DEVELOPMENT OF A PICO CONDUIT HYDROPOWER TURBINE WITHIN A CITY'S WATER DISTRIBUTION SYSTEM

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A project report submitted in partial fulfilment of the requirements for the degree of
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PROJECT REPORT SUMMARY

DEVELOPMENT OF A PICO CONDUIT HYDROPOWER TURBINE WITHIN A CITY'S WATER DISTRIBUTION SYSTEM

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Energy is the lifeblood of worldwide economic and social development. In recent years, South Africa (SA) has experienced local energy shortages that have resulted in interruptions in the supply of electricity, referred to as "load shedding". During such times, the monitoring and operation of water infrastructure become problematic. In combination with a culture of vandalism and theft of infrastructure components that have resale value, infrastructure becomes inoperable at an ever-increasing rate. Equipment functionality and levels of bulk water service delivery could be maintained through the development of alternative energy-generation methods in all spheres of the South African national, provincial, and local government.

Because of the energy shortages in SA, localised alternative energy-generation methods are being adopted to maintain the management and control of water systems. The solutions involve utilising energy more efficiently, optimising existing systems, and seeking new approaches for supplying electricity to water supply infrastructure. The introduction of small hydroelectric turbines and generators at strategic places where there excess pressure exists in the water supply and distribution system, is a relatively simple energy solution to recapture some of this renewable energy. This could typically be done at existing pressure-reducing stations (PRS) or anywhere along the pipeline, by

extracting hydroelectric energy to meet a specific demand, without compromising the main functioning of the supply system.

A number of water authorities throughout the world have realised the potential of conduit hydropower and have implemented generating schemes. In SA, there are 257 municipalities and several water supply utilities. All of these municipalities own water supply distribution systems that could be considered for hydropower installations. Fortunately, a number of conduit hydropower opportunities exist within City of Tshwane (CoT), due to its geographic location relative to the country's main water sources.

In CoT, water is distributed through a large water system that comprises 165 reservoirs, 39 water towers, 10 863 km of pipes, and more than 280 PRSs – some of which are operating at pressures of up to 250 m. The current reality is that regular load shedding results in a loss of control over parts of the water supply network. Retrofitting a hydroelectric turbine in an existing system, is a solution to address the constant demand for electricity at specific locations. This will ensure that communication with reservoirs – not only in isolated areas – for various operational, maintenance, and infrastructure management reasons, is maintained. This includes telemetry, pressure management, flow control and 24-hour monitoring and security systems.

In this study, a pico conduit hydropower turbine was developed and the application and the installation of a retrofit conduit hydropower unit into a city’s water distribution system was explored. The entire retrofitting process is described, with examples of three of the four types of conduit hydropower developments in CoT. A novel conceptual hydroelectric turbine generator was designed to be retrofitted easily in an existing valve chamber. The prototypes tested in this study resulted in the development of a pico hydropower unit (PHU) at a competitive cost. These PHUs could be applied in water lines, installed in series (inline) with the main water lines.

An inline pressure wheel (IPW) was developed and tested extensively over a period of four months to a point where the first commercial PHU (IPW2) was ordered for installation in CoT at the Klipgat Hospital Reservoir. This unit generates adequate electricity from the water network before discharging into the reservoir. A simplified control system manages the generated power to store sufficient power to run the equipment on-site and shuts down automatically when not needed, to prolong system life. The operation of this commercial IPW will be monitored and data will be collected during operation to evaluate the unit's performance and to contribute to future studies. The results could be used to improve the design and effectively of the commercial IPW series.

DECLARATION

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- The work contained in this thesis is my own original work;
- I did not refer to work of current or previous students, lecture notes, handbooks of any other study material without proper referencing;
- Where other people's work has been used, this has been properly acknowledged and referenced;
- I have not allowed anyone to copy any part of my project report;
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This project report is based on experiments in the water distribution network in the City of Tshwane. The opinions expressed are those of the author and do not necessarily represent the policy of the City of Tshwane.

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LIST OF ABBREVIATIONS

AADD	average annual daily demand
CFD	computational fluid dynamics
CoT	City of Tshwane
DME	Department of Minerals and Energy
DSS	decision support system
EMF	electromotive force
ESHA	European Small Hydropower Association
FSL	full supply level
HRM	hydropower retrofitting model
IEA Hydro	International Energy Agency Hydropower Implementing Agreement
IPW	inline pressure wheel
MIS	management information system
PAT	pump-as-turbine
PHU	pico hydropower unit
PRS	pressure-reducing station
PRV	pressure-reducing valve
RW	Rand Water
SA	South Africa
SCADA	supervisory control and data acquisition
TWL	top water level
UP	University of Pretoria
WDS	water distribution system
WTW	water treatment works
WWTW	waste water treatment works

LIST OF SYMBOLS

D	diameter of penstock or conduit (m)
g	gravitational acceleration (typically 9,81 m/s²)
H	effective pressure head (m)
h_f	friction loss (m)
H_n	Gross head difference (m)
H_G	Total static pressure (m)
h_l	secondary losses (m)
h_t	secondary losses of hydro turbine (m)
i	discount/interest rate or escalation rate (%)
I	electric current (A)
K	secondary loss coefficient
L	length of penstock or pipe (m)
LCC	life cycle cost (Rand)
n	number of years
P_m	mechanical power output (W)
P	power output of turbine (W)
P_1	pressure at Station 1 (m)
P_2	pressure at Station 2 (m)
Q	flow rate through the turbine (m³/s or ℓ/s)
t	time actually worked (h)
T	theoretical time (h)
V	potential difference (Volt)
v	velocity (m/s)
η	hydraulic efficiency of the turbine (%)
η_g	hydraulic efficiency of the generator
η_t	hydraulic efficiency of the turbine (%)
λ	friction coefficient of conduit
ρ	density of fluid (kg/m³)

1 INTRODUCTION

This section provides background information and describes the objectives for the exploitation of opportunities through creative and effective initiatives. The aim is to convert the potential energy available into the form of energy that is needed at a specific location for a specific application.

1.1 Background

Energy forms one of the bases of worldwide economic and social development. Where the delivery of energy from a country's traditional sources is disrupted, economic and social development are compromised. Africa is the most underdeveloped continent in terms of hydropower generation, with only 6 % of the estimated potential utilised. This should not be seen as a burden, but rather as an opportunity to be exploited at all possible levels. Hydropower could become a source of reliable and sustainable energy. Recently, South Africa (SA) has been experiencing local energy shortages, which resulted in national power (or “load”) shedding. During such times, the monitoring and operation of water infrastructure become problematic. The latter, combined with a culture of vandalism and theft of infrastructure components, results in inoperable infrastructure. However, standard functionality and levels of service could be maintained through the development of alternative energy-generation methods in all spheres of the South African national, provincial and local governments.

The need to develop localised energy-generating solutions to ensure that water infrastructure remains operational in SA became apparent due to (a) frequent and unpredictable disruptions in the supply of electricity and (b) increased vandalism of the electricity distribution network. These alternative energy solutions could ensure that the control and management of the water systems remain intact. Possible solutions might lie in utilising energy more efficiently, in the optimisation of existing systems, or even in seeking new approaches to supplying electricity to the water supply infrastructure.

On a macro scale, SA follows the worldwide tendency of continuous energy demand increases. This is primarily due to population growth and the adoption of different lifestyles. Although SA has abundant coal reserves from which energy could be generated, the country strives to develop alternative, particularly renewable, energy resources. The targeted renewable energy sources in SA include solar radiation, biomass, wind, and hydropower as described in the *Integrated Resource Plan* of 2019 (Republic of South Africa, 2019).

Globally, a number of water authorities have realised the potential of conduit hydropower and have implemented generating schemes (White, 2011; Fontana *et al*., 2012, Möderl *et al*., 2012). Although SA has limited potential for large hydropower schemes, there is significant potential for the development of economical units for small, mini, micro and pico hydropower plants. Large quantities of raw and potable water are conveyed daily either under pressurised or gravity conditions over large distances and elevations. These water transport systems have to be operated under sustainable water supply regimes, which is a very important aspect in the operation of any hydropower generation system.

In SA, there are 8 metropolitan municipalities, 44 district municipalities, and 205 local municipalities. This is a total of 257 municipalities and several water supply utilities with most of them owning gravity water supply and water distribution systems, which could be considered for conduit hydropower installations. Various locations in these systems are suitable for the installation of retrofit conduit hydropower units and may even be equipped with newly developed turbines or pumps-as-turbines (PATs). The City of Tshwane (CoT), the South African capital, fortunately, possesses a number of conduit hydropower opportunities. This is due to its geographic location relative to the country's main water sources and the elevation differences between the water sources and destinations.

1.2 Objectives of this study

The objective of this study was to develop and ultimately determine the sustainability and reliability of a conduit hydropower prototype turbine installed at a reservoir intake in an existing pressure-reducing station (PRS). The logged data, which included data of the energy generated, alternator voltage, water flow rate through the turbine installation, and the total operational and down time hours of the turbine, were used to evaluate the sustainability of the turbine. The final goal was to evaluate whether the generated power was sufficient to power the telemetry, communications, and monitoring equipment at a PRS.

1.3 Scope of the study

This project reflects on the test results of a modified Pelton-type turbine, retrofitted into a closed conduit. The study introduced four inline prototype turbine designs that were built and installed. Decision support system (DSS) software that was developed for another University of Pretoria (UP) research project (Loots *et al.*, 2015), was also applied in this research project. The results of the field installation are presented in the Conclusions section and the question of whether the prototype turbine is functioning as predicted, is addressed. The feasibility, sustainability, and reliability of the developed turbine are also discussed.

Because conduit hydropower generated from the water distribution system (WDS) is always a secondary function to the WDS function, turbine installations should, therefore, not be restrictive in any way. Here, the turbine was installed into an existing spool piece in the existing PRS. The turbine installations will not always be performed on a secondary feeder line or a by-pass line, as during this testing, and thus it should not jeopardise the water flow or cause interruptions to reservoirs.

Four turbine prototypes were installed and tested for functioning in the PRS: a modified AmpAir turbine, a modified Kaplan turbine, and two inline pressure wheel (IPW) turbines. This research study focuses on the results generated from the second IPW turbine (IPW2). This unit was newly designed, built, installed, and tested under different flow conditions. This was done to obtain different flow and pressure relations and to determine the power generated with different flow rates by the conduit hydroelectric turbine. The data from the tests were logged and used to calculate and generate graphs of the efficiency of this specific turbine in the field installation.

The existing operational water flow (ranging from 50 ℓ/s to a maximum of about 345 ℓ/s) and pressures (ranging from about 5 m to maximum of nearly 65 m) were used to generate a testing sequence and test procedure. The testing stage of the study was divided into short experiments with different flow and pressure values, limited by the normal flow and pressure values under operational conditions in the PRS.

The second part of the testing was performed by monitoring the turbine over a period of about four months. All the data were collected from the turbine set-up with a data logger during this testing period. This enabled the analyses to reflect reliability, efficiency, and energy produced.

The monitoring of the output of the turbines was performed with a dedicated, suit for purpose, manufactured test panel. This panel made it possible to monitor two different turbines at the same time. The turbines were linked to the test panel, which not only included monitoring instruments, but also a series of additional loads that could be increased or decreased, simulating power consumption. The data logger could record the water flow, water pressure, voltage, and current of both the hydropower turbine installations. Only one turbine installation was used for this research project and is described in detail in this project report.

1.4 Methodology

The methodology that was used for developing the testing of the IPW included the following processes:

- Evaluation of literature on existing hydroelectric power turbine development worldwide.
- Development and manufacturing of prototype model 5.
- Enhancement of the prototype model (IPW).
- Development of a testing facility in an existing water network.
- Installation of the IPW at the testing facility in a water network in such a manner that a variety of tests could be conducted on the installation:
    a) verifying the flow through the IPW;
    b) verifying the load on the IPW;
    c) verifying the configuration of the installation;
    d) determining the reliability of the IPW; and
    e) determining the efficiency of the turbine and alternator combination.
- Modifying the model as seen necessary.

- Performing long-term evaluation on the installation.

1.5 Layout of the report

The report consists of the following chapters and appendices:

Chapter 1: Introduction

The first chapter provides the general background for the study and it also describes the objective of this study. The methodology that was followed in the developing and testing of the IPW, is also discussed.

Chapter 2: Literature Review

This chapter refers to the literature available on the harvesting of available potential energy – dating from ancient Egypt and China, up to modern times. It also refers to a wide variety of international and local hydroelectric installations and some details are given of these cases. Specific referral is also made to installations in CoT and turbine types installed at these sites. A brief discussion is also provided on the selection method of types of turbines to be installed and electrical connection into the electricity grid.

Chapter 3: In this chapter, the development of different types of experimental turbines are discussed and the set-up and installation of these different types of pico hydropower units are illustrated and discussed.

Chapter 4: The design principles of the IPW are discussed and a closer look is given to the existing types of water wheels. The working of the modern alternator is investigated to determine whether it would work in combination with the IPW design. A detail design is made to integrate the turbine and the alternator into a single unit. The installation detail and layout are decided on and test procedures determined. Measurement requirements are determined and testing procedures finalised.

Chapter 5: The test results are described in this chapter. Results are interpreted and reliability and sustainability discussed.

Chapter 6: Recent research and development in closed conduit designs are compared with the results from the IPW that was tested and of the data that were gathered.

Chapter 7: Reliability and durability data from long-term test results of the IPW was gathered, and evaluated in this chapter, followed by reliability testing as measured against other pico hydropower developments.

Chapter 8: The conclusion chapter deals with observations of designs, tests, and interpretation of the test results of the project. Recommendations are made on further work that can be conducted in this field.

Chapter 9: This chapter provides a list of all references used in this document.

Appendix: The first commercial hydroelectric unit is illustrated here.

2 LITERATURE REVIEW

2.1 Introduction

In this chapter, the harvesting of available potential energy is demonstrated with a wide variety of international and local case studies where hydro energy is being generated. This energy is harvested from energy stored in closed conduit systems and converted into a sustainable and reliable power source. It demonstrates that the energy is in a usable form at a specific point or location at a specific time.

2.2 Hydropower in South Africa

According to Jonker-Klunne (2013), 10 % of the global hydropower potential is located within the African continent and only 4–7 % of this extensive resource has been developed. This is, however, only regarding the large-scale hydropower, with no proper statistics on small- and micro-scale hydropower. The author also mentioned that small hydropower can play a pivotal role in providing energy access to remote areas. These proposed units can be used either in stand-alone isolated mini-grids, or connected to the national distribution grid.

The National Energy Regulator of South Africa (2011) published the decision that municipalities need to register and maintain databases of all small hydropower units (<100 kW) within their areas. Reporting must be done on an annual basis and must include data on the number of units, time of use, capacity, etc. This decision was motivated by the power-sharing and power outages in SA at that point in time. This was further boosted by a range of new products to harvest renewable energy that appeared on the market. It is evident from the literature that a variety of applications for small-scale hydro plants exists in many different countries and that hydropower is an eco-friendly, clean power-generation method that harnesses natural resources and does not produce air pollution or greenhouse gases, ensuring the comfortable coexistence of humans, livestock, and plants (Ya, 2009). In SA, the completed pilot installations demonstrate the ability to develop renewable energy sources locally (Van Vuuren *et al*., 2014a). These installations act as showcases to hopefully unlock further projects to harvest more renewable energy.

South Africa still has a long way to go before most of the rural communities will be provided with reliable and sustainable electricity supply (Van Vuuren *et al*. 2014b). Van Vuuren *et al*. (2014a) further explains that primary electricity infrastructure (i.e. coal-fired power stations) cannot sustain a sufficient supply to meet the electricity demand from the existing electricity supply and distribution network. This also implies that consumers in the rural areas of the Eastern Cape and Kwa-Zulu Natal provinces will have to wait until the national electricity provider can increase their service-delivery capacity to serve rural communities, or consider alternative means to generate their own electricity. The important fact is that the provision of electricity to rural communities has the potential to improve the communities' standards of living. The reality is that many remote areas, small settlements, farms, and villages will not be connected to the national energy grid in the near future (Republic of South Africa, 2016).

Van Vuuren *et al*. (2014b) proposed the use of small-scale hydropower systems for rural electrification in SA to address this issue. This proposal culminated in the application for funding for small-scale hydropower development for rural electrification in SA. The funding proposal also stated that the aim of the project could be to include the uptake of micro-hydro technology to generate electricity. This initiative opened the doors and took a new look at existing hydropower technology and stimulated the development of and research for new designs and applications.

Over the last 20 years, rural upliftment included the supply of potable water to rural communities in SA. This resulted in the building of small dams and water intakes on the perennial rivers with pipeline and water networks to conduit water closer to the communities. According to Van Vuuren *et al*. (2013), there exists hidden potential in all of these schemes for either pico (<20 kW), micro (up to 100 kW), or even mini (up to 1 MW) hydropower units that could electrify a clinic, school, village cultural centre, or even a whole village.

According to the Department of Minerals and Energy (DME), unconventional hydropower development could take place in both rural and urban areas of SA (Republic of South Africa, 2002). The DME further stated that such hydropower developments could tap energy from irrigation canals, water pipelines, deep mining undertakings, etc. This statement already recognised the fact that waterways and systems can be seen as a source of energy to be converted into the needed form of energy at a specific point and time. The adopted classification of hydropower plants, according to their power output in SA, is provided in Table 2-1 (Van Vuuren *et al.*, 2014b).

Table 2-1: Classification of hydropower installations in South Africa

Turbine classification	Capacity output
Pico	≤ 20 kW
Micro	20 kW to 100 kW
Mini	100 kW to 1 MW
Small	1 MW to 10 MW
Macro/Large	> 10 MW

The total potential hydropower to be unlocked and developed in SA, based on a baseline study conducted in 2002, is summarised in Table 2-2 (Barta, 2013). This supports the opportunity to install a range of hydropower installations in SA.

Table 2-2: Hydropower category for development (Republic of South Africa, 2002)

Hydropower category for development	Installed capacity	Potential for development	
	MW	Firm (MW)	Long-term (MW)
Pico (up to 20 kW)	0,02	0,1	60,2
Micro (20 kW to 100 kW)	0,1	0,4	3,8
Mini (100 kW to 1 MW)	8,1	5,5	5,0
Small (1 MW to 10 MW)	25,7	63,0	25,0
Subtotal for pico/micro/mini and small hydro	**33,92**	**69,0**	**94,0**
Large conventional hydropower (> 10 MW)			
Run-of-river (e.g. direct intake or weir)		1200,0	150,0
Diversion fed (e.g. pipe, canal or tunnel)		3700,0	1500,0
Storage regulated head (e.g. barrage or dam)	635,0	1271,0	250,0
Total for renewable hydropower in SA	**687,0**	**5160,0**	**1994,0**
Large pumped storages (> 10 MW)	**1580,0**	**7000,0**	**3200,0**
GRAND TOTAL FOR ALL HYDROPOWER IN SA	**2267,0**	**12160,0**	**5194,0**
Imported macro hydroelectricity (> 10 MW)	**800,0**	**1400,0**	**35000,0**

The proportional contribution of the pico, micro and mini installations is quantified in terms of power contribution total and is relatively small. But in terms of functionality and in terms of contribution to stimulate rural development, its contribution is difficult to quantify. The existing operational parameters of commercial hydropower turbines available on the market, as described by Van Vuuren *et al*. (2014b), are listed in Table 2-3. This still leaves the opportunity to design and create new and innovative prototypes to convert water pressure energy into other forms of energy.

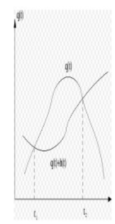
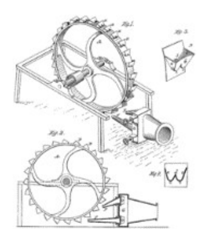
Table 2-3: Operational parameters of turbines (adapted from Van Vuuren, 2014b)

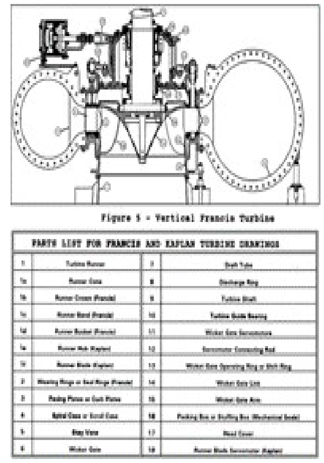
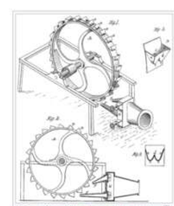
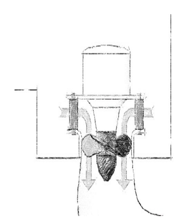
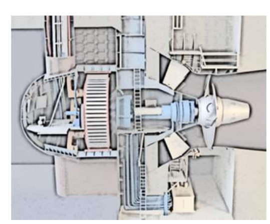
Pressure	Impulse	Reaction
High	Pelton Turgo Multi-jet Pelton	Francis
Medium	Crossflow Turgo Multi-jet Pelton	Francis Pump-as-turbine
Low	Crossflow	Propeller Kaplan
Ultra-low	Water wheel Screw type Hydrokinetic	Propeller Kaplan Siphon

2.3 History of hydraulic turbines

The development of hydroelectricity since the first water wheels in the ancient worlds of Egypt and China are illustrated in Table 2-4 (Viollet, 2017).

Table 2-4: The development of hydroelectricity

Year	Description	Image
Thousands of years ago	Water wheels in China and Egypt	
1707–1783	Euler turbine theory – Leonard Euler – still valid today	 
1820	Jean-Victor Poncelet developed an inward flow turbine	
1824	“Turbine” is a designation that was introduced in a dissertation by the French engineer, Burdin	
1827	Fourneyron designed a radial turbine and put to operation the first real turbine – power 20–30 kW and a runner diameter of 500 mm	
1840	Henschel and Jonval independently developed turbines with axial water flow through it. They were the first ones to apply draft tubes and, in that way, to utilise the water head between the runner outlet and tail water level	 Scientific American

Year	Description	Image
1849	Francis developed the radial turbine, named the Francis turbine	
1870	Professor Fink introduced an important improvement of the Francis turbine by making the guide vanes turn on a pivot in order to regulate the flow discharge	
1890	The American engineer, Pelton, developed an impulse turbine, called the Pelton turbine	 Figure from Pelton's original patent (October 1880).
1913	Kaplan designed a propeller turbine, named the Kaplan turbine	
To date	Subsequent developments were made on Francis, Pelton, and Kaplan turbines	

2.4 Types of turbine

2.4.1 Types of water wheel

During the 18th century, water wheels were classified into different types. The following classifications are used:

- undershot;
- overshot;
- breastshot; and
- pitchback.

According to Power in the Landscape (n.d.), the earliest water wheels in Calderdale, United Kingdom, were undershot wheels that were placed directly into the stream. They were used mainly on rivers, such as the Calder, with a large quantity of water available, but without much fall to create a high head. The water wheels that were built in the late 18th and early 19th centuries were usually overshot or occasionally breastshot wheels. The rotation was caused by the weight of the water. The application for this was in relatively small streams that could turn some large water wheels. The most common water wheels are listed in Figure 2-1 and discussed below:

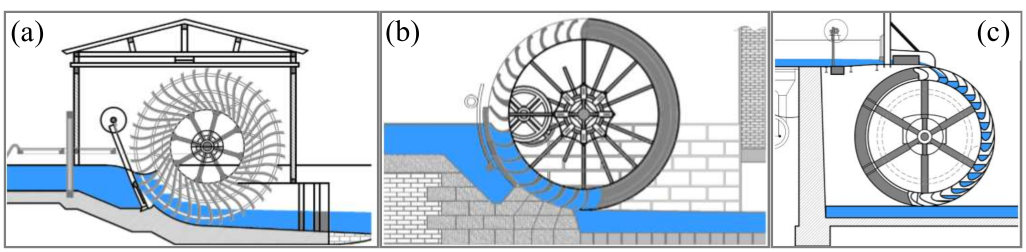


Figure 2-1: Type of water wheels: (a) under-shot water wheel; (b) breastshot water wheel; and (c) over-shot water wheel (from Loots *et al.*, 2014)

- **Undershot:** This wheel uses kinetic energy created by the flowing water pushing the wheel around. It was used for felling and in corn mills, as shown in Figure 2-1a. The design was also changed and a later version, the Poncelet wheel, was similar in construction, but had curved blades. This change made more effective use of the energy of the flowing water and did not require a large head of water.

- **Breastshot:** This type of water wheel receives energy from falling water which hits the blades at the centre height of the wheel, as demonstrated in Figure 2-1b.
- **Overshot:** The original design of the undershot wheel used the weight of the water to drive the wheel. With the overshot wheel, the rotation is caused by the pull of gravity on the water contained in the buckets, as illustrated in Figure 2-1c. In the close conduit design, the water is forced to fill the buckets which results in the rotation of the turbine. It is concluded that this design is extracting more of the available energy from the moving water.

2.4.2 The most commonly used hydropower turbines

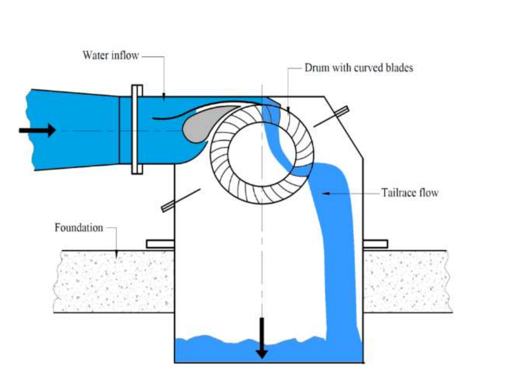
A summary of the most common turbines used in hydropower plants is shown in Figure 2-2 and discussed below.

