking a combination of axial and radial loads. Figure F.1 shows a free-body diagram of the lower shaft section including the runner, which is indicated by the grey rectangle. Table F.2 describes the labels used in the free-body diagram.

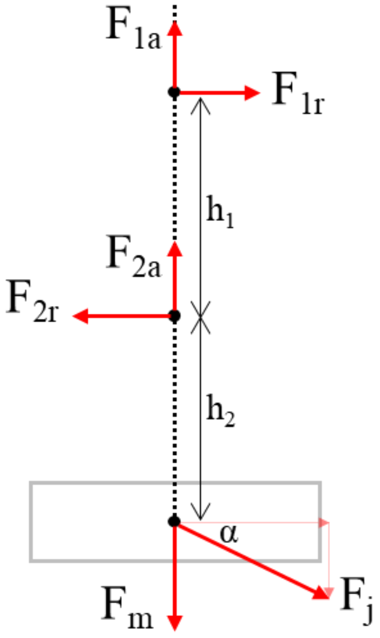

Figure F.1 - Free-body diagram of the lower shaft section.

Table F.2 - Description of the labels used in the free-body diagram.

Label	Description
F_j	Force of the jet
F_m	Force due to weight of the runner
F_{1a}	Axial reaction force at bearing 1
F_{1r}	Radial reaction force at bearing 1
F_{2a}	Axial reaction force at bearing 2
F_{2r}	Radial reaction force at bearing 2
α	Inclination angle of jet force to horizontal plane
h_1	Distance between bearing 1 and bearing 2
h_2	Distance between bearing 2 and the runner centre of mass

In the model, it is assumed that the centre of mass of the runner and jet force impact at the same axial position.

The force of the jet can be calculated using:

$$F_j = \dot{m}v = \rho A v^2 = \frac{\rho \pi {D_j}^2}{4} \qquad (F.1)$$

where m is mass, v is water velocity, ρ is water density, A is jet area, D_j is jet diameter, g is acceleration due to gravity and H is head.

To find radial forces, resolving moments about bearing 2 leads to:

$$F_{1r} = \frac{F_j \cos\alpha}{h_1} \qquad (F.2)$$

Then, resolving moments about bearing 1 leads to:

$$F_{2r} = \frac{F_j \cos\alpha\,(h_1 + h_2)}{h_1} \qquad (F.3)$$

Equating the axial loads:

$$F_{1a} + F_{2a} = F_m + F_j \sin\alpha \qquad (F.4)$$

Assuming that the complete axial load is taken by the lower bearing:

$$F_{2a} = F_m + F_j \sin\alpha \qquad (F.5)$$

The greatest loading will occur when H = 25m. The approximate mass of the runner and shaft is 2.1 kg. Dimensions h_1 and h_2 were determined by the geometry of the testing rig, whilst α is a constant determined by the turbine casing. Table F.3 shows the inputs and outputs to the bearing loading calculation.

Table F.3 - Parameters and values in the bearing loading calculation.

Parameter	Value
α	22.5°
h_1	0.105m
h_2	0.1415m
F_j	363N
F_m	20.6N
F_{1a}	0N
F_{1r}	452N
F_{2a}	160N
F_{2r}	787N

The greatest load of 787N is the radial load on the lower bearing.

F.2.2 Bearing selection

Despite the fact that the upper bearing experiences no axial load, for simplicity it was decided to select the same bearing type for both positions. Due to their ability to deal with axial and radial loads, an angular contact ball bearing was chosen.

Considering the dynamic load rating [54]:

$$L_{10} = \left(\frac{C}{P}\right)^{p} \qquad (F.6)$$

where L_{10} is bearing life for 10% failure rate after 10^6 revolutions, C is the basic dynamic load rating, P is the actual dynamic bearing load and p is an empirical constant (equal to 3 for ball bearings).

Assuming a design life span of 10 years at the operational speed of 1500rpm leads to:

$$\frac{C}{P} = 19.9 \qquad (F.7)$$

The selected bearing must exceed this value. Evaluating the available angular contact ball bearings for a 30 mm shaft diameter, SKF 7206 BE-2RZP was considered due to integrated sealing system [245]. As calculated previously, P = 787 N. For this bearing, C = 22,500 N. Therefore, C/P = 28.6 and the bearing is an acceptable choice.