2.4.2.1 Crossflow turbines

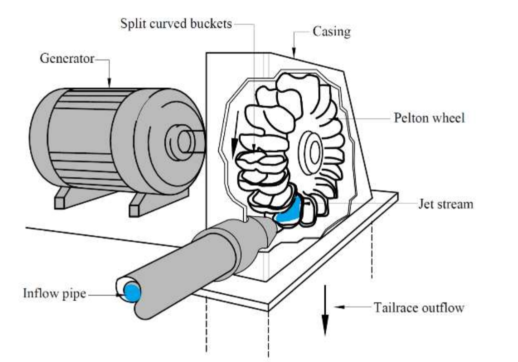
Crossflow turbines are most preferable when there are large variations in the flow rate due to cyclical change (Razak *et al*. 2010). Figure 2-2a shows that a crossflow turbine has a drum-like rotor with a solid disk at each end and gutter-shaped slats joining the two disks. A jet of water enters the top of the rotor through the curved blades and emerges on the far side of the rotor after passing through the blades a second time. The water is allowed to transfer some of its momentum on each passage through the rotor due to the shape of the blades, after which, now having little residual energy, it falls away (Paish, 2002). Thornbloom *et al*. (1997), considers an accurately designed crossflow runner as one in which "the water impinges on the top blade, is turned by the blade, and flows through the runner, just missing any shaft in the centre and impinges on a lower blade before exiting to the tailrace."

2.4.2.2 Pelton turbines

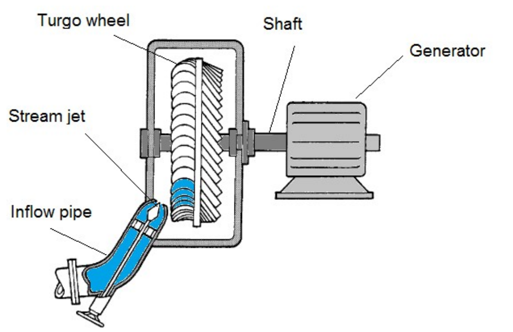
A typical single jet Pelton wheel can be seen in Figure 2-2b. In a Pelton turbine, one or more jets of water are directed tangentially onto a set of split curved buckets, connected to a wheel along its rim. The jet stream is directed inwardly, sideways, and outwardly by the curved buckets, producing a force on the buckets that causes the wheel to turn – resulting in a torque on its shaft (Paish, 2002). All of the head in the water flow is converted to kinetic energy at the nozzle. All this kinetic energy is then used for propelling the bucket. Finally, the deflected water falls into a discharge collector channel or weir.



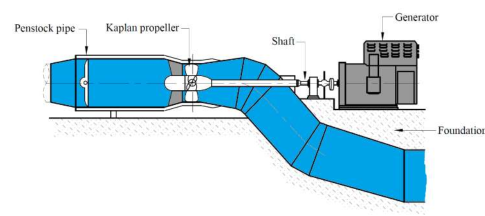
(a) Side view of a crossflow turbine (Paish, 2002)



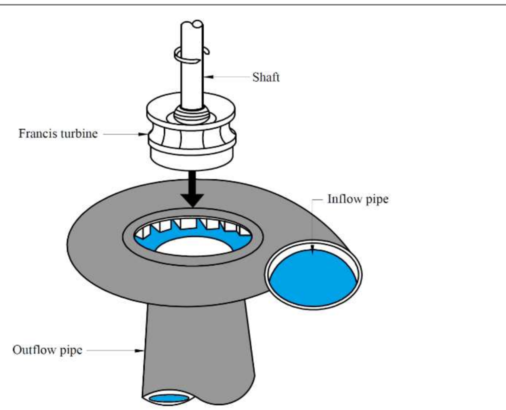
(b) Pelton wheel turbine (Paish, 2002)



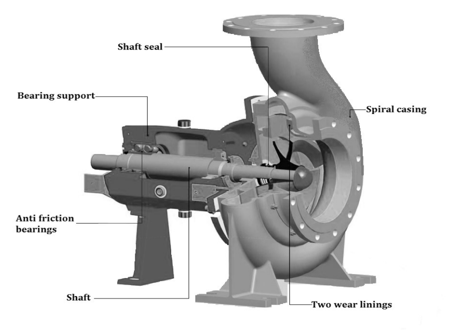
(c) Turgo wheel turbine (Paish, 2002)



(d) Axial-flow turbine fully embedded in water flow (Paish, 2002)



(e) Mixed-flow Francis turbine in casing (Paish, 2002)



(f) An example of a pump-as-turbine (Mellacher & Fiedler, 2013)

Figure 2-2: Summary of generally used turbine technologies

2.4.2.3 Turgo turbines

A turgo wheel functions very similarly to a Pelton wheel. The only difference is that in the turgo wheel, the jet stream is directed obliquely onto the buckets and impinges several buckets instantaneously (Gulliver & Arndt, 1991). A typical turgo wheel turbine is depicted in Figure 2-2c.

2.4.2.4 Kaplan and propeller turbines

Kaplan and propeller type turbines are reaction turbines that operate on the axial flow of water. They make use of the incoming flow of water by developing hydrodynamic forces that propel the runner blades (Paish, 2002). The runner functions in a completely water-filled casing. To achieve good efficiency, the water needs to be given a certain amount of swirl before meeting the turbine runner. Inlet swirl can be created by adding fixed guide vanes upstream of the runner. A Kaplan turbine has the advantage of adjustable blades. Figure 2-2d shows the typical set-up of an axial-flow turbine.

2.4.2.5 Francis turbines

Francis turbines are classified as a radial- or mixed-flow type. In radial- or mixed-flow runners, the flow of water exits at a different radius than the radius at the inlet. If the flow enters the runner with only radial and tangential components, it is considered as a radial-flow device. In mixed-flow devices, the flow enters with both radial and axial components. In a Francis turbine, water flows radially inwards into the turbine runner and is turned to emerge axially, as shown in Figure 2-2e.

2.4.2.6 Pumps-as-turbines

A large amount of research has recently been performed on the use of reverse-engineered pumps that can be used as hydraulic turbines Figure 2-2f). A standard centrifugal pump is run in reverse to act as a turbine; this is an attractive option, especially in developing countries, because pumps are mass-produced, and therefore more readily available and cheaper than turbines (Williams, 2003). However, PATs generally operate at lower efficiencies than conventional turbines, especially at partial flows.

Williams *et al*., (1998), from the Nottingham Trent University Micro-Hydro Centre, have been involved with the design and installation of various PAT schemes. The university demonstration scheme at a farm in Yorkshire has been running since 1991. The pumps are now mass-produced and, as a result, have many advantages over conventional turbines.

According to Pugliese *et al.* (2018):

> the use of Pumps As Turbines (PATs) in Water Distribution Networks (WDNs) is a viable approach to both generate small-scale hydropower energy and exploit the excess pressure. They represent an alternative to micro-turbines, providing interesting efficiencies and significant working conditions, at the expense of lower investment and maintenance costs.

2.5 The fundamentals of fluid mechanics

The basic fundamentals of fluid mechanics form the basis of hydraulic engineering, according to the European Small Hydropower Association (ESHA, 2004). Despite this statement, empirical relationships are applied to achieve practical engineering solutions. Interestingly enough, ESHA further states that there does not, and probably never will, exist a general methodology for mathematical analysis of the movement of fluids. However, it is important to take notice of the basic hydraulic principles of fluid mechanics and apply it in the designing and building of basic hydropower units.

2.5.1 Water flow in pipes

The potential energy in a body of water is defined by its velocity and the vertical height through which it descends, as illustrated in Figure 2-3. By applying this principle in water networks, the potential energy can be considered as the height difference between the reservoir water level and the point of investigation. The differences in water levels are what drives the flow of water through water distribution networks. This is also referred to as the “head of pressure” or the “pressure head”. This pressure head is a reflection of energy, referred to as “gravitational potential energy”.

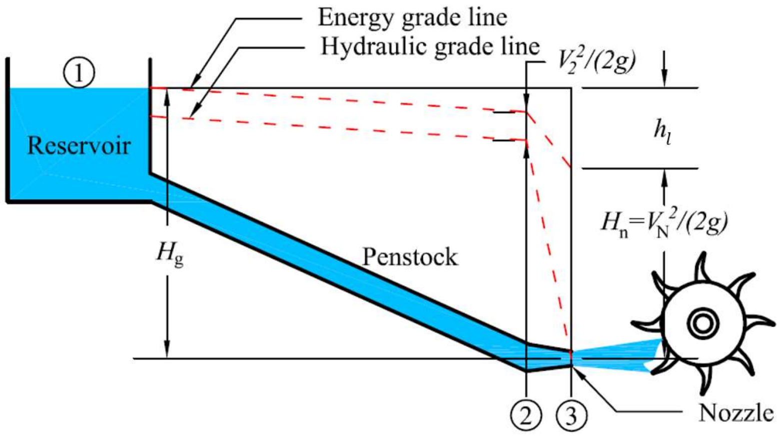


Figure 2-3: Hydraulic and energy gradient in a pipe system

The mechanical or kinetic energy in the water system forms due to the flow of the water mass. The total energy is the product of mass and velocity due to the effects of gravity and head combined. Although energy is normally expressed in Joules (J), in hydraulic applications, the unit of measurement is meters head pressure (m). Bernoulli's (1738) equation for the energy head in the water flowing in a closed conduit of circular cross section is as follows:

$$\boldsymbol{h_1 + \frac{P_1}{\Upsilon} + \frac{V_1^2}{2g} = h_2 + \frac{P_2}{\Upsilon} + \frac{V_2^2}{2g} + h_f + h_l} \quad \textbf{(2.1)}$$

Where:

h_1 = elevation of point 1 above data plane.

h_2 = elevation of point 2 above data plane.

h_l = secondary losses between point 1 and point 2.

h_f = friction losses between point 1 and point 2.

P_1 = pressure at point 1.

P_2 = pressure at point 2.

V_1 = velocity of the water at point 1.

V_2 = velocity of the water at point 2.

g = the gravitational acceleration.

γ = the specific weight of water.

From the Bernoulli equation, the total energy head at point 1 is the algebraic sum of the potential energy h_1 , the pressure energy P_1/γ and the kinetic energy $V_1^2/2g$. This is equal to the total energy head at point 2 that is the algebraic sum of the potential energy h_2, the pressure energy P_2/γ, and the kinetic energy $V_2^2/2g$ plus the friction losses h_f and the secondary energy losses h_1 in the pipe system between point 1 and point 2. Figure 2-4 illustrates the hydraulic and energy gradient in a pipe system with a pressure-reducing valve (PRV) installation. The function of the PRV in the system is to reduce the static pressure to a level equal to the top water level (TWL) of a reservoir, or to the working pressure in the water network that the specific supply system is feeding. If the normal height of an average reservoir is taken as 10 m and the supply pressure is 100 m of pressure, 90 m of pressure must be dissipated out of the system.

The most common method to dissipate the additional energy is with a PRV installation in the water system. An alternative method to dissipate this additional energy is through the installation of a hydropower unit.

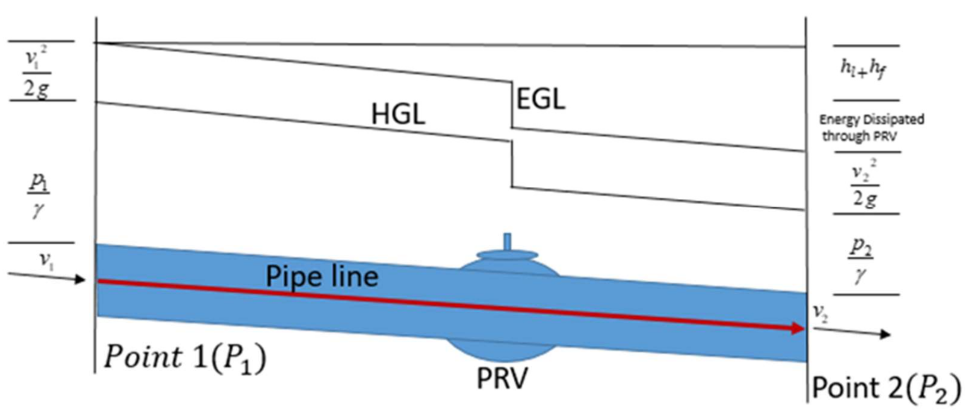


Figure 2-4: Hydraulic and energy gradient in a pipe with a PRV installation

2.5.2 Flow classification

Laminar flow can be defined as water flow in lamina or layers in the form of a series of thin-walled concentric pipes with the inner layers that move at a slightly higher speed. The maximum velocity of the fluid in the pipe will be in the centre of the pipe. The velocity distribution has the form of a parabola and the average velocity is approximately 50 % of the maximum centre line velocity.

A long straight glass pipe can be used to demonstrate the different flow conditions. A fine stream of coloured water can be introduced at the entrance to the pipe. This will indicate the fluid movement that will be indicative of the different types of flow of the water inside the pipe:

- laminar flow;
- transitional flow; or
- turbulent flow.

The interaction between slower- and faster-moving layers causes the flow to become turbulent. This is illustrated in Figure 2-5. Reynolds (1886) carried out experiments at the end of the 19th century and defined the transition from laminar flow to turbulent flow to be dependent on the velocity of the fluid, the viscosity of the fluid, and also the pipe diameter.

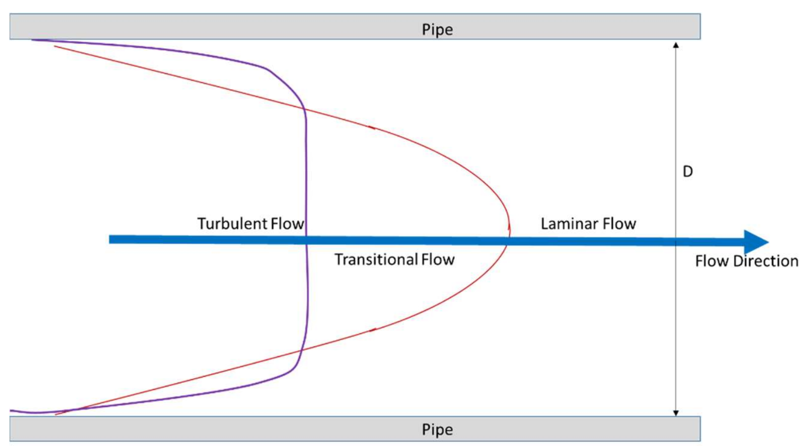


Figure 2-5: Velocity distribution for laminar and turbulent flow

With increased flow rate, the lamina flow suddenly starts breaking up and mixes with the surrounding water, forming turbulence or eddies. In addition, laminar water layers close to the pipe wall mix up with laminar layers in the middle.

$$\boldsymbol{R_e = \frac{D*V}{v}} \qquad \textbf{(2.2)}$$

Where:

R_e = Renolds number.

D = pipe diameter (m).

V = average water velocity (m/s).

ν = kinematics viscosity of the fluid (m^2/s).

Calculating the Reynolds number is an important method to classify or define the flow conditions in a pipe. The following values of the Reynolds number are an indication of the type of flow:

- Laminar (Re < 2300);
- Transient (2300 < Re < 4000); and
- Turbulent (4000 < Re).

2.6 Classification of turbine types

A turbine is an instrument that can be used to convert kinetic energy in water systems to mechanical energy. The turbine converts available system energy to energy of rotation. These turbines are primarily used to drive electric generators to produce local electricity or electricity that is connected to electric grids and distribution networks. Turbines are divided into two groups, namely: impulse turbines and reaction turbines.

2.6.1 Impulse turbines

According to Leon and Zhu (2014), in impulse turbines, all the flow energy is converted to kinetic energy before transformation in the runner. The flow velocity's directional changes transfer the impulse forces to mechanical energy that is available at the turbine shaft in the form of rotation of the shaft. The water is projected in the runner through jets that momentarily hit the runner to produce rotation thereof.

The total static pressure H_g, as shown in Figure 2-6, is the height difference between the top water level at point 1 of the source, and the turbine inlet at point 3. The gross head is the height difference between the top water level of the source and the tail water level at point 3. The effective head H_n available is the dynamic pressure head available at the turbine inlet after all losses are considered.

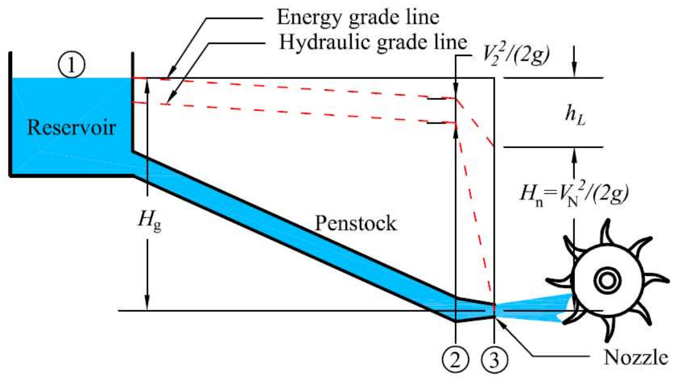


Figure 2-6: Impulse turbine energy lines and pressure heads (Leon and Zhu, 2014)

2.6.2 Reaction turbines

Leon and Zhu (2014) also stated that in the reaction turbines, two effects cause the energy transfer. Flow energy in the water system is transferred into rotational energy on the turbine shaft.

The first effect is when a decrease in pressure occurs between the inlet and the outlet of the runner. This is referred to as the reaction part of the energy conversion. The second effect is the transfer of vector forces with the directional changes of the flow velocity vectors when the liquid runs through the runner blade channels. This is then referred to as the impulse part of the energy conversion process. It should be noted that the fact that the runner is completely filled with liquid, makes it possible to measure the pressure difference between the inlet and outlet to the runner (Figure 2-7).

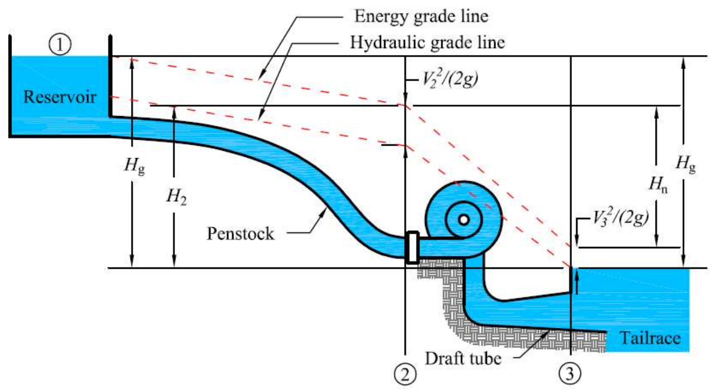


Figure 2-7: Reaction turbine energy lines and pressure heads (Leon & Zhu, 2014)

2.6.3 Energy conversion in hydropower plants

The formula used to calculate electric power produced in a hydropower plant is given as:

$$\boldsymbol{P = \rho Q g h \eta} \tag{2.3}$$

Also,

$$\boldsymbol{P = \eta_t \eta_g g \rho Q (H_g - h_l)} \tag{2.4}$$

Where:

η = turbine efficiency (%).

Q = discharge (m^3/s).

H_g = gross head (m).

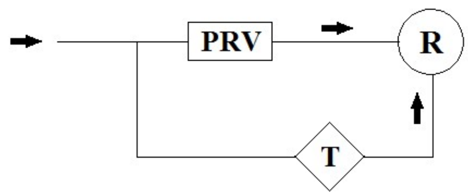
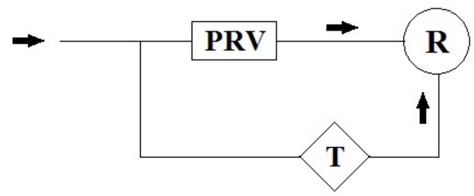
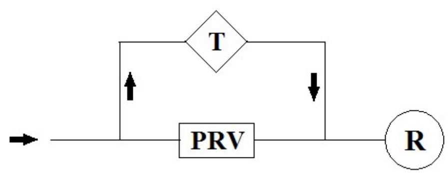
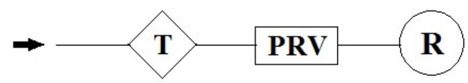
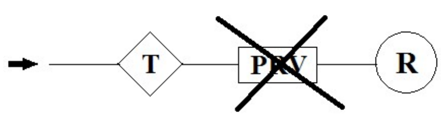
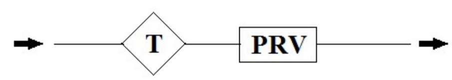
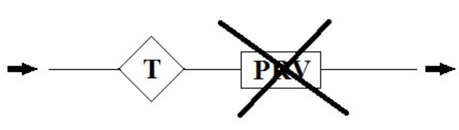
h_l = sum of the head losses (m).

g = gravitational acceleration (m/s^2).

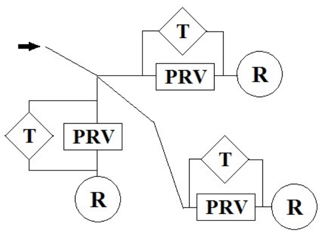
The generator and the turbine each have their own efficiency. The generator efficiency is η_g with the turbine's efficiency as η_t. The overall hydroelectric unit efficiency is given as η (= $\eta_g \eta_t$).

Table 2-5 illustrates the various ways in which a turbine can be installed within a water distribution network. The bulk of the configurations are either at a PRV or a reservoir, but it is important to note that these are not always the only options for conduit hydropower, especially when considering smaller hydropower alternatives. Examples of turbine designs that are used around the world, but that may also be viable as pico hydropower turbines (based on the classification as discussed in Table 2-1) are shown in Table 2-6. In addition, the possible configurations (as referenced from Table 2-5) for turbine installations based on the specific turbine design, provided in Table 2-6.

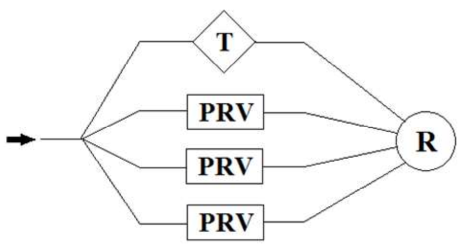
Table 2-5: Different conduit hydropower configurations (adapted from Van der Berg *et al*., 2019)

 (a) Turbine as PRV bypass – turbine discharges directly into reservoir (atmospheric discharge)	 (b) Turbine as PRV bypass – in section along pipe system
 (c) Turbine as PRV bypass – turbine does not discharge into reservoir – location at end reservoir	 (d) Turbine in series to PRV – location at end reservoir
 (e) Turbine replacement for PRV – location at end reservoir	 (f) Turbine in series to PRV – location along pipe system
 (g) Turbine replacement for PRV – location along pipe system	 (h) Turbine in series to PRV – turbine along pipe system – PRV at end reservoir

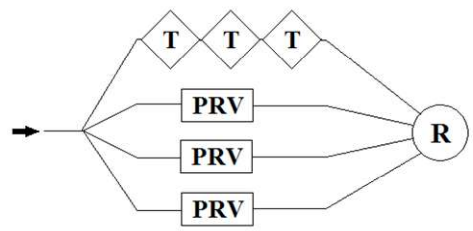
(i) Turbine in series to PRV – turbine along pipe system – PRV along pipe system considerable distance from turbine



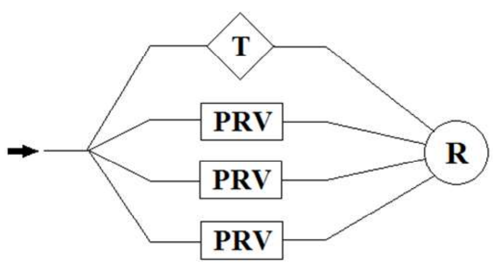
(j) Multiple reservoirs and turbine installations



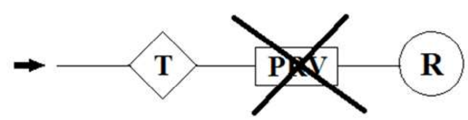
(k) Turbine parallel to PRV manifold at end reservoir



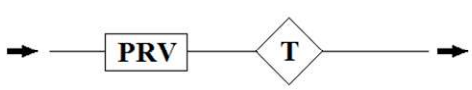
(l) Turbines in series – parallel to PRV manifold at end reservoir



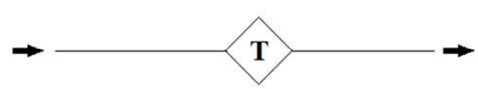
(m) Turbine parallel to PRV manifold at end reservoir (atmospheric discharge)



(n) Turbine replacement for PRV – location at end reservoir (atmospheric discharge)



(o) Turbine in series to PRV – location downstream of the PRV



(p) Turbine installed at any point in the pipeline

Abbreviations: PRV: pressure-reducing valve; R: reservoir; T:turbine

Table 2-6: Turbine designs with possible conduit hydropower installation configurations

Type	Design	Configurations
Impulse	Pelton	a, m, n
	Crossflow	a, m, n
	Water wheel	a, m, n
Reaction	Kaplan	b, c, d, e, f, g, h, i, j, k, l
	Hydrokinetic	None
	Vortex	None
	Francis	b, c, d, e, f, g, h, i, j, k, o, p
	Siphon	None
	Inline	b, c, d, e, f, g, h, i, j, k, l, o, p
	Pump-as-turbine	b, c, d, e, f, g, h, i, j, k, o, p

2.7 International perspectives

It is globally accepted that hydropower development has major potential and benefits. According to Ya (2014), rural areas are rich in natural resources including plentiful renewable energy potential. He also stated the importance of modernisation to achieve universal access to electricity because large percentages of populations are populations living in rural areas and are mostly located great distances away from national grid systems. In scoping studies, the emphasis was on the potential of power generation by retrofitting hydropower generation facilities at existing infrastructure. Also, on utilising the untapped energy on the supply side of storage reservoirs in water distribution systems where the excess heads are normally dissipated across PRVs. A conceptual hydropower retrofitting model (HRM) was developed (Van Vuuren *et al.*, 2011) to determine the viability of hydropower development at existing infrastructure by, amongst other, considering environmental impact, cost, and sustainability. Fontana *et al.* (2012) stated that:

> during the past few years, issues concerning sustainable management of water distribution systems have attracted interest through an integrated policy aimed at reducing leakage through a pressure management strategy. Pressure reducing valves (PRVs) are often used in water networks to prevent the downstream hydraulic grade from exceeding a set value, although they must be adequately located to maximize their effectiveness.

According to Pugliese *et al.* (2018), the use of PATs in water distribution networks is a viable method to generate hydroelectric power as well as to exploit any excess pressure.

The International Energy Agency Hydropower Implementing Agreement (IEA Hydro) and Programme exist (IEA Hydro; Van Vuuren *et al*., 2011) between the following countries: Canada, China, Finland, France, Japan, Norway, Spain, Sweden, and the United Kingdom, who have agreed that hydropower is the renewable energy technology that is currently commercially viable on a large scale. The four major advantages are that:

- it is renewable;
- it produces negligible amounts of greenhouse gases;
- it is the least costly way of storing large amounts of electricity; and
- it can easily adjust the amount of electricity produced to the amount demanded by consumers. Small-scale, fully automated installations could include reductions in manufacturing costs.

This leads to:

- small-scale hydropower becoming increasingly attractive. Unfortunately, on the social front, the impact of some hydropower projects has been the subject of vigorous environmental and social debating.
- the increased awareness of the sensitivity analysis and economic risk factors for small-scale hydropower projects. This implies that the developers or investors should have an overview of the project and should realise that a hydropower project has an economical risk and that they should base decisions on the feasibility and implementation possibility of such a project. Different methods have been developed to calculate and illustrate the risks and uncertainty.
- informed dialogue between developers and investors in hydropower.
- the creation of opportunities to finance developments and contribute to the development of communities.

2.7.1 Development in Switzerland

The Centre for Energy Policy and Economics of the Swiss Federal Institute of Technology (ETHZ), anticipates that the increasing energy consumption will influence the climate irreversibly in the next few years and will generate tremendous social, ecological, and economic impacts. They published this statement in a strategy document "Vision Energétique de la Suisse en 2050" (2017), for *Vision Energétique* that was also established by ETHZ. To resolve this increasing energy consumption, it was suggested that the solution is to guarantee the security of local energy supply and protect this environment. The solution aims to make use of sustainable power supply systems to resolve the quest for energy. This includes small and micro hydropower plants to produce sustainable energy.

The mountainous Swiss topography, with well-developed potable water infrastructure, made it especially attractive to harvest potential energy from the water infrastructure. Advantages include low construction costs and a renewable energy source. An example of such an installation is depicted in Figure 2-8.

Figure 2-8: A 22 kW Vogel pump turbine in the canton of Friborg, Cornaux

A computer tool was developed to evaluate the economic potential in existing supply networks. The development of this tool is supported by the Hydropower and Energy Department of Valais Canton in Switzerland. The basic and simplistic model can analyse the economic turbine potential at different locations in a water network and the result should motivate the construction of economically beneficial small hydropower plants, and therefore increase the production of renewable energy based on:

- modelling and simulation;
- hydraulic, energy, and financial modules;
- the utilisation of the economic module database;
- a catalogue of elements typically found in a hydropower plant with cost estimates; and
- analysis and comparison.

2.7.2 Development in Malaysia

Malaysia has many rivers, ranging in size. The potential to generate electricity exists throughout this network of rivers. Small hydro systems use run-of-river application methods and do not require dams, which is an advantage because of the low environmental impact. Although the capacity of micro and pico hydro systems may be small compared to larger potential hydropower installations, these have made it possible to produce off-grid electricity. This directly benefits the small communities and nearby settlements, with an example of such an installation shown in Figure 2-9. Power is predominantly provided to these areas using diesel or petrol generators where operating hours are limited and the operational cost extremely high due to high fuel and transport costs, and the limited availability of fuel at these remote locations. Small-scale hydropower installations ensure that these communities are lit up at night in an affordable way (Basar & Musa, 2015).

Figure 2-9: Rural renewable project in Borneo, 2018.

2.7.3 Development in the eastern Andes

North Peru, on the eastern slopes of the Andes (Ashden, n.d.), hosts some of the least-developed parts of this country. The difficult terrain and scattered population mean that few people have access to grid electricity. However, the large number of rivers and streams have a large potential for generating hydroelectricity. Peru has installed 47 micro-hydro schemes, with an average electric power of 33 kW that provides metered electricity to about 5 000 families. In general, the commodity of electricity from the micro-hydroelectricity plants provide good-quality lighting, refrigeration, and entertainment in homes. This also influences education and health. The positive impact on the economy and social stability can be seen by the return of many inhabitants, who initially tried to find a better way of living in the cities (Ashden, n.d.).

Some of these micro-hydro schemes are financed by the community members, partly through a loan from the Inter-American Development Bank and are mostly managed locally. Figure 2-10 shows an installation under construction on the slopes of the Andes in Peru. Practical action-trained technicians are responsible for the day-to-day operations and maintenance of the micro-hydro plants.

Figure 2-10: Slopes of the Andes micro-hydropower project in Nuñez, 2009 (Ashden, n.d.)

2.7.4 City of Keene Water Treatment Facility, New Hampshire

In the City of Keene in New Hampshire, an alternative energy company converts excess pressure in piping systems at the city's water treatment facility into clean, renewable power. They implemented the turnkey hydropower systems, custom-designed to fit the specific site, operational conditions, and constraints – inclusive of all requisite monitoring, control, and protective relays. The systems they designed and implemented can be stand-alone or integrated into existing supervisory control and data acquisition (SCADA) systems and can be fitted with sensors for smart water system monitoring. The principle is that energy can be recovered anywhere within the water distribution systems. Applications can include mandated releases, PRVs, and transfer stations.

2.7.5 Lucid Energy, USA

Lucid Energy is an American company that developed a multiple blade type inline hydropower turbine (depicted in Figure 2-11) that is grid-connected. This system generates environmentally friendly hydropower that has no direct impact on water service delivery. This design makes use of unique spherical turbine blades installed inside large-diameter water pipelines to harvest energy from the network when water passing through the turbine causes the turbine blades to spin. This results in converting excess water pressure into electricity. Multiple turbines can be installed in series on a pipeline to harvest the maximum available access energy.

Figure 2-11: Blade-type turbine produced by Lucid Energy (Lucid Energy, n.d.)

An advantage of this system is that it does not inhibit water delivery and that it operates in a wide range of pipe diameters combined with different combinations of pressures and flows. Lucid Energy stated that "unlike conventional hydropower and in-pipe PRV replacement technologies, the Lucid Energy Power System does not inhibit water delivery and operates in a wide range of pipe diameters and pressure/flows" (Lucid Energy, n.d.). This system does not require a bypass system as part of the installation and does not deplete most of the energy available in the pipe system as conventional hydropower plants do.

2.8 Conduit hydropower in South Africa

2.8.1 Background

South Africa experienced serious energy shortages since 2008. This resulted in a new drive to find and develop alternative energy resources. The culture of vandalism and theft of infrastructure make the provision of energy in a sustainable manner challenging.

Therefore, alternative methods of energy generation close to the location where energy is needed, are increasingly required.

As an example, in CoT, water is distributed through a large water system that includes 165 reservoirs, 39 water towers, 10 863 km of pipelines and more than 280 PRSs, of which some are operating at pressures up to 250 m.

A study by Van Vuuren *et al*. (2013) illustrated how the untapped water infrastructure could be harnessed successfully to provide hydropower and, in turn, that reliable source of energy. It was recommended that:

- the South African definition for the classification should be adopted and developed;
- the promotion and development of small-scale energy generation should be revisited;
- more research should be allowed for technical solutions and technologies to release more hydropower;
- pilot low-head installations should be constructed to showcase the potential at waste water treatment works (WWTW);
- investigations should be done on canal systems to equip them with kinetic turbines for demonstrative purposes;
- one should include an example of retrofitting of hydropower technology on existing low-head dams;
- guidelines should be developed that could be used by designers of WWTW and irrigation systems assisting in the design and implementation of generating facilities from the planning stage of the infrastructure;
- manuals should be developed to assist prospective small low-head hydropower developers/proponents for rural electrification in dealing with the technical design, site evaluation, financial, and regulatory aspects of such developments;
- detailed studies should be undertaken regarding the legislative and regulatory aspects of small hydropower, especially for run-of-river schemes; and
- that the implementation of new developments should be staged to show the contribution to the power situation in SA, be it small.

2.8.2 Conduit hydropower in water supply and water distribution systems

The classification types of conduit hydro installations for CoT and the amount of energy produced at specific sites are shown in Table 2-7.

Table 2-7 : Classification of conduit hydropower plants in South Africa

Classification	Description	Output
Type 1	Installation is seen as a commercially viable hydropower installation which augments the city's electricity system. Output would be grid connected. The supply voltage and frequency will be determined by the existing grid.	The output must be 3 phase 420 V AC at 50 Hz.
Type 2	This application is used to supply electricity for consumption on the water treatment works (WTW) and reservoir/PRS sites. Output would be an island installation.	The output can vary from 250/420 V AC at 50 Hz to 12/24 V DC.
Type 3	Installation is an inline turbine installed into valve chambers or at specific locations in bulk pipelines. This application is used to supply energy to control systems, security systems, monitoring systems and telemetry.	The output can vary from 12/24 V DC that can be converted to 250/ 420 V AC at 50 Hz.
Type 4	Low-head installations with the output being an island type installation.	The output can vary from 250/420 V AC at 50 Hz to 12/24 V DC.

2.8.3 Summary of existing conduit hydropower plants in South Africa

There are a few conduit hydropower facilities that have been developed in SA, as summarised in Table 2-8.

Table 2-8: Existing conduit hydropower plants in South Africa

Pilot plants	Owner	Turbine	Installed capacity	Type of installation	Island/grid connected
Pierre van Ryneveld	City of Tshwane	Crossflow	14,9 kW	Type 2	Island
Queenswood	City of Tshwane	Pump-as-turbine	4 kW	Type 2	Island
Zeekoegat	City of Tshwane	Syphon	1 kW*	Type 4	Island
Bloem Water	Brandkop	Crossflow	96 kW	Type 2	Island
Annlin	City of Tshwane	Pump-as-turbine	Three 48 kW turbines	Type 2	Grid connected/ Island
Wemmershoek water treatment plant	City of Cape Town	2 x Francis	700 kW	Type 2	Island
Blackheath water treatment plant	City of Cape Town	1 x Turgo	5 kW	Type 2	Island
Faure water treatment plant	City of Cape Town	1 x Turgo	1,475 k W	Type 2	Island
Steenbras water treatment plant		2 x Turgo	340 kW	Type 2	
eThekwini Municipality	Newlands 2	Pelton	Two 1 kW turbines	Type 2	Island

*In progress to be tested

The photograph in Figure 2-12 was taken in Bloemfontein at the Brandkop reservoirs of Bloem Water. It is a 96 kW Banki or crossflow unit installed at the feed into the bulk reservoir.

Figure 2-12: Turbine installation at Bloem Water's Brandkop reservoir. Crossflow (Banki) – type 2, island installation

Another design makes use of PATs. The potential hydropower generation at the inlets to storage reservoirs was evaluated with a pilot installation that was erected at the Queenswood reservoir in CoT, depicted in Figure 2-13. The results from this pilot installation are presented in a scoping study highlighting the untapped hydropower-generating potential from pressurised conduit (Van Vuuren, 2010).

Figure 2-13: Pump-as-turbine testing installation – type 2, first installation

Shein *et al*. (2013) provided the following definitions of synchronous and asynchronous generators:

> Synchronous generators are standard in electrical power generation and are used in most power plants. Asynchronous generators are more commonly known as induction generators. Both of these generators are available in three-phase or single-phase systems. And, both machines may have the same stator design but different rotor design .

A combination of synchronous and asynchronous turbines was installed at the Annlin reservoir site, as depicted in Figure 2-14. This reservoir, that is situated on the northern slopes of the Magaliesberg in Pretoria, supplies water to the northern suburbs of CoT. These turbines were installed at the inlet pipe system that feeds into the Annlin reservoir.

Figure 2-14: Annlin installation – type 1, grid-connected, pumps-as-turbines

Zeekoegat is a WWTW and a hydropower turbine was installed on the outlet of the plant as a syphon over the dam wall. This installation is depicted in Figure 2-15.

Figure 2-15: Zeekoegat installation – type 2, island syphon

Two 1 kW Pelton hydropower turbines (Figure 2-16) were installed in eThekwini Municipality at the Newlands reservoir. The power that is generated is used on-site and the installation is a containerised installation.

Figure 2-16: eThekwini Municipality Newlands installation, two Pelton turbines – type 2, island installations

2.8.4 Conduit hydropower potential in the City of Tshwane's water distribution system

The geographical position of CoT (Figure 2-17), which is situated in the Gauteng Province (the economic hub of SA), allows for ample opportunity for the development of retrofit conduit hydropower – especially in the rural and remote parts. The provisions of the *Municipal Systems Act, 2000* (*Act 32 of 2000*) impose a duty on the municipal council, within the municipality's financial and administrative capacity to, inter alia, strive to ensure that municipal services are provided to the local community in a financially and environmentally sustainable manner. It also encourages and promotes the development of renewable energy in SA.

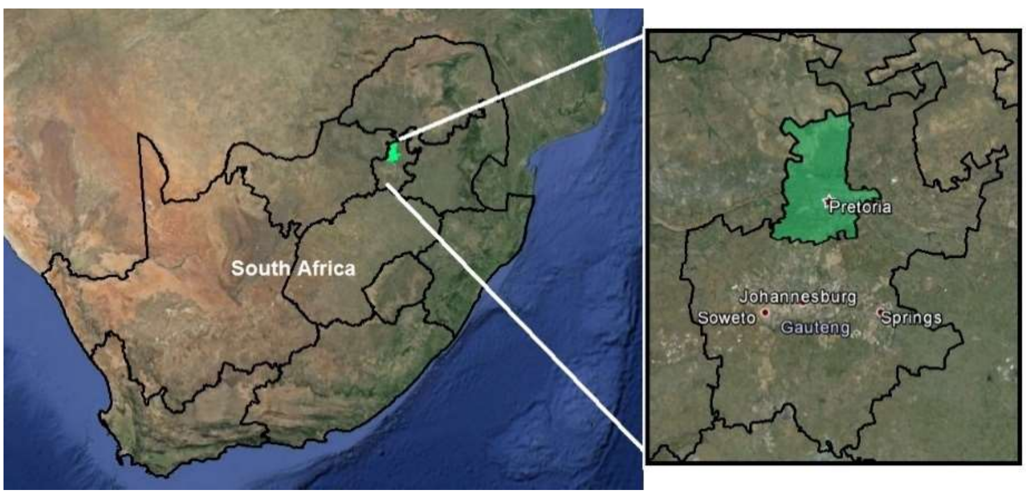


Figure 2-17: City of Tshwane (Pretoria), Gauteng Province, South Africa

In CoT, water is distributed through a large water system that includes 165 reservoirs, 39 water towers, 10 863 km of pipes, and more than 280 PRSs. The bulk of the water is supplied by Rand Water (a water utility) extracting the water from the Vaal River system and pumping it to the Johannesburg area into bulk storage reservoirs. From there it enters the CoT municipal area via three bulk supply pipelines. The full supply levels (FSLs) and elevation differences of the respective reservoirs are given in Table 2-9.

Table 2-9: City of Tshwane bulk water supply (elevation differences between

source and end reservoirs)

Rand Water Reservoir			CoT FSL (m)	ΔH (elevation difference) (m)
Supply line	**Name**	**FSL**		
1	Klipfontein	1693,8	1160,0	533,8
2	Esselenpark	1616,4	1419,0	197,4
3	Vlakfontein	1662,7	1404,7	258,0

Abbreviations: CoT: City of Tshwane; FSL: full supply level

As the water enters the CoT area, the excess pressure needs to be dissipated to the TWLs of the storage facilities, or where it is directly linked into the distribution system at a specific water pressure to maintain a certain level of service. This is usually done by means of PRSs equipped with PRVs.

Most of these water supply/distribution systems can, in addition, be equipped with all types of generators such as turbines or PATs or other newly designed units with which the energy can be dissipated. The primary function will always be the supply of water to the end-user and the power generation will be in a supplementing role. The installation of inline hydroelectric turbines in pressurised pipe systems will also reduce the required maintenance on PRVs. The capacity of hydroelectric installations can vary to suit the application for the amount of power to be generated or needed.

The University of Pretoria, supported by the Water Research Commission, engaged in various research projects investigating the potential of extracting the excess hydropower energy from the water infrastructure in CoT. An initial scoping study was performed by Van Vuuren (2010) to obtain a first-order estimate of conduit hydropower potential in the CoT water distribution network. The scoping study identified the ten larger reservoir sites in CoT, (Table 2-10). A very conservative approach was followed to calculate the potential annual hydropower generation from these supply pipelines that end at the reservoirs. Only a fraction (50 %) of the available static head was assumed to be available to generate power and a load factor of 25 % was assumed (i.e. power can be generated for 6 hours per day).

Table 2-10: Hydropower capacity at different reservoirs in CoT (Loots *et al.*, 2014)

Reservoirs	TWL (amsl)	Capacity (kℓ)	Pressure (m)	Flow (ℓ/s)	Annual potential power (kWh)
Garsfontein	1 508,4	60 000	165	1 850	3 278 980
Wonderboom	1 351,8	22 750	256	470	1 292 471
Heights LL	1 469,6	55 050	154	510	843 673
Heights HL	1 506,9	92 000	204	340	745 062
Soshanguve DD	1 249,5	40 000	168	400	721 859
Waverley HL	1 383,2	4 550	141	505	721 483
Waverley LL	1 332,9	4 550	166	505	721 483
Akasia	1 413,8	15 000	193	340	693 930
Clifton	1 506,4	27 866	196	315	663 208
Magalies	1 438,0	51 700	166	350	624 107
Montana	1 387,6	28 000	82	463	407 829
Total annual potential power (kWh)					**10 714 085**

Abbreviation: TWL: top water level

Subsequently, further studies by UP (2015), investigated the top five sites and refined the generation potential at these sites, as listed in Table 2-11.

Table 2-11: Hydropower generation potential at reservoirs in CoT (UP, 2015)

Reservoir site	Estimated average capacity (kW)	Estimated annual generation potential (kWh/a)*	Turbine type
Garsfontein	740	5 185 900	Francis
Klapperkop #2	372	2 607 000	Francis
Klapperkop #3	267	1 871 100	Francis
Heights LL	265	1 857 100	Francis, Pelton or Turgo
Heights HL	455	3 188 600	Francis
Akasia	275	1 927 200	Francis, Pelton or Turgo
Total	**2374**	**16 636 900**	

* Utilising a conservative load factor of 0,8

From the table above, it is clear that potential micro and mini conduit hydropower sites exist in CoT. These sites would, however, provide more electricity than what would be required on the site, as a potential source of energy for telemetry systems, monitoring and controlling water flow and pressure, by making use of a local retrofit power unit. These sites would rather be grid-connected to make full use of the potential.

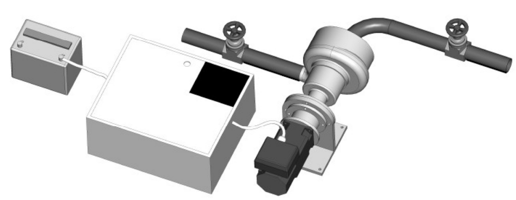
The retrofit hydroelectric potential is the perfect solution to solve the power needed to have communication with reservoirs in isolated areas for various operational, maintenance, and infrastructure management reasons. This includes telemetry, pressure management, flow control, and 24-hour monitoring/security systems. In other areas, it can be fed into the electricity grid.

2.8.5 Pico hydropower turbines

There are a number of different turbines that are used for hydropower generation, as detailed earlier. There have been some new turbine developments and some of the more common turbines have also been modified or scaled down to enable pico hydropower generation. Some commercially available pico conduit hydropower generation turbines are listed in Table 2-12.

Table 2-12: Commercially available pico turbines for conduit hydropower installations

Description	Picture
Cla-val E-Power MODEL X143HP Provides power by using the pressure drop across a PRV to run a generator. Generates up to 250 watts of power to operate everything in the valve chamber including: - electronic control valves - sump pumps, - lighting - communications equipment Source: www.cla-val.com/electronic-power-generators	

Description	Picture
Soar Hydropower's micro turbine series are designed for power generation in new or existing water networks and can be installed on any 50 mm or larger pipeline. Micro 300 Series, 300 W maximum power output, 12–24 V DC/120 V AC configurations. Soar's inline turbines are a series of compact hydropower generation units, designed specifically for conduit power recovery, available for standard pipe sizes from 100–600 mm. Source: www.soarhydro.com	
Leviathan benkatina The technology behind the Benkatina in-pipe turbine is multifactorial. Unique combinations of blades, nozzle and blade ratios, air compression, sensors, rpms, controls, and more that make the turbine adapt to this unique environment of limited space and variable flows. 5–10 kW. Source: www.benkatina.com	
Toshiba The Micro Hydro series comprises five different standard unit models, depending on the combination of flows and net. 1–200 kW modules of axial-flow propeller type. Source: www.toshiba-energy.com/en/renewable-energy/product/	
IREM ECOPAT 500 with a centrifugal PAT and G503 generator, permanent magnet generator, with 24 V DC output and maximum output of 500 W at 3000 rpm. It also has a R-500 electronic regulator. Source: www.irem.it	

Description	Picture
Hydrocoil Over 1,5 kW from a small, light, injection-moulded unit. Hydropower in a helical, in-line turbine with venturi-enhanced turbine technology Source: www.hydrocoilpower.com	
Voith Fuji Hydro, Kawasaki The micro-tubular turbine was designed for installation in water supply lines and similar applications. It is an axial (tubular) turbine with a diameter of 300–750 mm.	
Lucid Energy LucidPipe utilises a unique, lift-based, vertical axis spherical turbine that fits inside of large diameter, 600–2400 mm, water pipes. Water flows through the hydrodynamic turbine, generating power as the turbine spins. Due to the lift-based design, the system generates power (15–90 kW) across a very wide range of flow conditions, volumes, and velocities. Source: www.lucid-energy.com	

2.8.6 The need for small-scale hydroelectric units

This literature review provided an overview of the worldwide development and implementation of small-scale hydroelectric power plants. The design detail of the units depends on the water pressure and flow that are available to generate electricity. A wide range of turbines was developed during the last two decades, based on principles used by ancient communities to pump water or to do work, for example, the grinding of wheat to produce flour.

The pico hydropower units (PHUs) developed and tested in this study were all located at the inlets of reservoirs to utilise the excess energy available in the pipeline before the water enters the reservoir. The PHUs were not designed to utilise the full energy potential on-site, but rather to only generate enough electricity to satisfy the energy demand of the site. Specific energy needs typically include:

- telemetry;
- security systems;
- alarm systems;
- pressure and control management;
- electric fencing;
- battery charging;
- lighting
- telecommunications; and
- remote water quality testing laboratories.

The need to develop and build pico-sized power plants were identified in the literature review. This led to a concept design, detail design, and eventually the building and testing of different PHU.

3 DEVELOPMENT PROCESS OF THE PICO TURBINE

3.1 Typical methodology in developing a conduit hydropower plant

The methodology given in the *Conduit Hydropower Development Guide* for small conduit hydropower plants (Van Vuuren *et al*., 2014a), suggested that the following components form part of the development process:

- Results obtained with the DSS software are used to conduct the pre-feasibility study and various first-order analyses – phase 1.
- Regulations and permission to perform the study, are obtained.
- Phase 2 of the DSS is used to identify the specialist design input required.
- Details of the installations are designed.
- Operation and maintenance required, are determined.

The DSS (phase1) is presented in Figure 3-1 and Figure 3-2 in the form of a flow diagram. This diagram indicates the decision-making and guidance route that was applied in this study.

Figure 3-1 indicates the route that would be followed without the inclusion of a PRV in the system. This system was used to illustrate that a pressurised conduit turbine, used in this study, could be installed into the Pierre van Ryneveld PRS. However, for this study, a turbine and a PRV were installed in the system. This combination of different energy dissipating mechanisms could operate as a combination in a pipeline, reducing the pressure in the system.

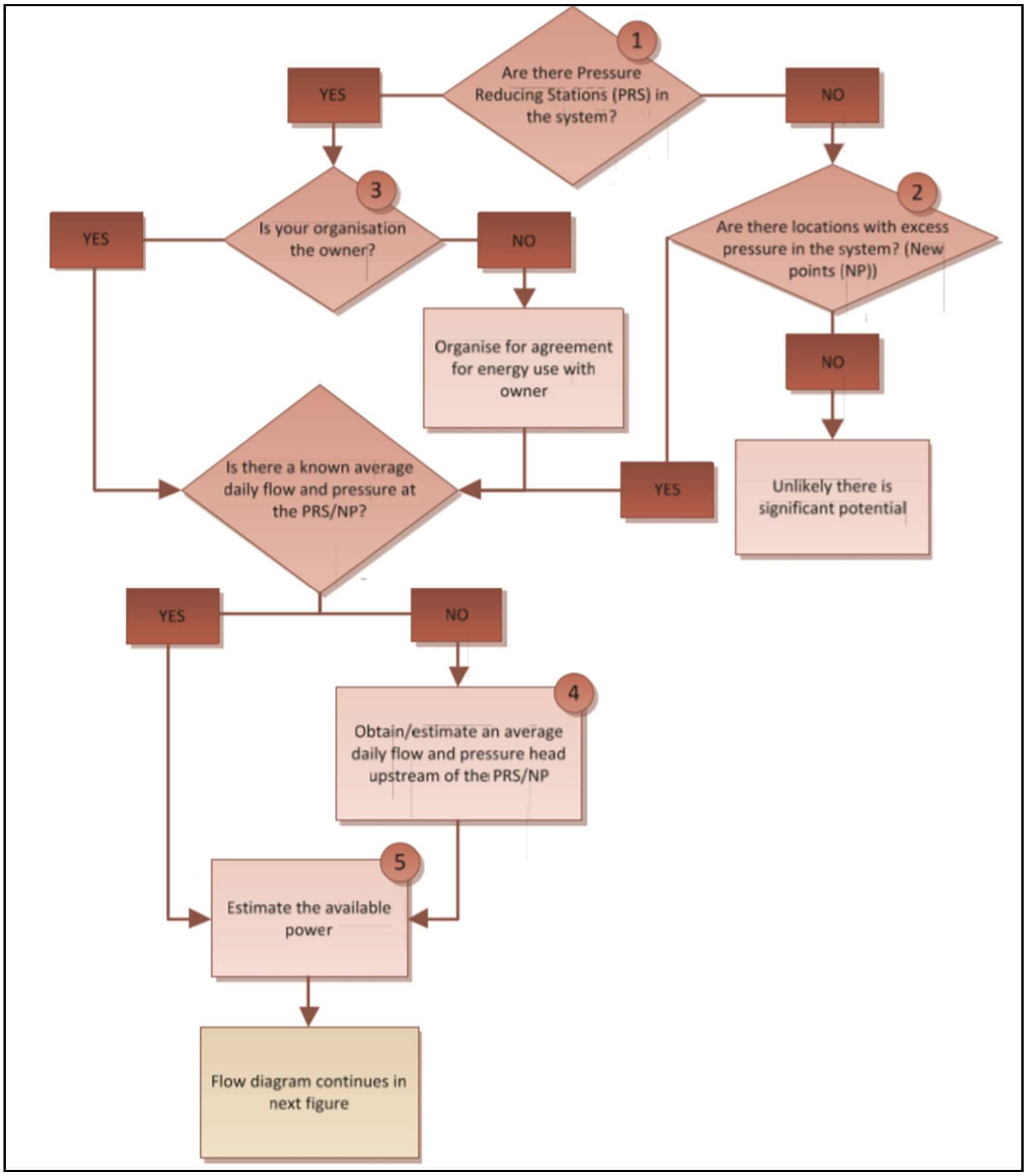


Figure 3-1: Decision support system (Van Vuuren *et al.*, 2014a)

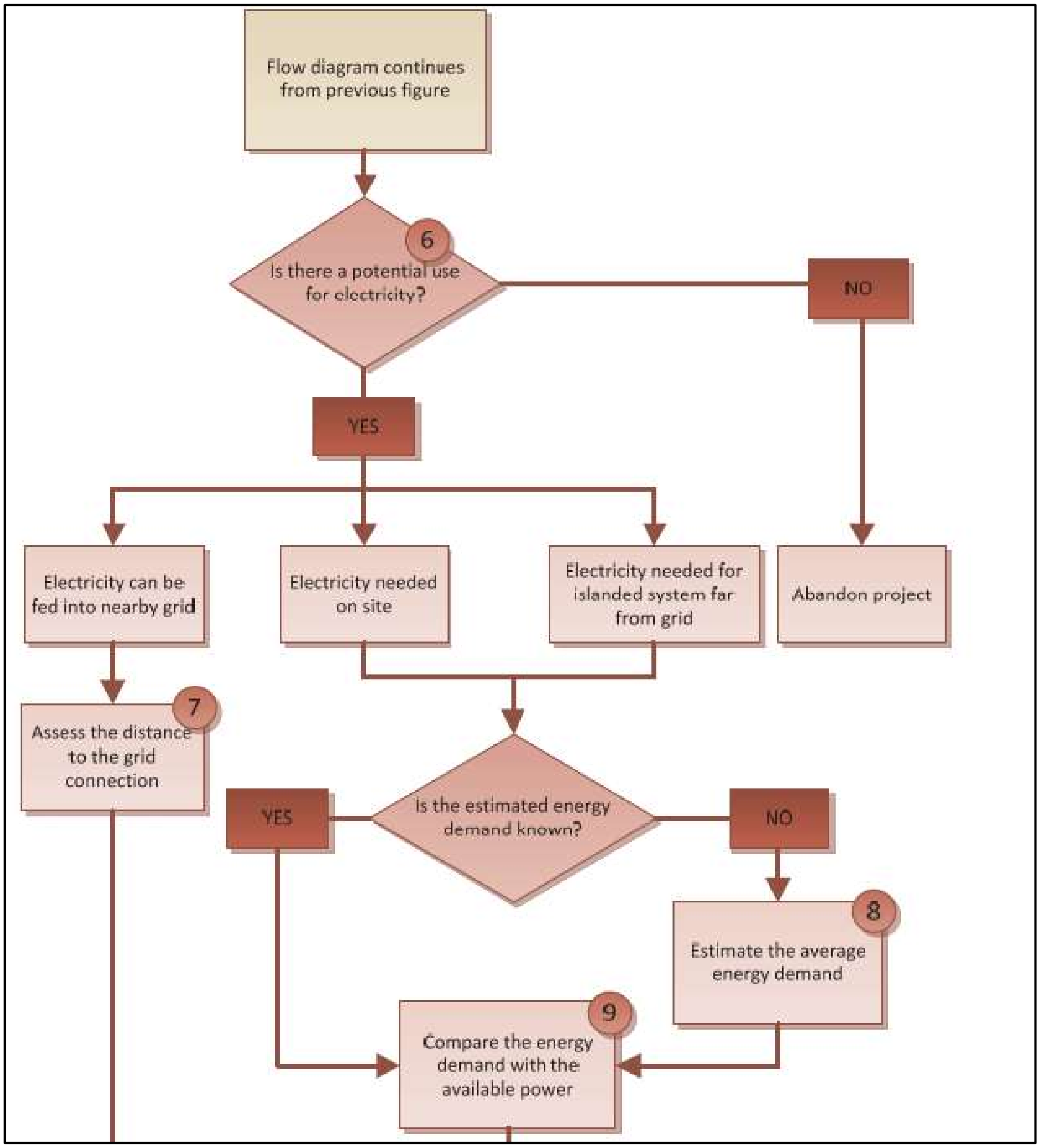


Figure 3-2: Decision support system – continued (Van Vuuren *et al.*, 2014a)

The DSS could be applied up to the point where the available energy becomes comparable with the energy demand. The feasibility of the installation is not always measured by the monetary value of the installation or the payback period. The subsequent or indirect benefit to generate electricity at the point where it is needed is also a criterion used to evaluate the availability of the turbine.

If the payback period is to be calculated, the savings of this type of installation should be compared to the alternatives to provide electricity to the facility via conventional national or municipal electricity transmission lines. The sites where the energy is needed, are normally remote or exposed to vandalism. As a result, the high risk associated with vandalism of these sites became a crucial component in the calculation and evaluation.

Methods to convert available water pressure energy into energy needed at a specific location has secondary monetary benefits that can be debated and possibly quantified. For example, the travel and personnel costs from a maintenance facility to these remote sites can be incorporated into the calculations.

Although the implementation of new developments and designs of small-scale retrofitted conduit hydroelectric installations are not contributing much to the total electricity demand, its functionality and application at a specific location can have a large impact in creating other benefits to operations and a variety of support systems and mechanisms. The conventional efficiency of turbines are compared below in Figure 3-3, but when comparing the efficiency of new designs and developments in very small turbines, the functionality of the available electricity is of much more importance than to have a turbine with high efficiency. Thus, the criteria to evaluate this new approach to turbine design is a combination of efficiency and the benefit to have electricity available, rather than to design highly efficient turbines.

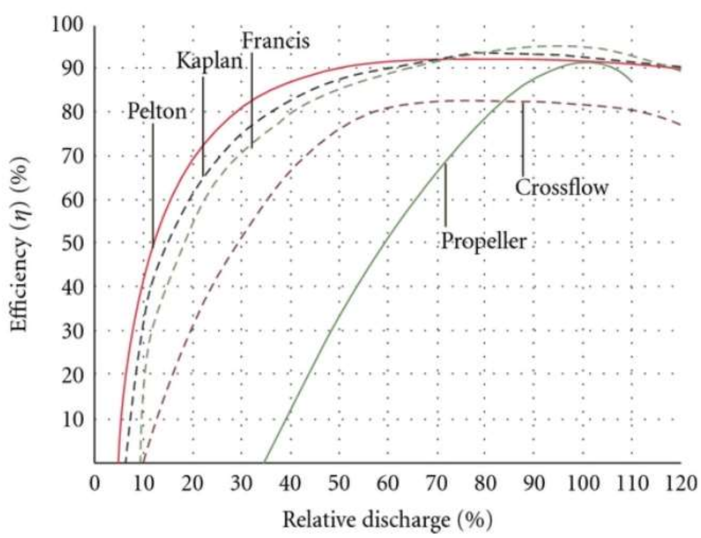
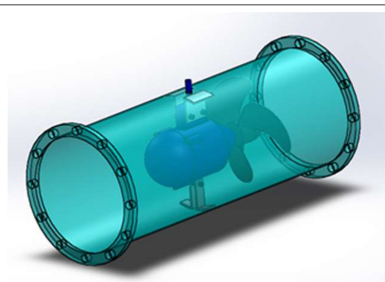


Figure 3-3: Conventional efficiency of hydro turbines (Chiyembekezo *et al*., 2012)

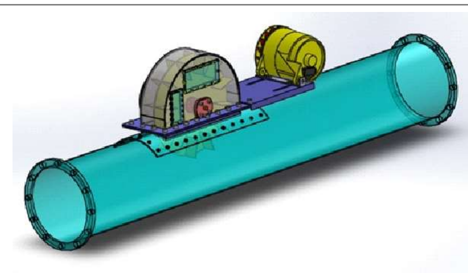
3.2 Pico turbine developments

The aim of this research was to develop a pico hydro unit to provide a specific amount of electricity to meet the demand of the site. Four inline prototype turbine designs were developed, built, and tested. The four prototypes are discussed below and one prototype was tested and evaluated in more detail.

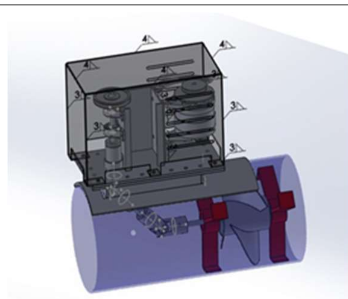
One of the design criteria of the prototype hydropower turbines is that it must be easy to retrofit the installation into the existing water distribution or supply systems. This can be achieved by means of a turbine unit that can be installed into a spool piece. Alternatively, an easily removable unit mounted onto a baseplate on top of the pipe system, could be considered. The baseplate was also designed in such a way that it can accommodate different prototypes. That means that the prototypes can easily, with minimum down time, be installed and removed from the turbine baseplate when needed. This principle of utilising a spool piece and a bolt-on base made it easy to retrofit the units in an existing PRS. A number of different pico conduit turbines were developed and tested, which are summarised in Figure 3-4, followed by a description of the units in the following paragraphs.



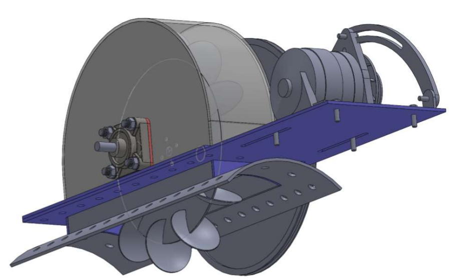
(a) Prototype 1: AmpAir turbine



(c) Prototype 3: IPW1



(b) Prototype 2: Modified Kaplan turbine



(d) Prototype 4: IPW2

Figure 3-4: Different pico conduit turbines developed and tested

3.3 Pierre van Ryneveld reservoir system test site

3.3.1 General arrangements

The Pierre van Ryneveld reservoir system is situated in the south-eastern part of CoT and was used for the testing of the retrofitted power units. The layout given in Figure 3-5 illustrates all the reservoir distribution systems in CoT. The different colour polygons each represents a different system. In this study, the Pierre van Ryneveld system was used for the experimental installations and the average annual daily demand (AADD) was obtained from the management information system (MIS) and used for calculations.

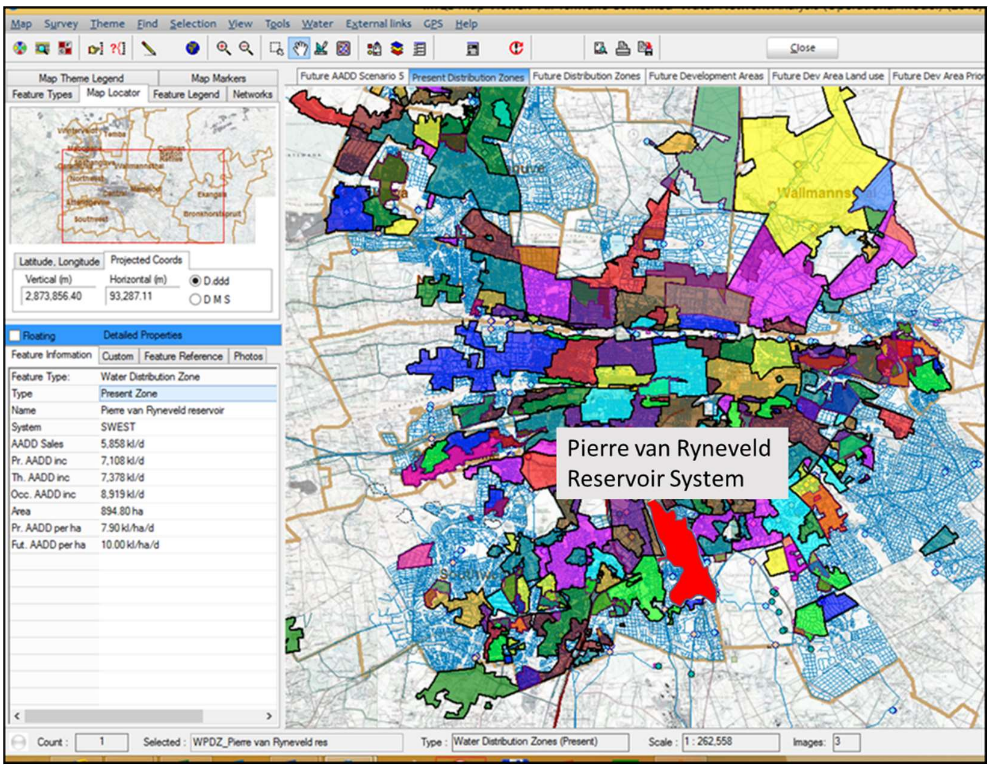


Figure 3-5: Reservoir distribution zones in the City of Tshwane (IMQS, 2015)

The Infrastructure Management Query System (IMQS) software (v.6, IMQS, Johannesburg, SA) was used for general information and layout of the reservoir and supply lines. The AADD of the reservoir supply was given as 7,40 Ml/d (Figure 3-6). From the data that were collected and logged, the average flow varied between 6,30 and 6,84 Ml/d.

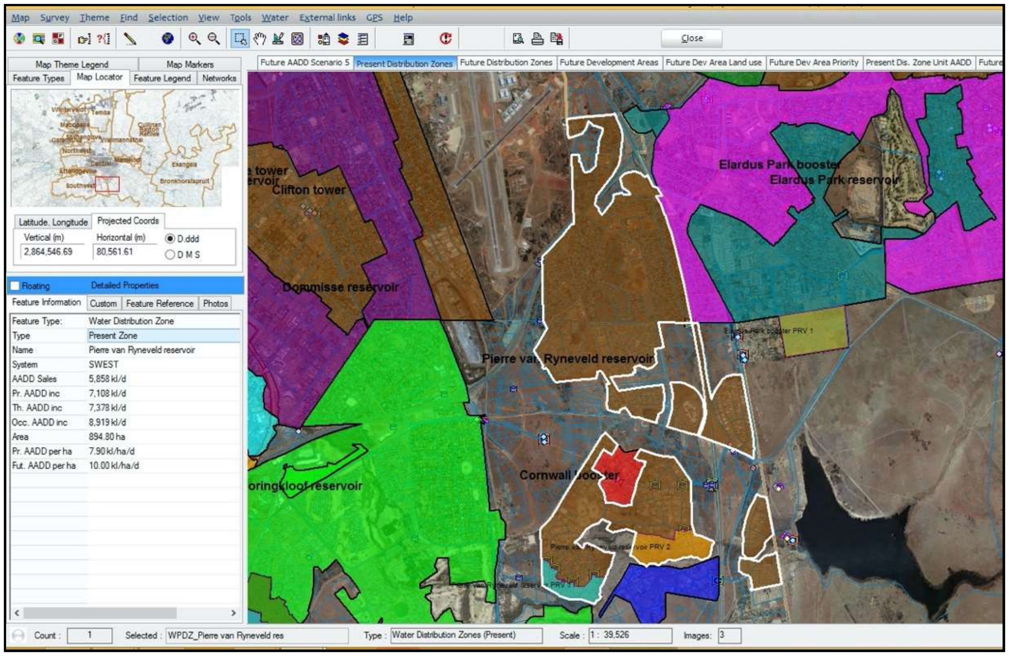


Figure 3-6: IMQS illustration of the distribution zone and the average annual daily demand (IMQS, 2015)

The graph in Figure 3-7 represents the AADD and the average monthly flow for the time that prototype 4 (IPW2) was tested. These measured flows were lower than the AADD, due to the fact that the tests were conducted during the winter season.

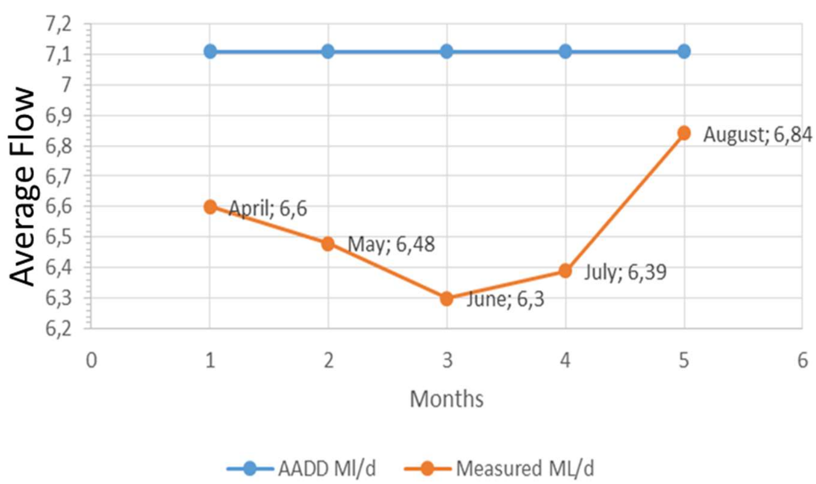


Figure 3-7: Flow data collected for prototype 4

3.3.2 System layout in the pressure-reducing station

The layout of the PRSs is standardised throughout CoT as far as possible, for both practical and maintenance reasons. This standardisation approach was also followed at the chambers at Pierre van Ryneveld. The PRVs are housed in reinforced concrete chambers with standard dimensions. It consists of the pipework below ground level and a top structure at ground level. The aerial view of the layout of the existing Pierre van Ryneveld PRV chamber is given in Figure 3-8.

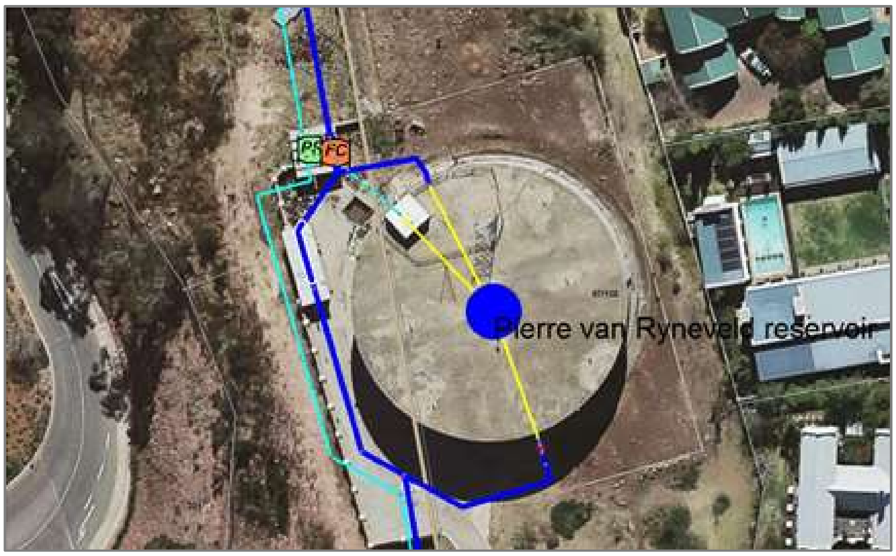


Figure 3-8: Aerial photograph of Pierre van Ryneveld reservoir layout

This chamber installation dissipates excess energy from the Rand Water bulk supply system to TWL pressure. This implies that the PRV installation will terminate the flow into the Pierre van Ryneveld reservoirs once the levels reach TWL in the two reservoirs. These two reservoirs supply water to the southern parts of the Pierre van Ryneveld suburb.

The water supply into the chamber is from Rand Water that currently supplies water at a pressure of about 60 m at the upstream side of the PRV installation. The reservoir TWL is about 9 m above the PRV installation. This difference between the supply and TWL energy lines is about 50 m of pressure to be dissipated, which is ultimately available for power generation. The amount of electricity that can be generated is a combination of the pressure difference, the flow rate, and the efficiency of the turbine.

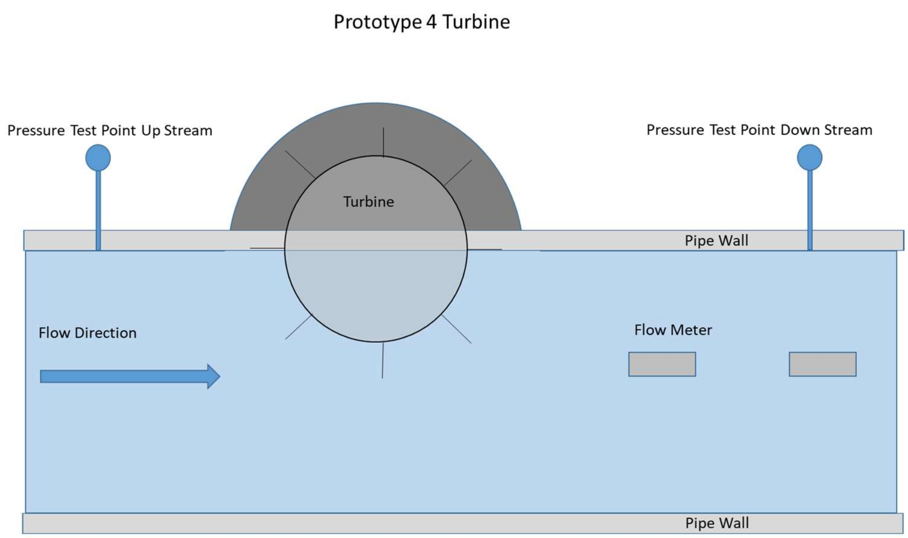


Figure 3-9: Illustrated side view of the prototype 4 installation (Davel, 2015)

Although approximately 50 m is available, the IPW2 turbine will not be able to utilise all this available energy. The installation of the IPW2 is on the downstream side of the PRV. During the test, the amount of generated energy was measured against the pressure difference before and after the turbine, as illustrated in Figure 3-9. Equation 2.4 was used to calculate the turbine efficiency based on the available energy due to the pressure difference the turbine. The generator efficiency will be combined with the turbine's efficiency and referred to as the IPW2 turbine efficiency.

The layout and position of the components in the bypass line testing section is shown in Figure 3-10. The first and the last component of this typical installation is an isolation valve to isolate the entire installation. The first downstream component is the PRV, followed by the water meter. The hydropower turbine is installed after the water meter. Testing points were added upstream and downstream of the isolation valves, as well as before and after the installed components to determine the pressure head loss through them.

TYPICAL STEEL PIPE FITTINGS AND ITEM LIST			
ITEM NR.	DESCRIPTION	NO. OFF	DIMENSIONS
①	500ø x 300ø STEEL REDUCER. BOTH ENDS FLANGED SABS 1123 – 2500/3	4	
②	300ø FLANGED BUTTERFLY VALVE WITH SPINDLE (OR SIMILAR APPROVED) BOTH ENDS FLANGED TO SABS 1123 – 2500/3.	4	
③	300ø VAG STRAINER, PN25, STAINLESS STEEL SCREEN & BASKET. ENDS FLANGED TO SABS 1123 – 2500/3. (OR SIMILAR APPROVED)	2	
④	300ø CLAY– PRESSURE REDUCING VALVE COMPLETE, OR SIMILAR APPROVED. PN25. ENDS FLANGED TO SABS 1123 – 2500/3.	2	
⑤	300ø MEINECKE TURBINE COSMOS WPD WATER METER, PN16. BOTH ENDS FLANGED TO SABS 1123 – 1600/3. (OR SIMILAR APPROVED)	2	
⑤	300ø MEINECKE TURBINE COSMOS WPD WATER METER, PN16. BOTH ENDS FLANGED TO SABS 1123 – 1600/3. (OR SIMILAR APPROVED)	2	
⑥	300ø STEEL STRAIGHT. ONE END FLANGED TO SABS 1123 – 2500/3. ONE END FLANGED TO SABS 1123 – 1600/3.	2	MIN 5D=1500; DETERMINE ON SITE
⑦	500ø STEEL MANIFOLD REDUCE TO 2 X 300ø REDUCERS. ONE END FLANGED TO SABS 1123 – 2500/3. ONE END FLANGED TO SABS 1123 – 1600/3.	2	
⑧	300ø VIKING JOHNSON DISMANTLING JOINT (OR SIMILAR APPROVED), PN16. BOTH ENDS FLANGED TO SABS 1123 – 1600/3.	1	
⑨	300ø X 900mm STEEL STRAIGHT, PN16. BOTH ENDS FLANGED TO SABS 1123 – 1600/3.	2	MIN 3D=800
⑩	300ø VIKING JOHNSON DISMANTLING JOINT (OR SIMILAR APPROVED), PN16. BOTH ENDS FLANGED TO SABS 1123 – 2500/3.	4	

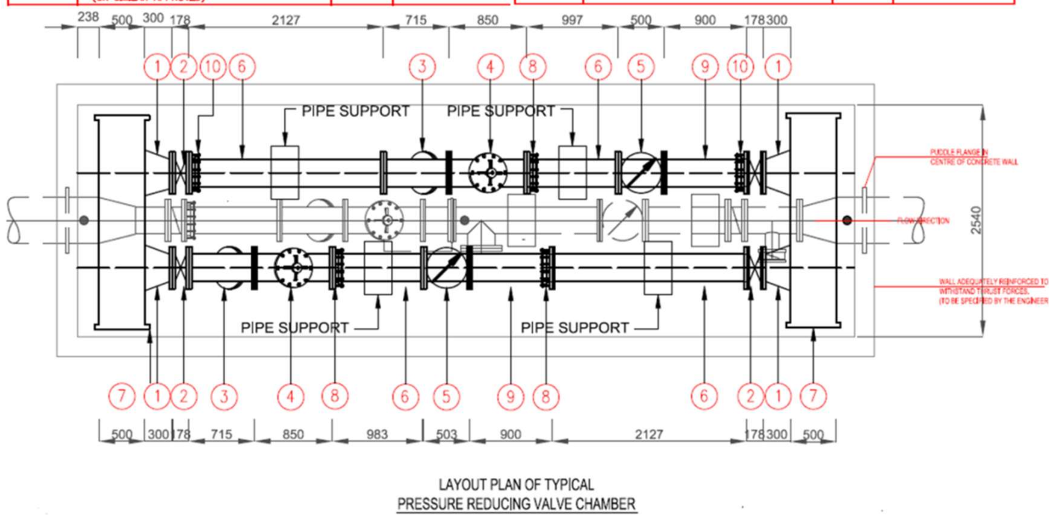


Figure 3-10: Pierre van Ryneveld pressure-reducing valve chamber layout

Figure 3-11 is a photograph illustrating the layout of the PRV chamber at the Pierre van Ryneveld reservoir. There are two 300 mm steel pipelines connected to a manifold. Water enters the manifold and is distributed into the two PRV installations. The layout and the use of two parallel PRV installations made it possible to maintain the primary water supply at all times and secondary, to generate electricity. This way, there will always be one line supplying water to the reservoirs and the power can be generated as a secondary function in the second PRV line. The components illustrated are typical of PRV chamber installation in CoT. This includes butterfly valves, spool pieces, PRVs, Viking Johnson couplings, and water meters.

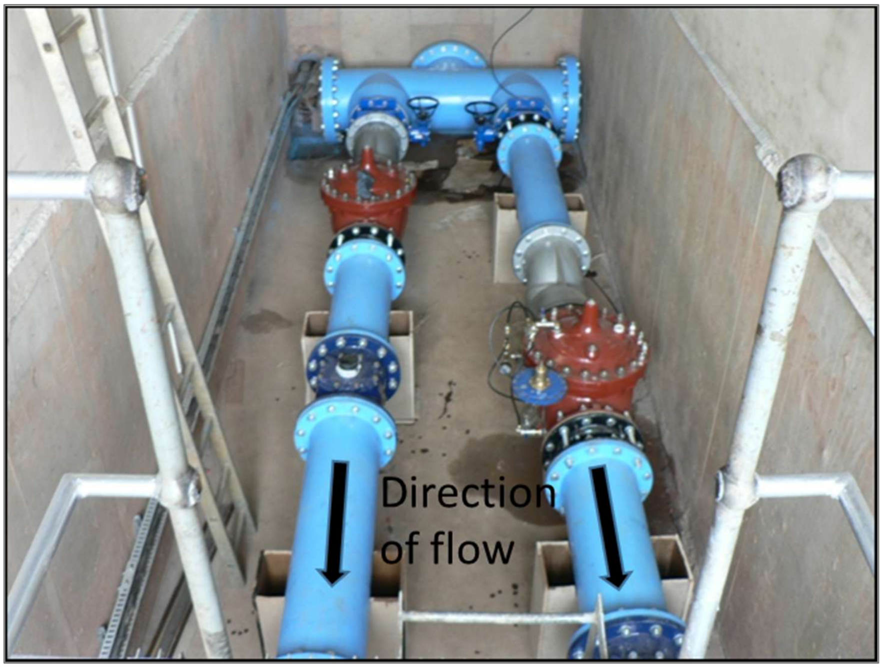


Figure 3-11: Photograph of the Pierre van Ryneveld chamber layout

3.4 Test procedures

The measuring instruments and devices were correctly installed and tested for proper functioning before the turbine was evaluated and data were collected. An important aspect was to always open the downstream valve (valve 2, Figure 3-12) first, to ensure that the hydropower turbine installation was not pressurised to upstream pressure levels (P1 and P10, Figure 3-12), but limited to the maximum pressure of the downstream system, which is TWL (P5 and P6, Figure 3-12). The excessive upstream pressure could damage the hydropower turbine installation and instrumentation.

The testing consisted of two tests: The first was to do a series of open and close sequential tests at certain intervals to determine the characteristics of the specific prototype. A second test was to let the unit run for long periods of time in the scenario of a permanent installation to monitor the sustainability and reliability of the prototype turbines. These tests will reveal the technical and design flaws of the turbine and provided the opportunity to redesign or modify certain aspects of the prototype. Down time in the long-term testing will be indicative in evaluating the reliability of all the components of the prototype.

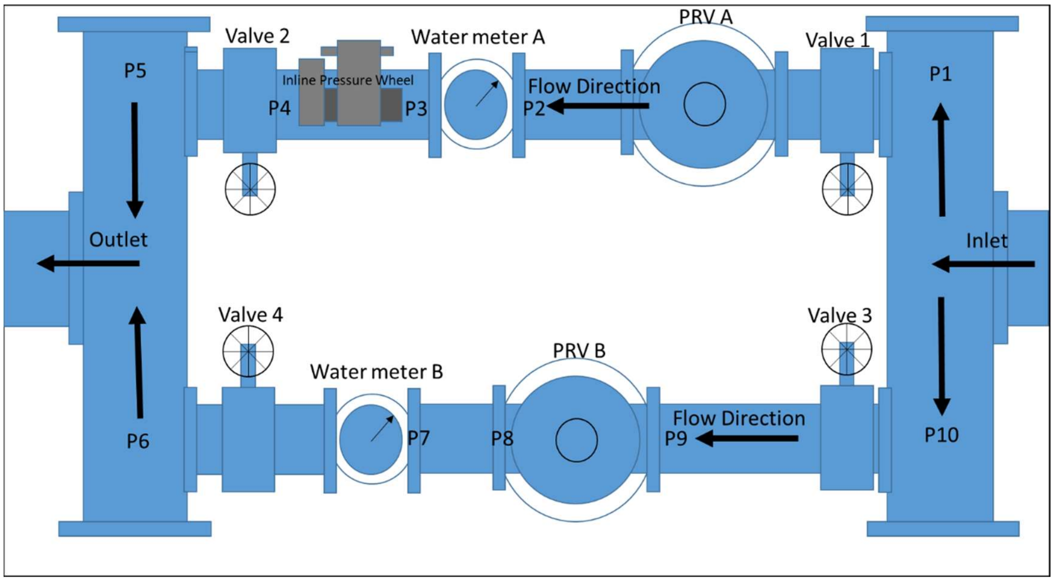


Figure 3-12: Schematic illustration of the pressure measuring points

Downstream valve 2 had to be opened first to ensure that the installation is not unnecessarily pressurised. The turbine is put to work by opening the upstream valve 1 and letting the water feed the reservoir through the turbine installation. The valve was manually opened to control the flow. The flow and velocity were monitored on the instruments and steps in velocity were created in increasing steps of 0,5 m/s in the pipeline. The data logger was set up to take snapshots of monitored values from the measuring points every 5 seconds.

Valve 1 was opened until it reached the full opening position. Then the procedure was repeated for the closing of the valve until the full closed position was reached. The downstream valve (valve 2) was closed after it was confirmed that the upstream valve (valve 1) was completely closed, to prevent damage to the hydropower turbine installation and instrumentation.

A series of tests were conducted to gather enough data to compare the results of all the individual start and stop sequence data gathered. All the data were plotted on different graphs to reach different monitoring objectives.

3.5 Measuring equipment

The installed measuring equipment and sensors varied from pressure transducers, a data logging device, flow meters, voltage meters, and ampere meters, to frequency or rpm meters, installed in the valve chamber (Table 3-1).

Table 3-1: Sensors used in this research study to capture data

Measurement	Measure point	Instrumentation	Output	Channel
Main inflow pressure	P1 and P10	Pressure transducer	4–20 mA	1A
Main outflow pressure	P5 an P6	Pressure transducer	4–20 mA	1B
Upstream prototype pressure	P3	Pressure transducer	4–20 mA	3A
Downstream prototype pressure	P4	Pressure transducer	4–20 mA	3B
Flow		Ultrasonic flow meter	4–20 mA	4B
Alternator amps		Shunt resistor	mV	11A
Battery amps		Shunt resistor	mV	11B
Charge regulator volts		Direct to logger	V	9 V

The instrumentation used during the previous testing procedures was refitted and tested. This instrumental test configuration as depicted in Figure 3-13 and Figure 3-14 (component layout diagrams) was maintained throughout the testing phase of the study.

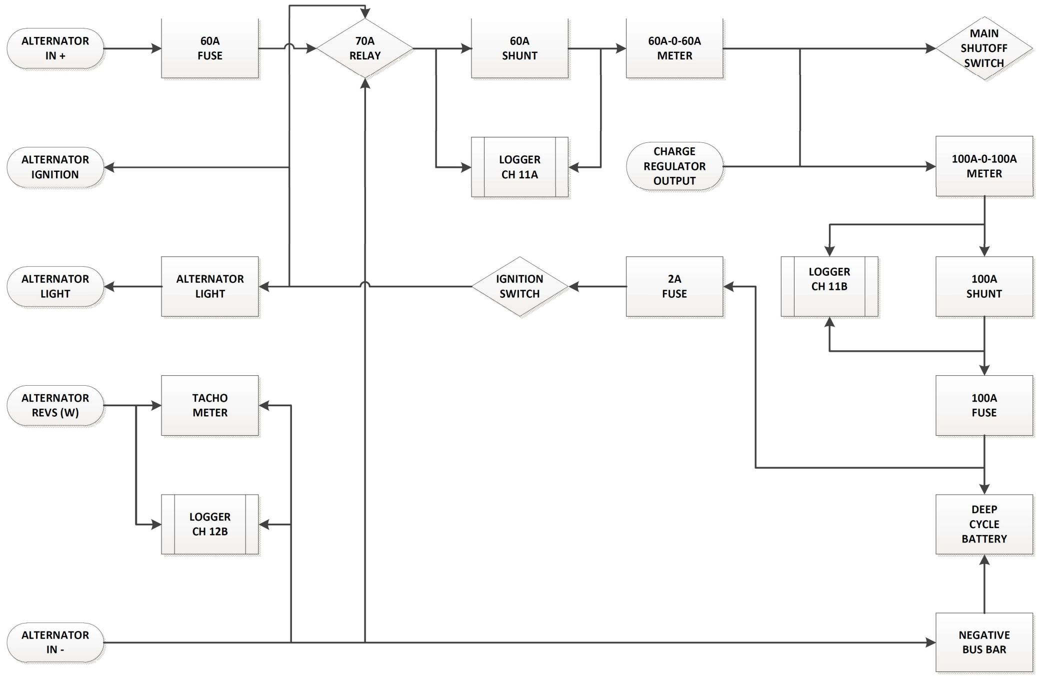


Figure 3-13: Panel design for alternator input, turbine control, monitoring, and logging equipment

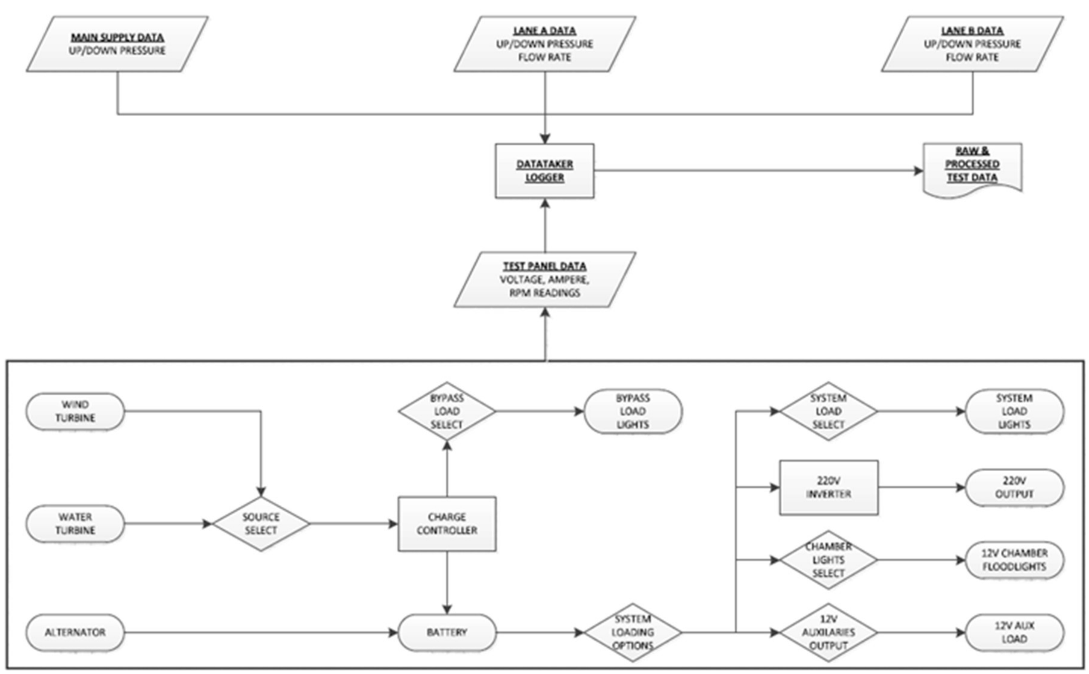


Figure 3-14 : Pierre van Ryneveld test facility low voltage hydropower test panel layout

Figure 3-15 presents a photograph of the complete logging installation test panel at the turbine installation site that was used for the testing of all the turbine prototypes.

Figure 3-15: Instruments and logging equipment

The combination of parameters was recorded and logged with the dataTaker DT85M Series 3 data logger with 16 channels, as shown in Figure 3-16 (Thermo Fisher Scientific, Waltham, MA, USA). The logger was set to record measurements in 5-second intervals. Logged data could be retrieved either after the research was completed or immediately after individual tests were conducted.

Figure 3-16 : Logging device used during turbine testing

3.6 Prototype configurations

3.6.1 Prototype 1: modified AmpAir turbine

The first prototype was the Modified AmpAir turbine. The turbine is a combination of an off-the-shelf permanent magnet generator with the impellor as a unit, which is installed into a spool piece – as shown in Figure 3-17. The AmpAir is typically used in free-surface flow installations, however, in this study, it was installed as a pressurised installation in a pipe. This turbine requires a charge control unit as part of the installation and is used to produce energy to charge a series of batteries. This unit was also tested for functionality, but the evaluation of the test results falls outside of the scope of this research project report.

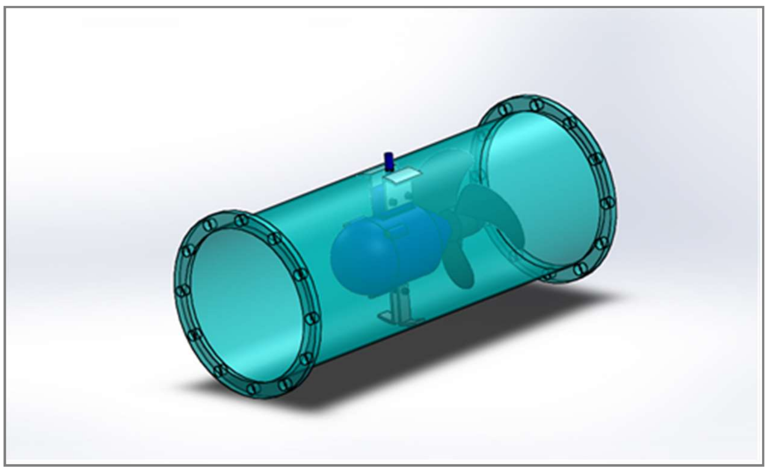


Figure 3-17: Modified AmpAir turbine

Figure 3-18 displays the AmpAir unit before installation into the spool piece. The unit acquired included a water-resistant electric cable installed to the unit to ensure a waterproof installation connecting the turbine with the charge control unit.

Figure 3-18: AmpAir unit before installation

The modified AmpAir turbine that was installed into a spool piece is shown in Figure 3-19. The AmpAir turbine is the simplest form of turbine to build. It is the basic installation of the AmpAir unit into the spool piece demonstrated in Figure 3-19. The installation entails the welding of brackets into the spool piece and bolting the turbine into place.

Figure 3-19: AmpAir unit in a spool piece

The final installation of the modified AmpAir prototype turbine is illustrated in Figure 3-20. This is permanently built into a spool piece and the retrofitted installation entails the removal of an existing spool piece and the replacement of the spool piece with one in which the AmpAir is installed. It is also simplistic and leaves a clean neat installation, which is secure and difficult to vandalise, with only the electric cable protruding from the spool piece.

Figure 3-20: AmpAir installation in Pierre van Ryneveld valve chamber (prototype 1)

3.6.2 Prototype 2: modified Kaplan turbine

The second prototype turbine was based on the Kaplan design. An impellor was mounted onto a shaft inside a spool piece and the rotational energy was transferred to the outside with a shaft, by making use of constant velocity joints, also referred to as CV joints. Finally, a pulley was mounted on the outside end of the shaft. These shafts were supported by a set of mounted bearings on the outside of the pipe. The pulley then drove a mounted alternator with a v-belt. The design can be seen in Figure 3-21. A view from the bottom of the turbine, drawn to better illustrate the CV joints and shaft configuration connecting the impellor and pulley shaft, is shown in Figure 3-21(a). Figure 3-21(b) illustrates the impellor inside the spool piece, which indicates the simplicity of the design.

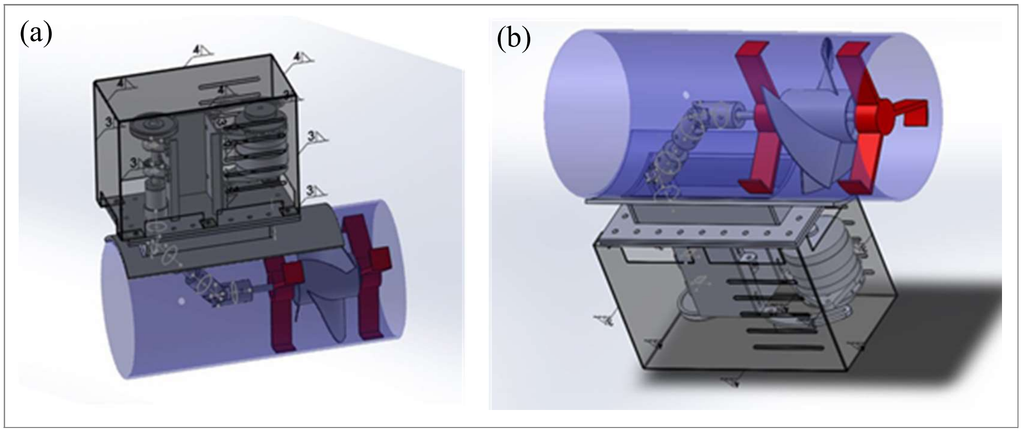


Figure 3-21: Modified Kaplan turbine prototype unit;
(a) alternator configuration and (b) runner configuration

The completed prototype, which was built into the spool piece, is shown in Figure 3-22. It also shows that the competed installation was compact and relatively small.

Figure 3-22: Modified Kaplan prototype turbine
(prototype 2) – interior view

The completed and assembled unit was neatly covered with a metal box with ventilation grooves to ensure sufficient ventilation for the alternator (Figure 3-23). The electric wiring used was elementary automotive wiring and the electric charging control system that was used, was part of the internal components of the alternator.

Figure 3-23: Modified Kaplan prototype turbine (prototype 2); (a) exterior view; (b) exterior side view with cover

3.6.3 Prototype 3: inline pressure wheel 1 turbine

The following prototype that was tested was a modified Pelton wheel with flat impellor blades mounted on the runner of the turbine. The IPW1 is depicted in Figure 3-24.

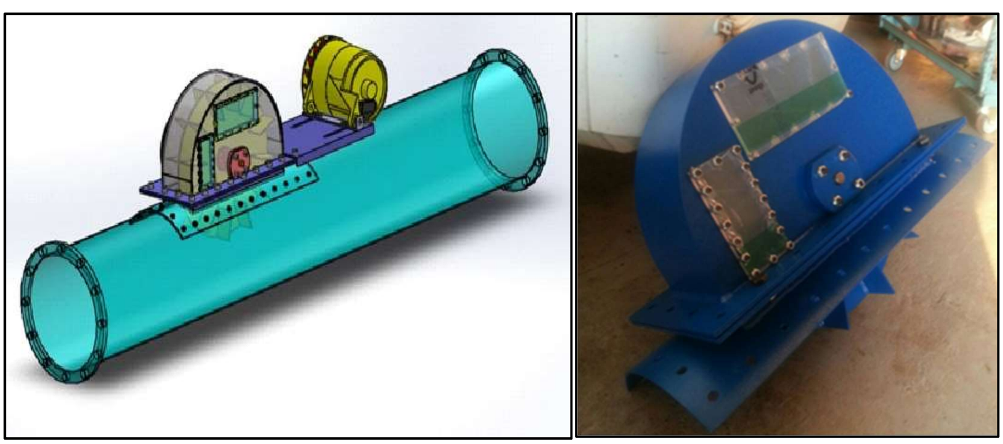


Figure 3-24: Inline pressure wheel 1 (IPW1, prototype 3)

3.6.4 Prototype 4: inline pressure wheel 2 turbine

The runner of the IPW1 was modified in the IPW2 by replacing the flat blades on the runner with scoop-shaped blades. This modification can be seen in Figure 3-25.

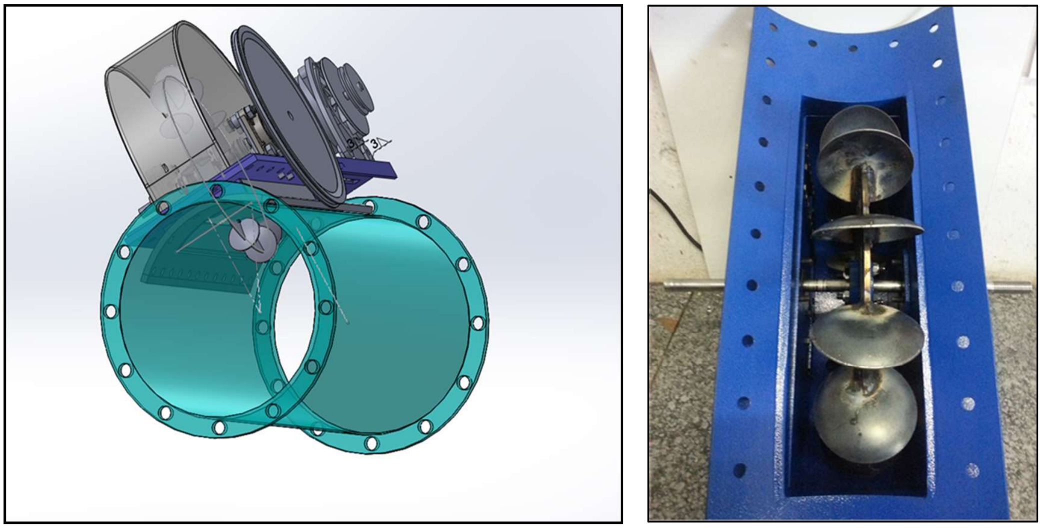


Figure 3-25: Inline pressure wheel 2 (IPW2, prototype 4)

The advantages and disadvantages of the four pico conduit turbines that were tested in this study are shown in Table 3-2.

After evaluation of the results that were obtained thus far, it was decided to perform the additional testing with the IPW2 due to:

- the simplicity of the design;
- easy retrofit installation; and

the bucket shape of the impellor blades – it is postulated that it would behave better in the liquid and the efficiency would be better than that of the IPW1.

Table 3-2: Advantages and disadvantages of the tested pico conduit turbines

Turbine	Advantages	Disadvantages
Prototype 1 AmpAir Turbine	Off-the-shelf product. Easy to install in a spool piece. Turbine is inside the spool piece.	Needs a voltage regulator. The turbine can over speed. The unit is filled with oil for pressure stabilisation.
Prototype 2 Modified Kaplan Turbine	Turbine is inside spool piece. Impellor is an off-the-shelf product. Uses an off-the-shelf alternator.	Bearings of the impellor shaft runs inside water. Bearing design and selection of materials are difficult. Angle of universal joints are problematic.
Prototype 3 IPW1	Simplistic design. Turbine is inside spool piece. Impellor is an off-the-shelf product. Uses an off-the-shelf alternator. Alternator is outside the spool piece and easy to access. Easy to install on existing water pipes.	Mechanical seals are difficult to design and build.
Prototype 4 IPW2	Simplistic design. Turbine is inside spool piece. Impellor is an off-the-shelf product. Use an off-the-shelf alternator. Alternator is outside the spool piece and easy to access. Easy to install on existing water pipes.	Mechanical seals are difficult to design and build.

The basic design principles applied in the design of the IPW2 (prototype 4), will be investigated and discussed in Chapter 4.

4 DESIGN PRINCIPLE OF THE INLINE PRESSURE WHEEL PROTOTYPE 4 (IPW2) HYDROPOWER TURBINE

4.1 The functioning concept of pressure wheel

The design principle and the workings of this turbine were based on an analogy with the sciences behind the mechanism of an oar of a rowing boat. Although relatively little is known about the exact mechanisms that explain the motion of rowing boats, boats move because momentum is transferred to the water by the rowers and their oars, causing the boat to move forward.

The basic principle for the water wheel to turn, is the transfer of the momentum of the moving water to the oar-shaped water wheel buckets, resulting in the bucket moving with the water, as shown in Figure 4-1. The bucket appears to be locked onto the moving water. The form of the bucked must enable the water to move the buckets with the water and ensure lock-up between the bucket and the water. The surface area of the bucket will determine the force that the water has on the bucket, which will, in turn, determine the torque of the system (Dudhia, 2001).

In the first design, IPW1 (prototype 3), the bucket was a basic straight-blade design and did not concentrate the water pressure to create the maximum force on the bucket and resulted in maximum lock-up between the water and the bucket.

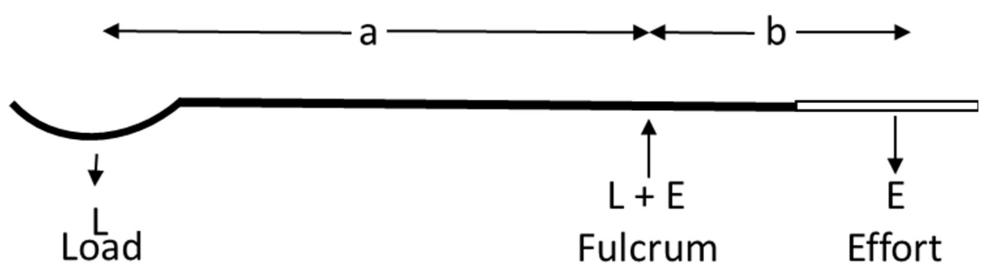


Figure 4-1: Forces on a rowing oar (Dudhia, 2001)

4.1.1 Technical design of water wheels

The unit consists of the alternator and the water motor or water wheel. The matching of the components partially followed a textbook design, and partially a selection from existing off-the-shelf products. The power output needed should be 12 V or 24 V. This output can be sourced directly from the alternator to provide power to equipment. This characteristic is put to use in the IPW1 and IPW2 and is depicted in Figure 3-21, Figure 3-23(a), Figure 3-24 and Figure 3-25. The detail design of the IPW with the automotive alternator as part of the turbine configuration is given in Figure 4-2. An exploded view of the IPW design is depicted in Figure 4-3, illustrating the alternator mountings and adjustment mechanism to adjust the tension on the v-belt. Another option is that the excess generated energy can be stored in a battery system.

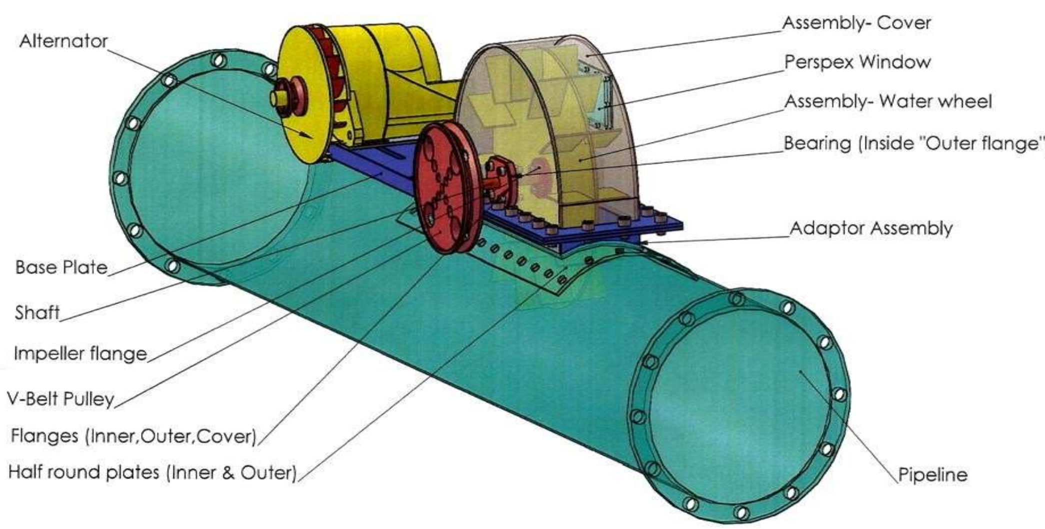


Figure 4-2: Component detail design of IPW1

The components that were selected to build the turbine unit, were based on simplicity and availability. The assumption was made that the alternator to be used will be a 12 V automotive type of alternator. The very basic criteria and specifications were determined through the specifications of the application of the power generated. The 12 V alternator option was selected for the prototype 3 and 4 systems. It should be noted that the most commonly produced alternator on the market is rated in 12 V or 24 V outputs with a range of current ratings. In addition, most of the equipment such as telemetry and alarm systems operate on 12 V or 24 V.

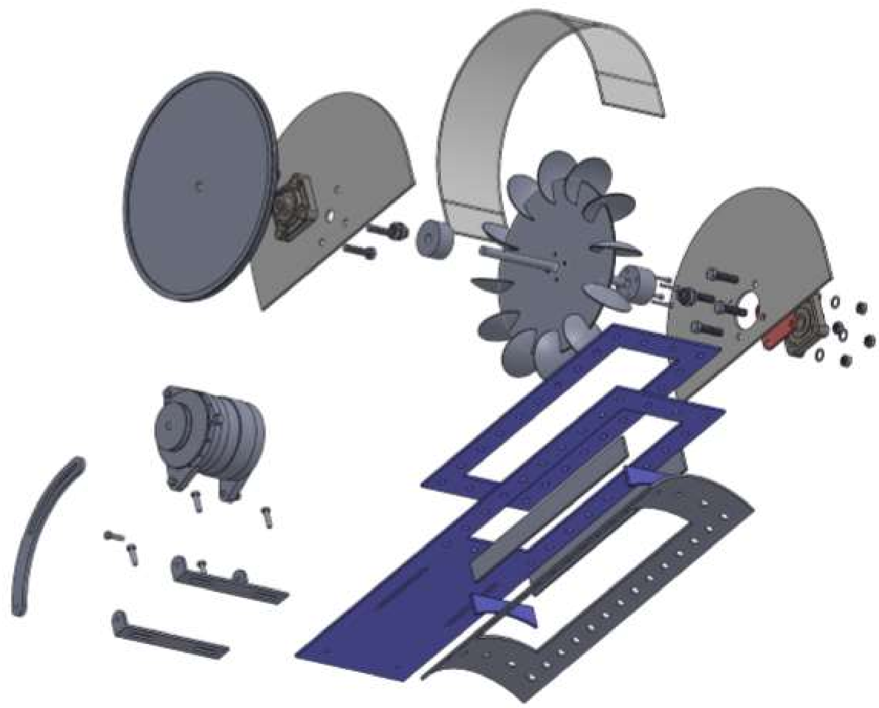


Figure 4-3: Exploded view of the IPW2 design

The unit selected is the 12 V 65 A unit that produces 14,2 V and a maximum of 65 A on a continuous supply. The output characteristics of the automotive alternator are illustrated in Figure 4-7. The shaft revolution at which the alternator starts to produce energy differs from manufacturer to manufacturer and from model to model. The test and behavioural results of the alternator installed in this study are provided in Chapter 5 of this report.

A detail design of the IPW2 was performed for manufacturing purposes and shown in Figure 4-2, followed by the exploded view in Figure 4-3. In the detail design, the complete unit was further componentised to enable the manufacturing of each and every part of the IPW2 separately. This exploded view was also used during the assembling phase to identify and place parts.

The drawings for the manufacturing were compiled according to the details needed for the manufacturing of all the components and is depicted in Figure 4-4 and Figure 4-5.

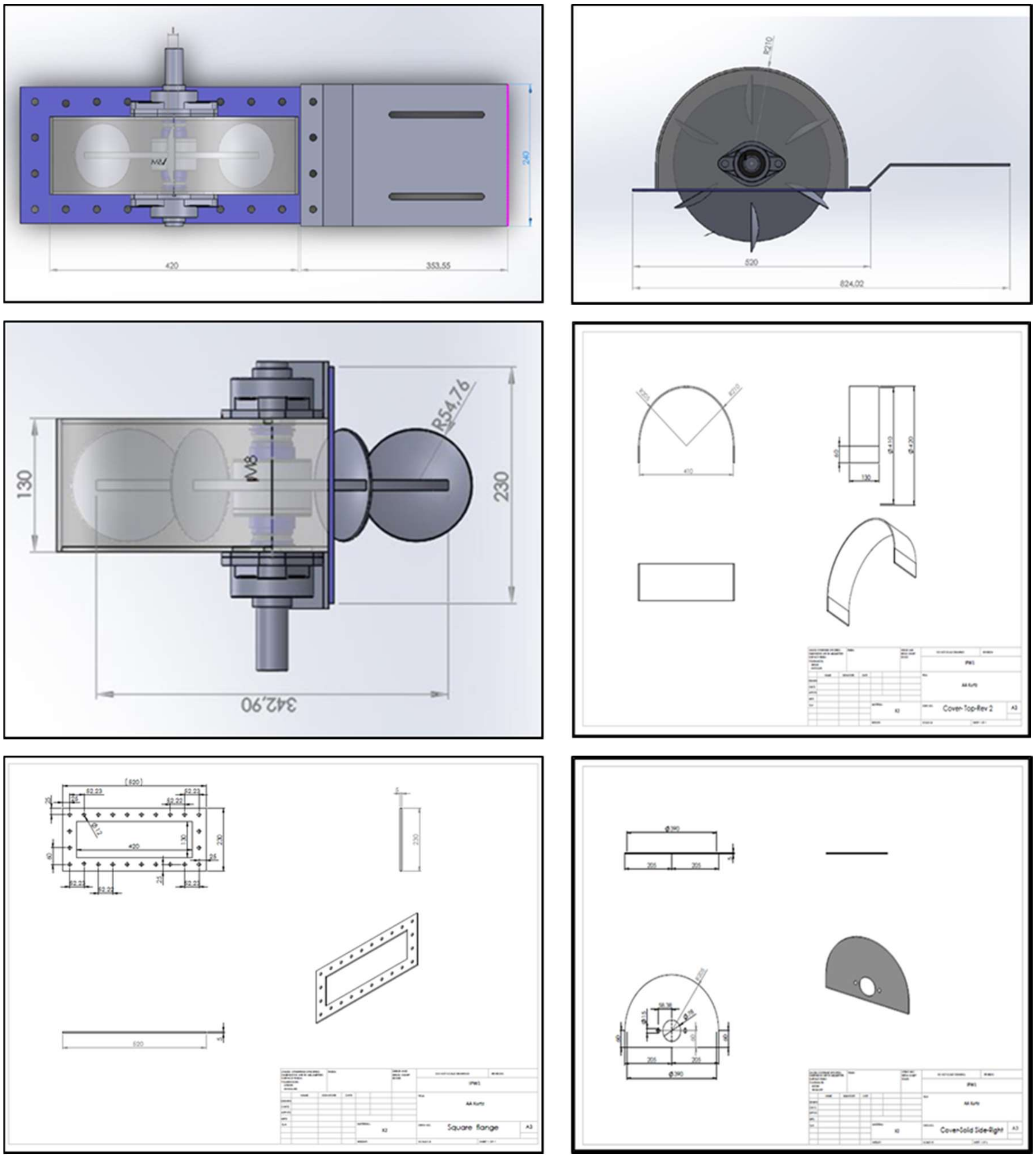


Figure 4-4: Detail design drawings part 1 of the IPW2 design

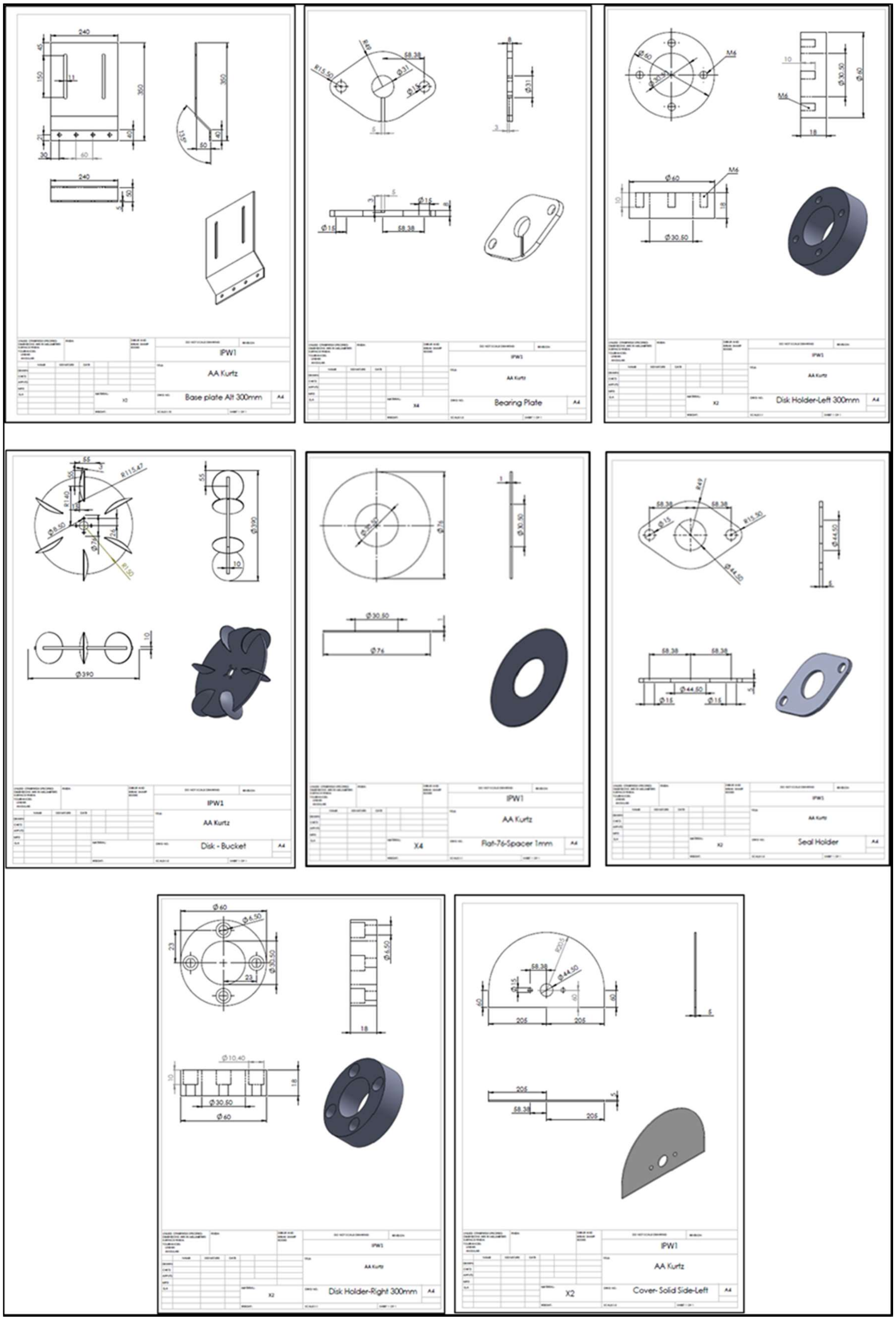


Figure 4-5: Detail design drawings part 2 of the IPW2 design

4.2 Using an alternator for a pico hydropower installation

4.2.1 General workings of an automotive alternator

The mechanical rotational energy that is harvested from the pipe network at the turbine shaft, needs to be converted into electrical energy. This demand can vary from low DC voltage with a low current to higher AC voltage with a higher current. For application in an IPW, a DC motor with permanent magnets can be installed, or an alternator can be used (Olding & Eagle, 2000). A sectional view of all the major components of a typical 12 V automotive alternator is presented in Figure 4-6.

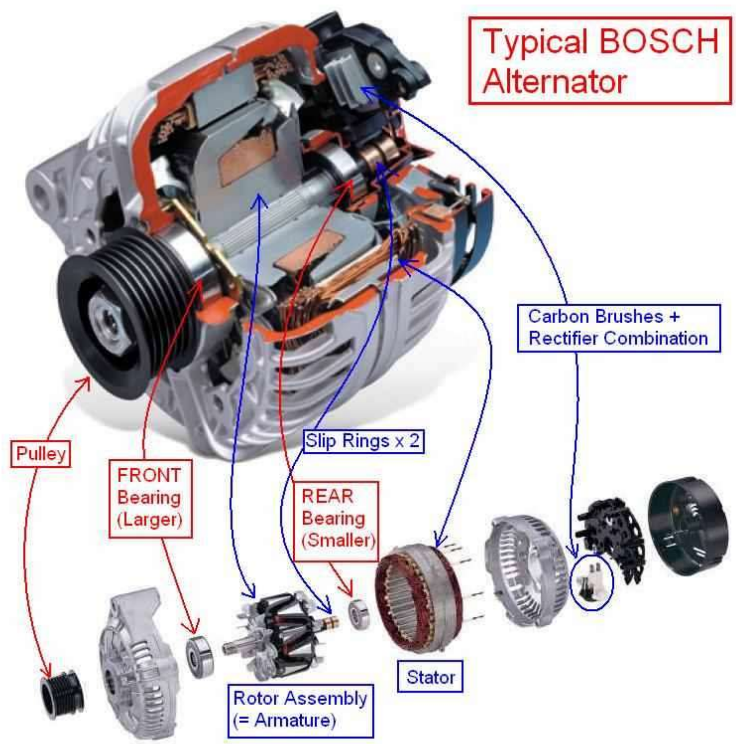


Figure 4-6: Typical 12 Volt automotive alternator (Olding & Eagle, 2000)

In an alternator, there are two concentric coils of wire: a stator coil, the static outside coil that does not rotate; and a rotator coil, the inside coil that rotates when the alternator's pulley is turned. The rotating fields are also referred to as the alternator's "field". In comparison, the DC motor has permanent magnets, whereas an electromagnet is created in the alternator when current flows through the field coil. The alternator's current strength is directly proportional to the strength of the magnet, which determines the amount of current that flows through this field.

An electric current is generated in the stator coil when the rotor rotates and the resultant magnetic field moves through the stator windings. The magnetic field alternates through the zero-voltage line and sweeps back and forth through the stator coil, producing an alternating current. The rotational speed, or frequency, can be measured from the alternating current that has the same frequency or rotational speed than which the alternator's pulley is rotating at.

Sufficient knowledge of alternator behaviour is important to enable the successful application thereof into the IPW electrical system. The alternator must be connected to a battery to supply the initial current to excite the alternator and getting it to start producing power.

The primary application, or purpose, of an automotive alternator is specifically to charge batteries. The alternator produces alternating current, which is converted or rectified to a direct current through a diode bridge. This direct current can be used to charge a battery. The direct current can also be used to supply the field coil with current during operation, to create the permanent electric field. The feed is only needed until the alternator is capable of producing its own electricity. This point is referred to as the point of excitation. Once the alternator is producing electricity, it is self-sustaining and it delivers a constant voltage with varying amperes.

The voltage generated in the alternator depends on two variables:

- the strength of the magnetic field; and
- the speed at which the alternator's field is rotating.

The regulator must regulate the voltage across the battery to a steady 14,4 V, which is the optimal voltage required to recharge 12 V deep cycle batteries. The voltage is regulated or stabilised by regulating the amount of current flowing to the field coil. After excitation, the alternator generates internal energy to keep the electric field excited and regulated at 14,4 V.

If the output voltage is too high, the regulator lowers the current flowing to the field coil. Contrastingly, if the output voltage is too low, the regulator increases the current flowing to the field coil. Simply put, as long as the alternator can maintain the minimum rotational speed to be excited, it will supply a stable 14,4 V.

In the application of the IPW and its electrical system, it is essential to keep the delivering output constant at 14,4 V across the poles of the battery. The essential part of the behaviour of this alternator is that variation in the alternator rotational speed will have no effect on the voltage output of the alternator. The power output of the alternator will depend only on the load attached to the alternator. This feature renders the alternator the preferred power generator to attach to the IPW to produce power.

The behaviour of the alternator before the exciting point, or exciting revolution speed, is of such a nature that the current that flows inside the field windings to create the electric field is unregulated. The revolution is still too slow to produce more energy than what is supplied, at this stage, from the battery system. This implies that the unit with its battery system will utilise power from the batteries up to the point of exciting.

A light bulb is wired in-between the field coil and the battery to serve as a diagnostic tool to determine when the alternator is excited. A switch can also be installed instead of the light bulb. If the switch remains closed, it would allow the alternator to be excited if the turning speed has reached a large enough current to supply electrical energy. It should be noted that the current to the field coil remains unregulated until the alternator becomes excited and produces energy.

Another important point to note with regard to the behaviour of the alternator is that the moment that the alternator becomes excited, there is a high initial current in the field coil that makes it extremely difficult for the alternator to turn. Olding and Eagle (2000) stated the following:

> An electromotive force (EMF) will oppose any change in current in the stator coil. The larger the change in current, the larger the opposing EMF. If a large current is initially flowing through the field coil, even a low rotor speed will result in a large change of current in the stator coil. The opposing EMF will make the alternator very difficult to turn. Once the alternator is turning, this EMF will disappear; it is generated only by large changes in current, not large currents in and of themselves. However, the initial EMF may be too large a force to overcome, and the alternator may never become self-sustaining.

This explains the characteristic of the alternator turning quite easily until the alternator is excited, or in other words until the EMF is starting to oppose the rotation. This will result in current flowing in the charging circuit and the rotation of the alternator becoming difficult.

4.2.2 The behaviour of the alternator

The graph in Figure 4-7 illustrates the different alternators and their excitation characteristics, in other words, their behaviour when rotated until the speed is reached when they produce energy. The shaft revolution at which the alternator starts to produce energy differs between different manufacturers and models. The output results of the alternator that was installed in this project are provided at a later stage in this report.

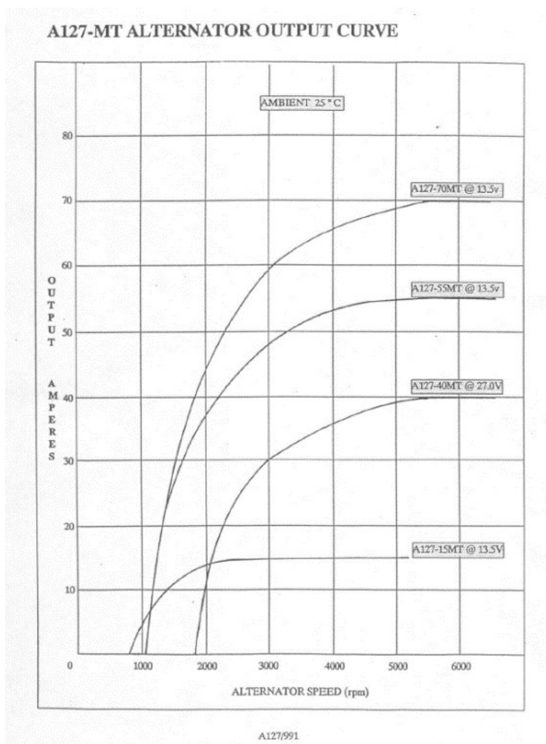


Figure 4-7: Excitation characteristics of an alternator (Marine, 2017)

The output power from the alternator is also temperature-dependent. Figure 4-8 indicates the difference in the ampere load produced between the alternators at a cold start-up temperature versus the output at operating temperature. The output at low temperature reaches a maximum value of 76 A at 4 500 rpm, and at working temperature a value of 65 A. This implies that the alternator loses nearly 30 % of its capacity before its working temperature is reached.

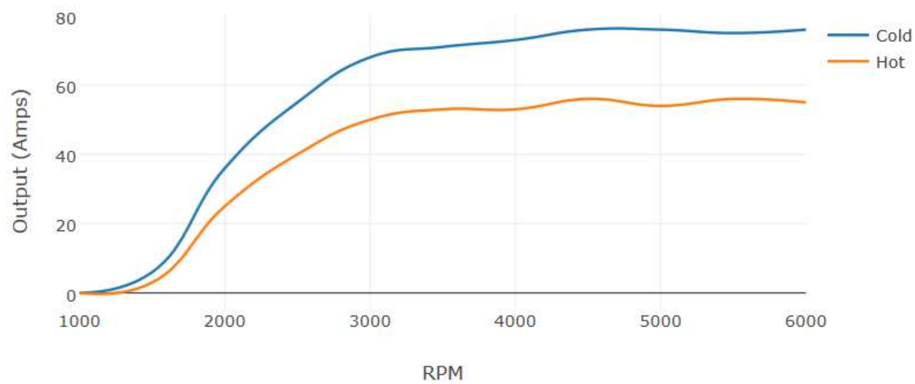


Figure 4-8: Current output comparison between a hot and a cold alternator (Balmar, 2016)

4.2.3 Alternator and generator connections

In general, there are four connections that must be made between the alternator and the battery system:

- The alternator's metal case must be connected to the battery's negative terminal.
- The positive pole or connection point on the alternator must be connected to the battery. Current will flow from the alternator to the battery after the alternator is excited.
- The low resistance point must be connected to a push-button switch or as in standard applications, a light bulb that will supply current to the field coils.
- A revolution or frequency meter should be connected directly to the field coils to indicate the alternator speed.

In this study, the turbine, prototype 4 (IPW2), was installed on a shaft with a pulley assembly that resembles the overshot water wheel (Figure 4-9). The water wheel was secured on the impellor shaft with a set of grip screws and the pulley was secured on the shaft with a press on fit.

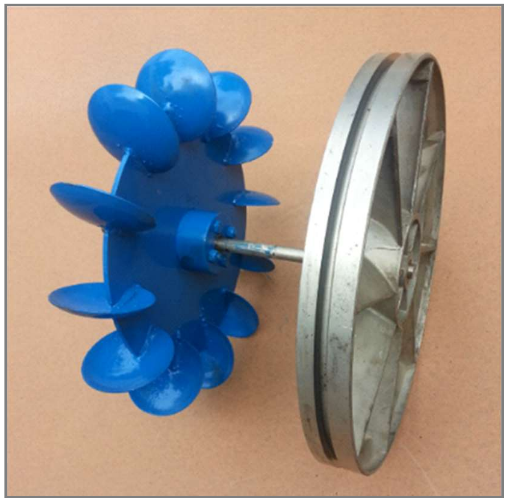


Figure 4-9: IPW2: pulley and impellor shaft

The turbine wheel, shaft, and pulley assembly that were fitted into the turbine wheel housing based on the undershot water wheel design (Figure 4-10). Perspex panels were installed to allow monitoring in the case of air accumulation in the wheel housing.

Figure 4-10: Prototype 3 and 4 – runner housing with runner assembling

The planned design (top view) for the IPW2 hydropower pico turbine is presented in Figure 4-11. The positioning of the wheel inside the water pipe (side view) is shown in

Figure 4-12. The depth of the turbine inside the pipe will be determined and explained later in the detail design.

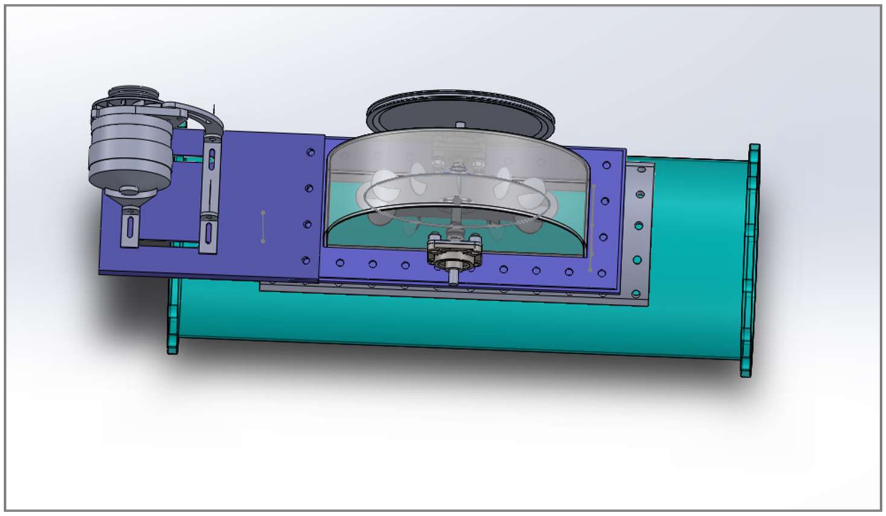


Figure 4-11: Three-dimensional design illustration of the IPW2 turbine installation – top view

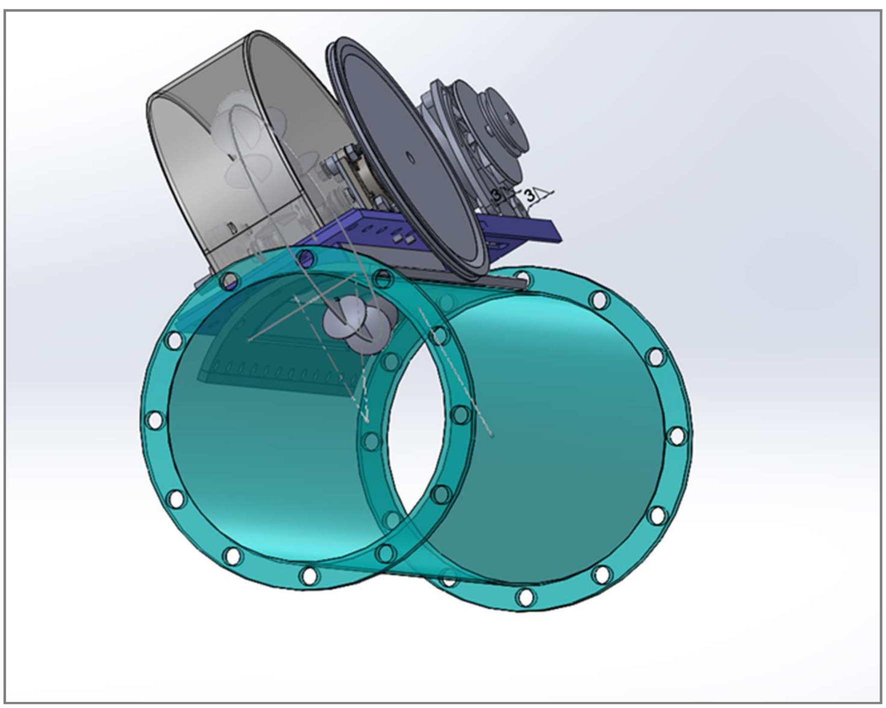


Figure 4-12: Three-dimensional design illustration of the IPW2 turbine installation – side view

4.2.4 V-belt selection

The mechanism that was selected to convey the rotational movement from the prototype's runner pulley to the alternator pulley, was a standard v-belt. The motivation behind this is that the v-belt is a very simplistic and well-tested design with high reliability. Different v-belt models and sizes were also readily available. A practical benefit of this set-up was that the pulley system was easily accessible to make alterations and modifications – for example, to adjust v-belts or change the pulley ratios. It was necessary for this to be easily accessible, as the final rotation speed of the IPW was not known and changes to the pulley diameter and speed relation might have been necessary.

The total load that the v-belt can support is a factor of the belt contact area. A more modern design is the multi-groove pulley design, with multiple smaller grooves, increasing the contact area and thus also increasing the load it can handle. The information in Table 4-1 was used to select the belt type that was used for prototypes 3 and 4 in this study. It is clear that dual v-belts and serpentine belts (Table 4-1) can support much larger loads.

Table 4-1: Alternator v-belt selection table

Belt type	Belt width	Maximum horse power load	Highest recommended output
Single V	3/8	3,5	80 A @ 12 V, 30 A @ 24 V
Single V	1/2	4,5	110 A @ 12 V, 45 A @ 24 V
Dual V	1/2	12,0	310 A @ 12 V, 220 A @ 24 V
Serpentine	6-groove	N/A	310 A @ 12 V, 220 A @ 24 V
Serpentine	8-groove	N/A	310 A @ 12 V, 220 A @ 24 V

Abbreviation: N/A: not applicable

4.2.5 Alternator voltage regulator

In automotive alternators and systems, the current in the alternator is supplied by an internal regulator, which drives the alternator to a specific voltage value. For this study, the output voltage of the alternator that was used was 14,2 V. The motivation behind the selection of the automotive alternator with a built-in alternator voltage regulator was, again, the simplicity of the unit. It is a readily available product that is well tested and based on a reliable technology with several applications. The alternator unit is also inexpensive and easy to install and modify to suit the application. Prototypes 3 and 4 were typical automotive applications with an alternator and battery system – very comparable to the systems used in small wind turbine units.

4.3 Submergence of the runners of prototypes 3 and 4

The positioning of the runner into the pipeline is dependent on the type of flow in the pipe in which the hydropower unit is to be installed. The flow type, according to the classification of flow, can be determined with the Reynolds formula, as discussed in Chapter 2 (equation 2.2).

For slow flow conditions, the installation is proposed to be the deepest to secure access to the maximum exposure to energy in the moving water. The velocity in laminar flow conditions will be as low as 0,013 m/s and will be too slow to be used for this study.

The three proposed positions of the turbine runner in the pipe can be seen in Figure 4-13. These positions are dependent on the identified flow in the pipe. However, investigation of the optimum placement of the turbine wheel within the pipe is not addressed in this project.

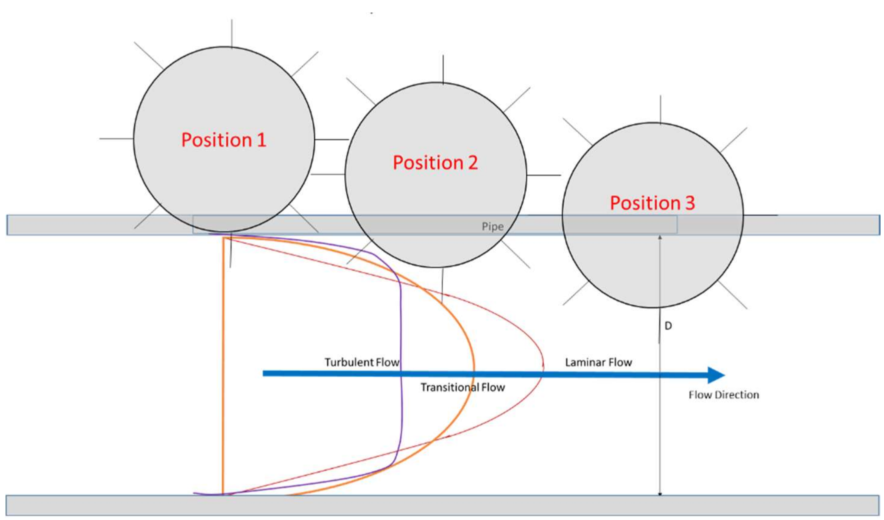


Figure 4-13: Proposed installation positions of the turbine runner

The hydropower prototype demonstrated in Figure 4-13 indicates the proposed installation positions on the mounting bracket on the pipe and the depth of the wheel in the pipe, according to the calculation of the type of flow anticipated in the installation. According to the Reynolds definition and calculated value, the Reynolds number for the installation is 8,0 x 10^6, indicating turbulent flow in the pipe. Therefore, the placing of the prototype hydropower turbine was performed according to position 1, as suggested in Figure 4-13. This turbine positioning, in terms of depth, is further illustrated in Figure 4-14.

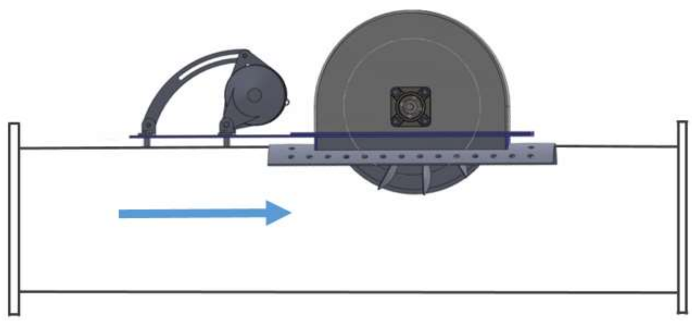


Figure 4-14: Indication of the depth of the turbine runner in the pipe

4.4 Efficiency of the IPW2 turbine

The turbine prototypes were not developed with the focus on efficiency of the turbine configurations, but for generating specific amounts of energy needed on site. The production of this required energy had to be at the point of consumption on the installation sites. The hydropower prototype did not require continuous flow to produce sufficient energy for the applications on-site, as there was battery storage available. The design standards of CoT are based on the 36-hour storage capacity of the reservoir. As a result, there will be time periods without any flow in the supply lines on which the hydropower unit is installed. The basic energy demand of an average valve chamber will include energy for telemetry, lighting, pressure and flow controllers, and security equipment. This equipment functions on a standardised 12 V or 24 V input voltage, which is in line with the standard voltage outputs of the alternators used in this project. The use of the 12 V and 24 V output voltages from the alternators made it practical and easy to store the excess power in a configuration of 12 V batteries. Electrical power will be available from the 12 V batteries on a permanent basis and if a small amount of 250 V is needed, it can be provided with the use of inverters. The application of this design is also suitable in cases where the water flow varies. The flow in the water system depends on the water demand, which fluctuates during the 24-hour daily water demand cycle. The water demand also shows large flow and consumption variation during the different seasons of the year.

The hydraulic and energy gradients in a pipe system with a turbine installation are illustrated in Figure 4-15. In CoT, a reservoir has a typical height of 10 m and flow velocities of between 0 and 4 m/s in the feeder main water supply. Flow in the system varies between 0 and 250 ℓ/s. If the basic potential of available energy is calculated with:

$$\boldsymbol{P = \eta\gamma Q(H_g - h_l)} \qquad \textbf{(4.1)}$$

The planned equipment on the reservoir site requires on average only between 100 W and 150 W to operate. The aim was thus to develop a turbine that can extract between 100 and 150 W of energy from the energy available in the pressurised conduit system.

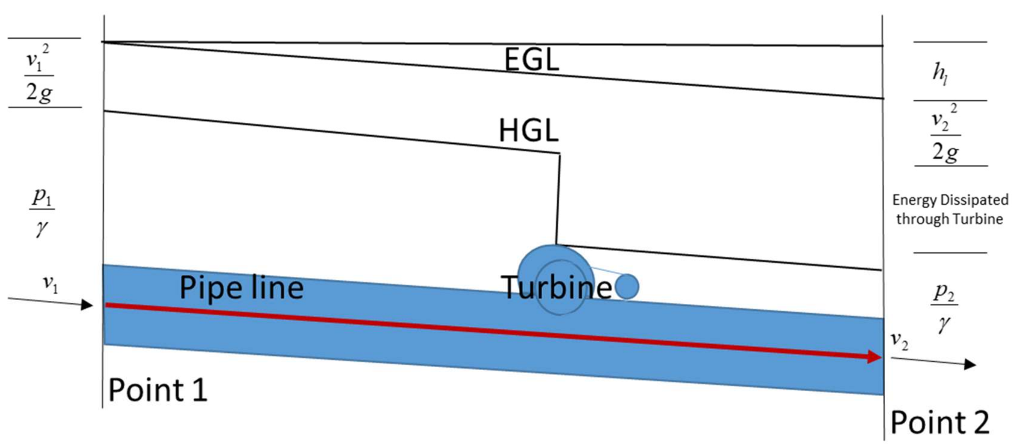


Figure 4-15: Hydraulic and energy gradient in a pipe system with a turbine installation

4.5 Retrofitted installation

The bolt-on-base plate that was designed for this study, is illustrated in Figure 4-16. The design is of such a nature that a rectangular hole was cut in an existing pipe or spool piece. The square base was then bolted onto the existing pipe. This design ensures that the installation is simplistic and that the turbine can be removed without the removal of a pipe segment. Extensive welding was also not required.

For the installation, the pressure in the pipeline was required to be zero in order to perform the initial insertion and to secure the baseplate. The rest of the installation included drilling and installing bolts and nuts. If the turbine should be removed, a cover plate (Figure 4-16) could be installed on the turbine baseplate and the pipe system could be operational within a short time.

Figure 4-16: Retrofitted mounting piece for an inline pico hydro turbine

Figure 4-17 shows a photograph that was taken while the unit was operational and the functioning of the mechanical water seals was monitored.

Figure 4-17: IPW2 retrofitted on the installed baseplate

After all the final adjustment were completed, the IPW2 was commissioned (Figure 4-18) and connected to the test panel and batteries. Data were collected with the data logger and the performance could also be visually monitored from the different meters and lights that were installed in the test panel.

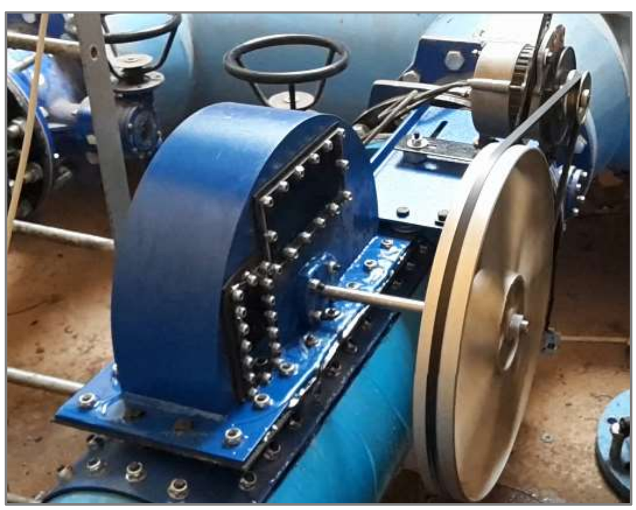


Figure 4-18: IPW2 in operation

4.6 Test bench setup

The IPW2 was installed in a test facility with variable speed pumps that can deliver up to 300 l/s of flow depicted in Figure 4-19.

Figure 4-19: Two centrifugal parallel connected centrifugal pumps

The installation consisted of a water tank as water supply shown in Figure 4-20, two centrifugal parallel connected centrifugal pumps, pipe work and various measuring instrumentation. The pump's motors were both fitted with variable speed drives to enable different flow rates for testing at different flow rate conditions.

Figure 4-20: A water tank as water supply at the test bench

A venturi is also part of the test setup to measure the flow in the system given below in Figure 4-21.

Figure 4-21: A venturi installed as part of the test setup

Figure 4-22 illustrates the turbine installed in a 250 mm diameter pipe system with two reducers from 300 mm diameter to 250 mm diameter to accommodate the IPW2 .

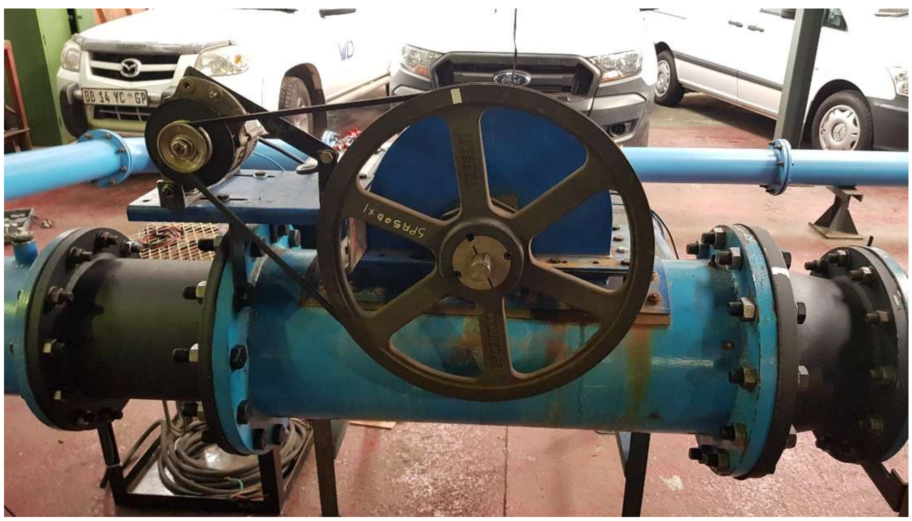


Figure 4-22: IPW2 installed into the test bench

4.6.1 Test procedure

Pressure testing points were installed on the pipe system upstream and downstream of the IPW2 to log the pressure difference over the turbine installation. Figure 4-23 below was taken during the testing of the IPW2.

Figure 4-23: In process of testing the IPW2

Two 10 bar pressure transducers were used to generate a signal between 4 and 20 milliampere and the data was logged on a HOBO logger, shown in Figure 4-24 below, at 2 second intervals.

Figure 4-24: The HOBO logger connected to a power supply and pressure transducer

The base line for the zero values and corrections were calculated and applied to the two sets of readings.

The first test was done with the turbine running with no load and no fan belt installed and the results are listed in the table Table 4-2.

Table 4-2: Alternator test with the turbine running with no load and no fan belt installed

No Load No Belt			
P1 kPa	P2 kPa	Flow l/s	RPM (Turbine)
17,3	15,5	137,02	140
26,8	22	166,36	172
24	21	166,1	172
43	40	220,18	232
54	49	244,82	269
63	57	258,82	289

The second test was conducted with the fan belt installed and results listed below in Table 4-3.

Table 4-3: Alternator test with the turbine running and fan belt installed with no load

No Load with Belt			
P1 kPa	P2 kPa	Flow l/s	RPM (Turbine)
16,5	13	133,76	107
24	22	165,3	149
45	38	220,18	216
57	48	244,82	247
64	55	258,82	271

The third test was done with the fan belt installed and connected to a 12 Volt battery to determine the excitation rpm of the alternator and the charging volts. The alternator exited at 880 rpm and the charging volt was 14,4 Volt.

4.6.2 Efficiency test

The tests were done at a targeted constant flow rate of 220 l/s. The load was incrementally increased by adding 50 watt 12 volt lights to the excited alternator with an internal load of approximately 800 Watt. A total of five lamps were incrementally added, one 50 Watt at a time, to simulate an increasing load on the system illustrated below in Figure 4-25.

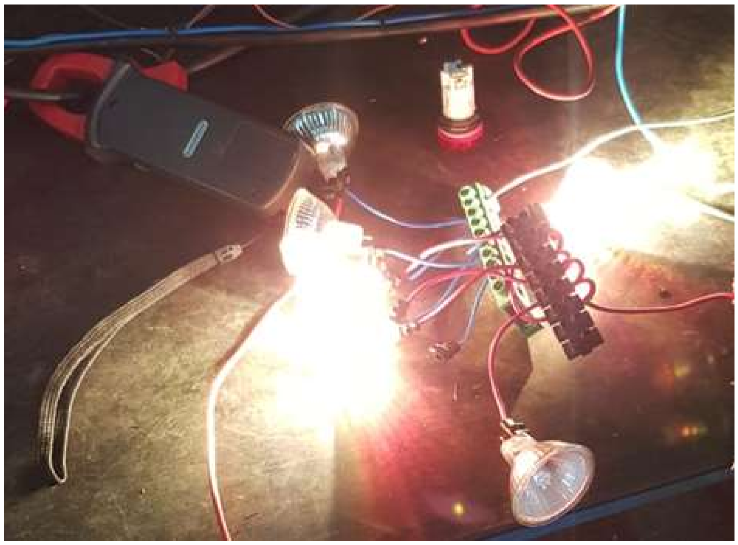


Figure 4-25: Diagram of the different losses in the alternator for different gear ratios (Örn, 2014)

The combined results of the incremental pressure readings upstream and downstream of the IPW2 are shown on Figure 4-26.

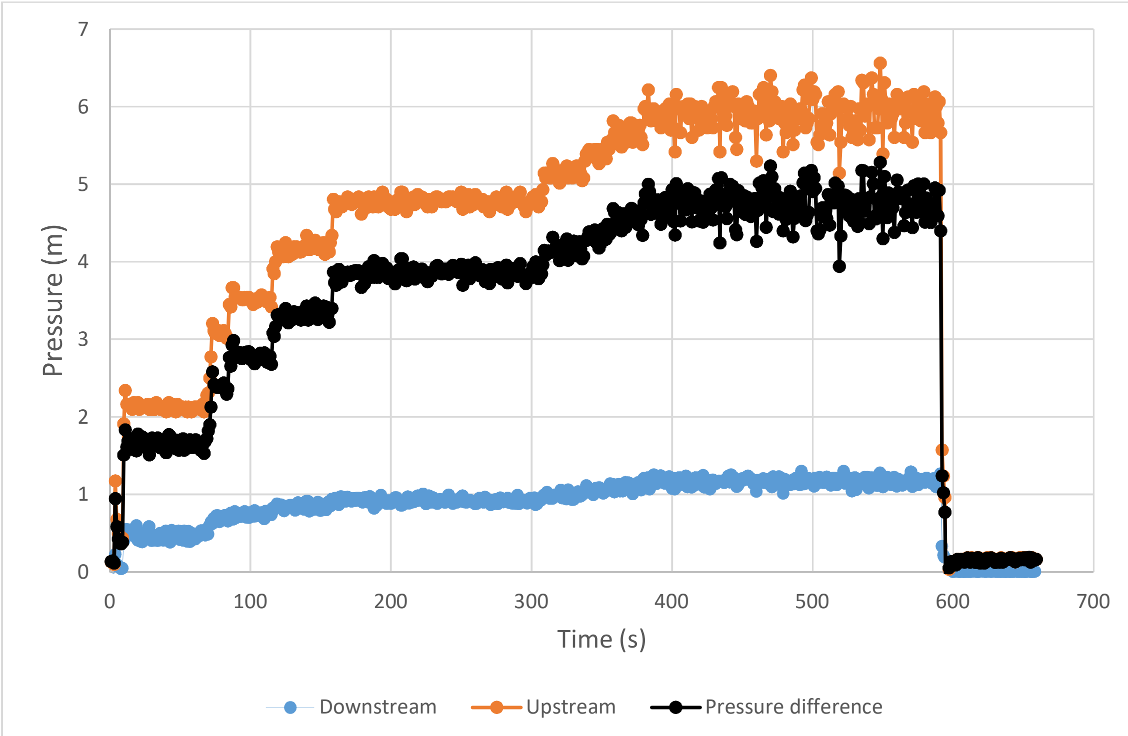


Figure 4-26: Pressure difference upstream and downstream of the IPW2

Table 4-4: Alternator test load increments

Constant Flow with Load Increments				
Flow (l/s)	**Amp**	**Volt**	**Watt**	**RPM (Alternator)**
221	5,1	14,8	73	1800
238	10,2	14,3	147	1500
248	15,3	14,1	220	1668
266	20,4	14,4	294	1660
266	25,5	14,6	367	1720

The graph in Figure 4-27 was used to determine the internal power consumption for a typical 65 Amp 14.2 Volt alternator. Various components contribute to the alternator losses as depicted from the figure. A value of 800 Watt was used as power value consumed by the alternator during this test period and calculations shown in Figure 4-27.

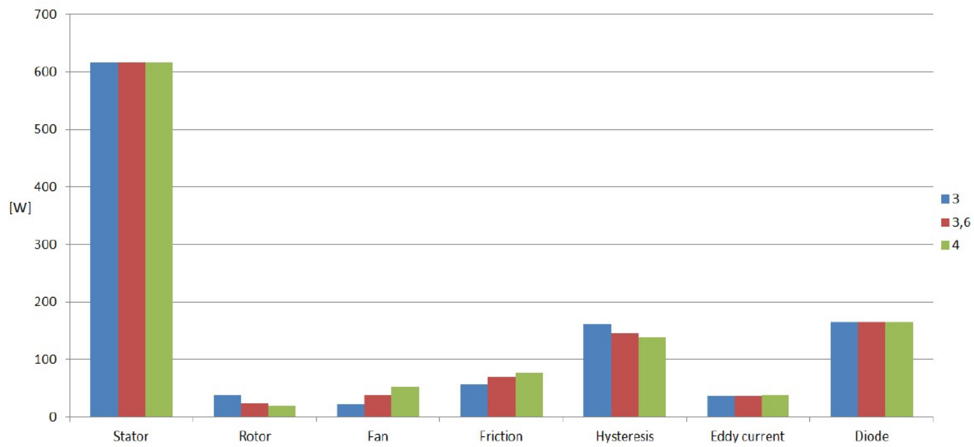


Figure 4-27: Diagram of the different losses in the alternator for different gear ratios (Örn, 2014)

The available hydraulic power is defined as $P_H = \gamma Q \Delta H$, with γ the water specific weight, Q the discharge, and ΔH the head drop calculated between upstream and downstream of the IPW2.

Figure 4-28 used the load created by the lamps as the power generated (P_g) for the calculation for the efficiency (η) curves with the efficiency calculated as the relation of the power available due to flow and pressure and the power generated in $\eta = P_g/P_H$.

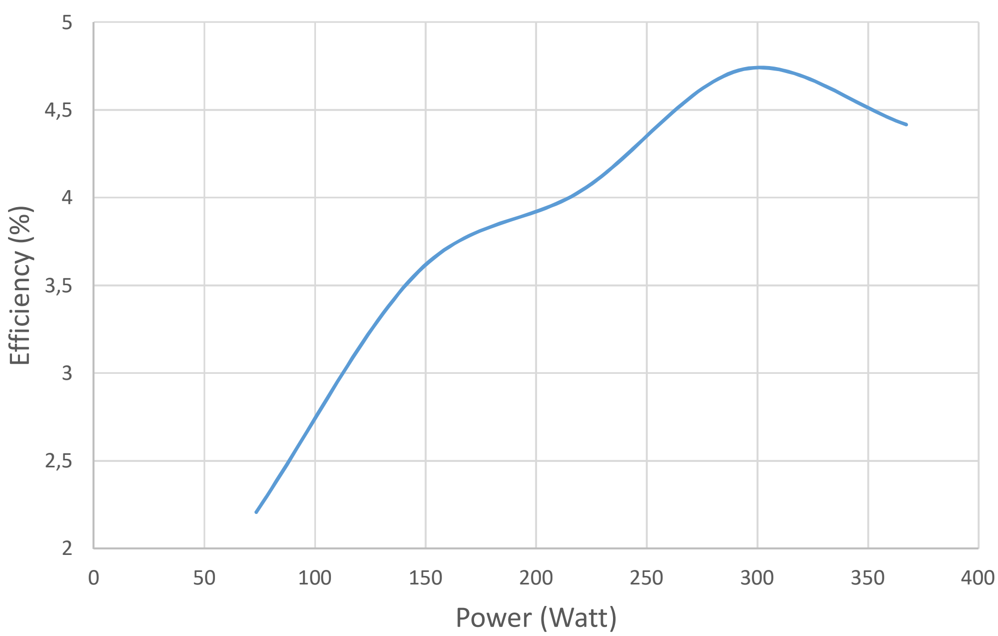


Figure 4-28: Power generated against total efficiency of the installation

4.6.3 Net efficiency of the IPW2 installation

Figure 4-29 used the total power internally used by the alternator combined with the load created by the lamps (P_n). This value was used as the total power generated by the unit for the calculation for the efficiency (η) curve. The efficiency was calculated as the relation of the power available due to flow and pressure and the power generated (P_n) in $\eta = P_n / P_H$.

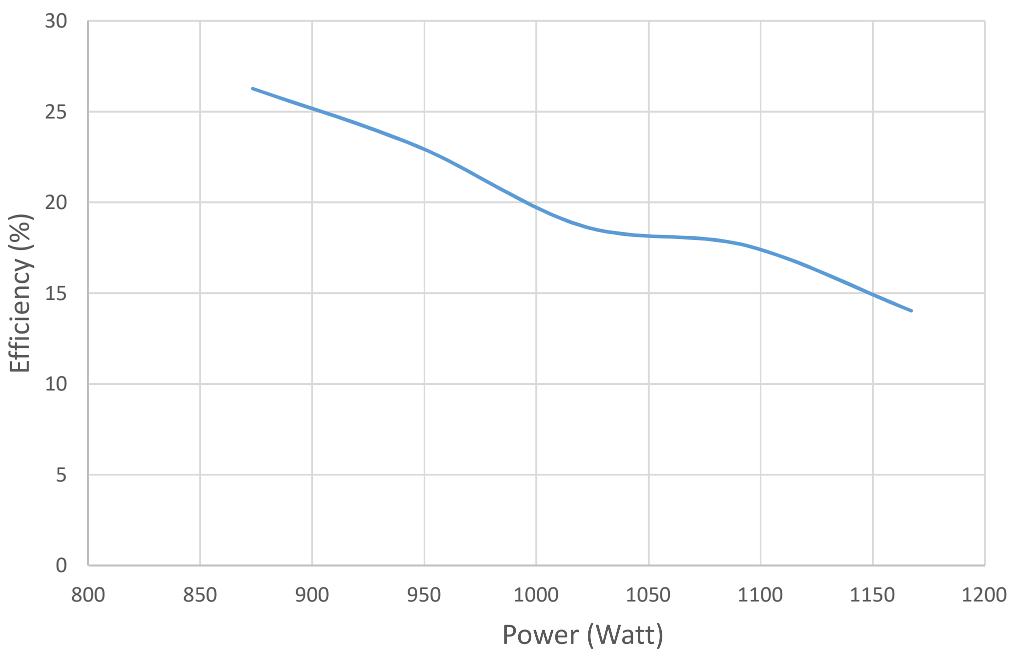


Figure 4-29: Efficiency of the IPW2

5 TEST RESULTS

5.1 Introduction

The first objective of the testing that was performed in this study was to log all characteristics of the water supply through the existing PRV installation before any changes were made to the installation. Measurements were taken and data of the water travelling through the PRV were collected from the primary feed line in the PRV chamber. These characteristics included the flow through the PRV, pressure upstream and downstream of the PRV, and the velocity of the water through the PRV.

All turbine installations in water networks had to be done without disrupting the sufficient feed of water to the reservoirs. To investigate the flow conditions in the existing system, the operating pressure and flow in the system were plotted on graphs to compare it with data collected with the logging system after installation of the turbine.

The second objective was to analyse the behaviour of the prototype turbine in the system and the influence it has on the flow and pressure in the pipe. The data that were gathered and logged was downloaded and saved in a spreadsheet configuration. The data were also analysed to gain information that reflects:

- the water system behaviour before and after turbine installation; and
- the characteristics of the hydropower turbine tested.

The parameters that were required from the water system included the upstream pressure and flow before the turbine was installed, and data during operation with incremental flow increases and decreases. Data on the voltage and power produced were also collected. A pressure decrease across the prototype turbine was needed to perform a reverse calculation of the optimum point of efficiency of the turbine and at which flow and speed it occurred.

It was also important to determine the power range of the turbine, which is the result of the water flow rate and physical characteristics of the turbine itself. The reliability and durability of the prototype were determined during the longer testing period and continuous running under normal operating conditions in the chamber installation.

5.2 Pressure and flow readings before turbine installation

The Bernoulli (1738) equation mentioned in Chapter 2 was used to determine the theoretical relationship between the upstream flow and pressure in the 300 mm diameter installation. The flow in the pipe followed the profile depicted in Figure 5-1.

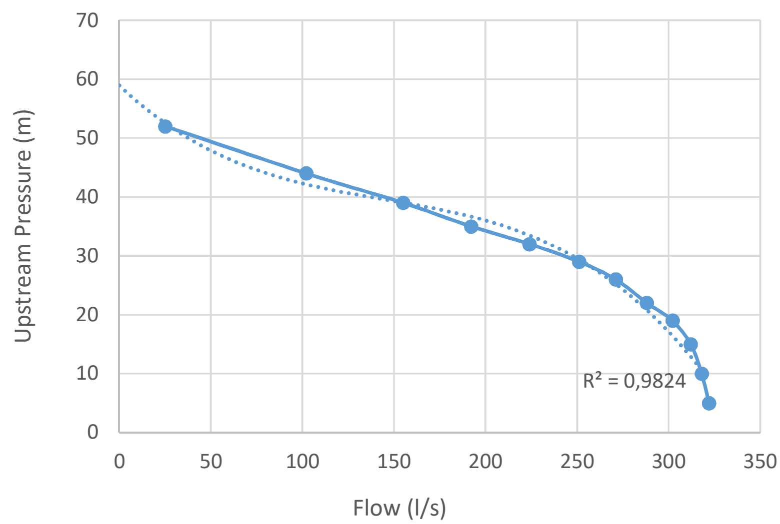


Figure 5-1: Pressure flow relation before turbine installation

Data were also collected from the installation after the IPW2 was installed. The aim of gathering this information was to determine the total amount of potential energy available in the system and to again obtain an indication of the system behaviour when the prototype turbine is installed in the test pipe section.

5.3 Pressure and flow readings after installation of the turbine

It is important that the installation must not throttle the water flow into the reservoir to such an extent that the reservoir cannot supply sufficient water during peak demand. The upstream monitoring of flow was compared with the required flow quantities in order to supply enough water to the reservoir. This upstream flow is depicted in Figure 5-2.

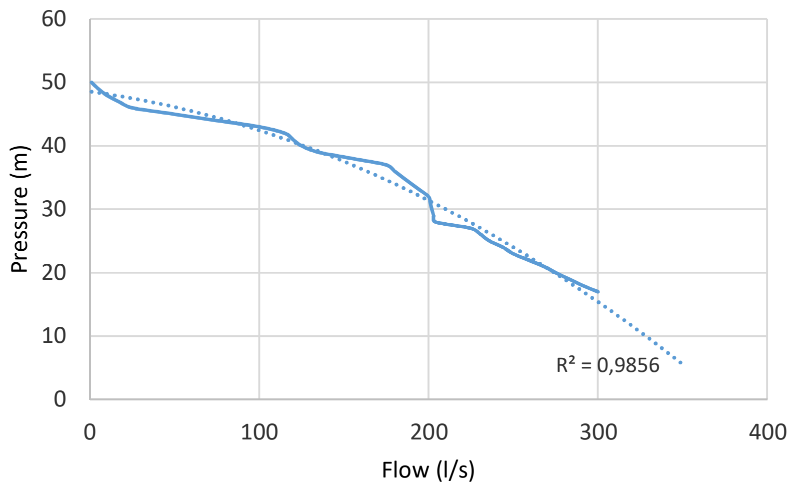


Figure 5-2: Upstream flow and pressure after installation of the turbine

The system behaviour before the installation was compared to the flow conditions after the installation was performed. Data collected over four months as part of the second testing phase were used to determine the best fit for an equation to calculate the flow and pressure-flow relationship after the turbine installation. Data were statistically analysed and are presented in Figure 5-3. A trend line was added to generate a formula for further analyses of the data.

The formula of the trend line can form a second or a third-degree polynomial equation. The trend line can be used to determine the pressure-flow relationship theoretically for alternative conditions for this installation upstream of the turbine installation. The 90% exceedance of the flow occurred at 337 ℓ/s (Figure 5-3), which implies that the pressure in the system will not decrease to below about 11 m water pressure.

The alternator model used in in the turbine assembly in the IPW2 is an ALT200 (Beta) 60 A 14.2 V economical replacement type alternator for universal applications with a plastic fan system.

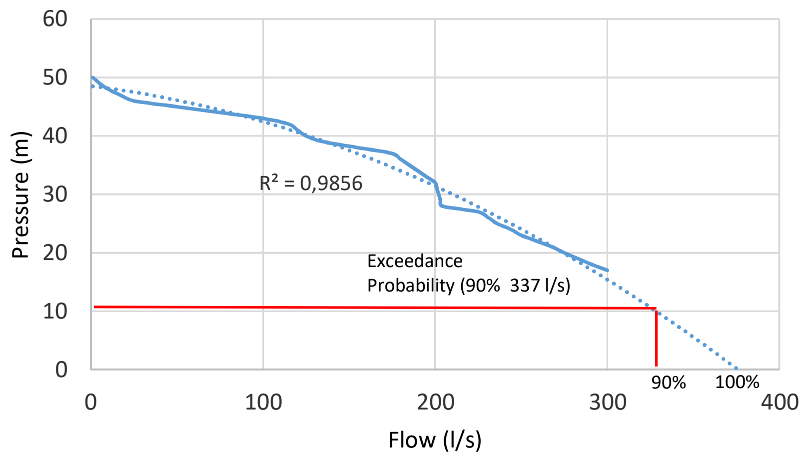


Figure 5-3: Exceedance probability of the supply flow

From Figure 5-4 it is evident that the turbine rpm against the flow velocity in the pipeline is not perfectly linear. This indicated that the turbine experienced an increase in torque at some stage during its acceleration. The deceleration was smoother after the turbine reached a point where it was no longer excited and no longer contributed to increasing the potential energy stored in the battery.

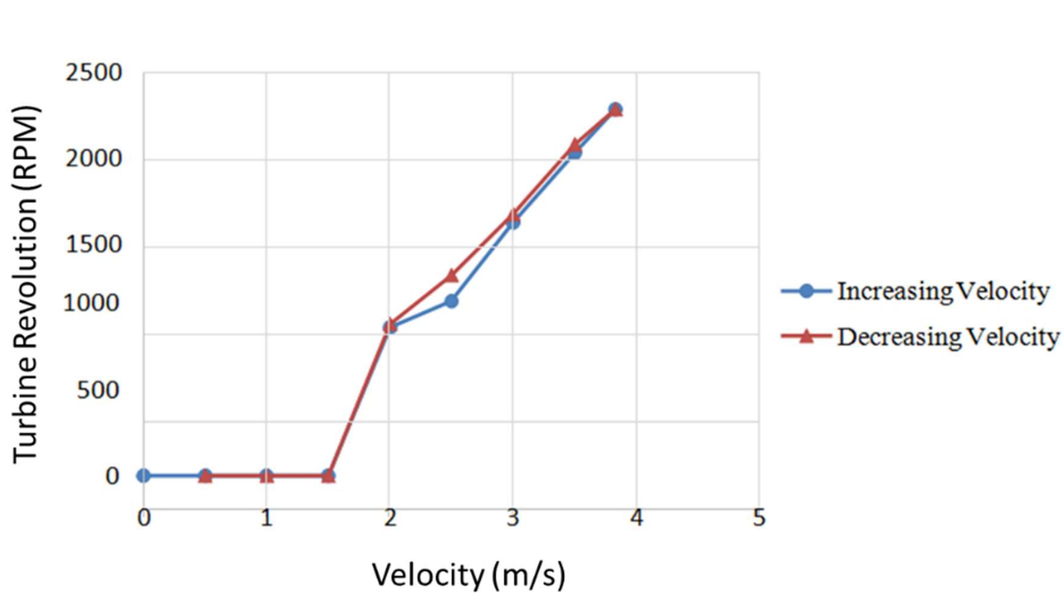


Figure 5-4: Alternator revolution and deceleration vs fluid velocity

The excitation and de-excitation behaviour of the alternator is presented in Figure 5-5. The fact that the alternator was starting to deliver energy at about 220 ℓ/s and terminating the delivery at about 100 ℓ/s, was considered as a specific characteristic of the specific make and model of the alternator.

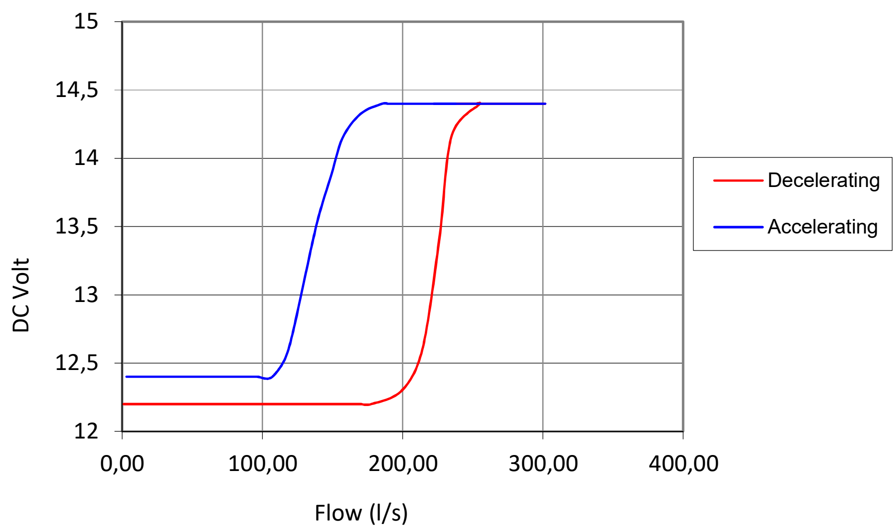


Figure 5-5: Alternator acceleration and deceleration voltage vs fluid velocity

The graph in Figure 5-6 indicates the differences in the behaviour of the alternator voltage between the acceleration phases. The alternator voltage increases after the alternator is excited and starts to contribute to the battery potential. An alternator can only deliver a stable voltage to the battery until the point where the alternator's maximum power rating is generated. During these tests, this point was never reached, and a maximum stable voltage was delivered to the battery.

The decrease of the impellor rpm during the excitation phase indicates the point at which the alternator experienced the electromagnetic pulse effect. The suspicion was that the resistance against the rotation caused much more disarray in the water flowing through the impellor, thus causing more turbulence and disturbances. The analysis of this flow behaviour was not covered in this study.

The power output also increased with the increase in flow rate. At 2 m/s, the alternator speed decreased for a short period, although the voltage (and power output) increased. This interesting phenomenon can possibly be explained by the total area of the turbine impellor reacting to the water flow in the pipe and energy being absorbed by the turbine. At that moment the energy was not enough to continue the linear relation when the initial excitation of the alternator was completed. This sudden increase in resistance against rotation due to excitation was possibly the reason for the momentary decrease in turbine velocity. When the flow rate increased and more flow energy was converted into rotational movement, the linear relationship between rotation speed and power was re-established. After excitation, the turbine recovered and continued its steady linear increase, as indicated in Figure 5-7.

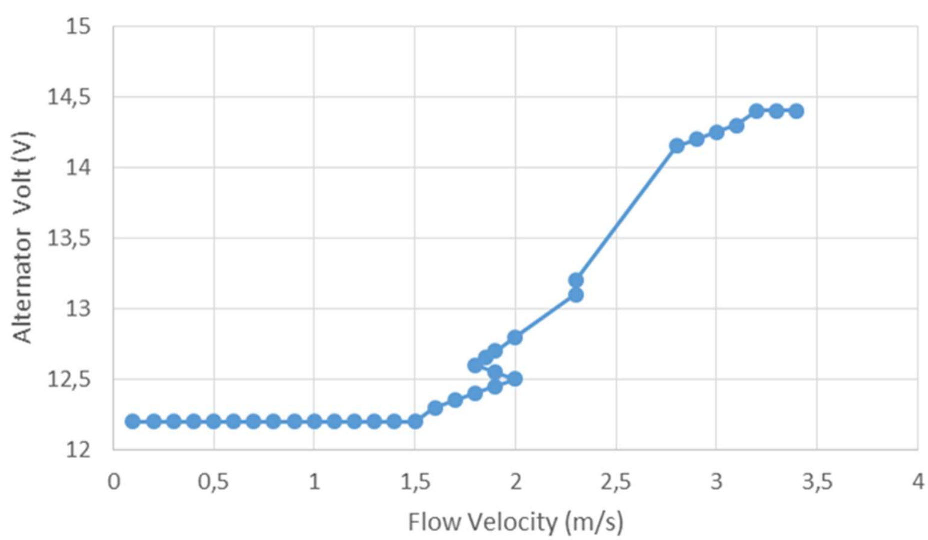


Figure 5-6: Alternator voltage vs water flow velocity

The flow velocity is plotted against the alternator voltage in Figure 5-7. It should be noted that just after the alternator had reached the charge activation speed, the first phase of excitation, at 107 ℓ/s, the battery voltage started increasing. As the flow increased, the voltage suddenly rose with a near-linear relationship between the turbine velocity and the battery voltage between 1,8 and 3,2 m/s at the fully excited phase.

These two conditions can also be described as a stage where the impellor turns slower than the speed of the water that forces it to rotate, forming an asynchronous condition.

With increased water velocity, the turbine falls back into a more synchronous condition. This can be investigated in more detail in further research and falls outside of the scope of this study. This is also a detail design aspect that can be researched and revisited before producing the turbine for commercial purposes. However, it does not influence the sustainability of the turbine as a unit.

From Figure 5-7**,** which shows the battery voltage against time, it is evident that the alternator contributes to the battery potential. After the alternator was run at a speed to excite the alternator and increase the voltage in the system, the flow velocity was decreased and water flow then switched off completely and the alternator stopped delivering power to the system. A small positive voltage difference was observed in the battery voltage reading without the alternator contributing energy to the battery.

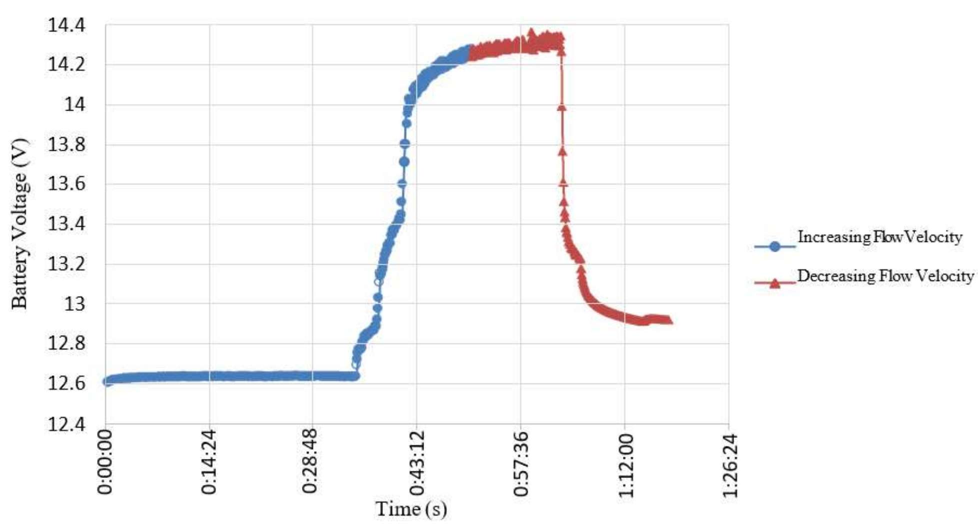


Figure 5-7: Alternator voltage during the alternator self-sustaining/excitation phase

The graph in Figure 5-8 shows the alternator voltage plotted against the flow in the pipe during the alternator acceleration phase. The alternator voltage increased, basically immediately, after the alternator was excited, to a maximum voltage delivered (14,4 V). The voltage after this point remained stable with the increasing flow rate. The delivered voltage was stable and contributed to the sustainable power delivered.

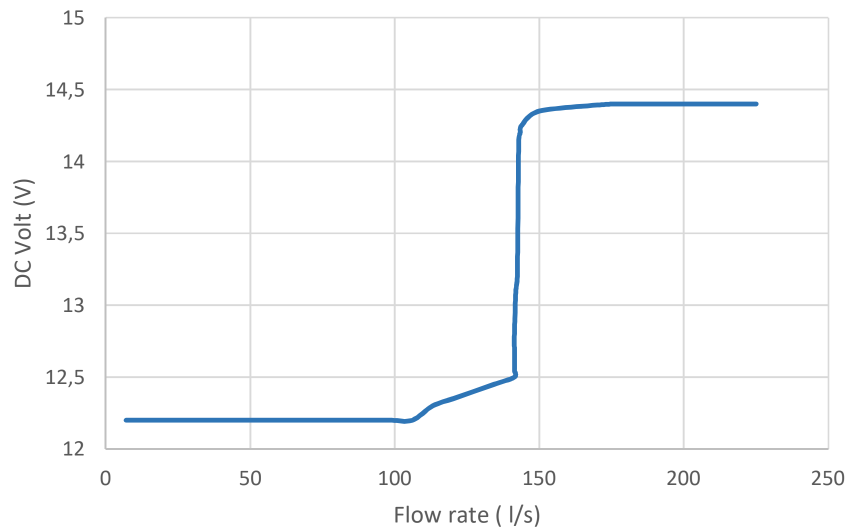


Figure 5-8: Measured alternator voltage against the flow in the pipe (ℓ/s)

It can be concluded from Figure 5-9 that the efficiency of the turbine was speed-related. The maximum power output was reached at a speed of approximately 2,5 m/s (Figure 5-10). After this peak, the power decreased with increasing flow velocity.

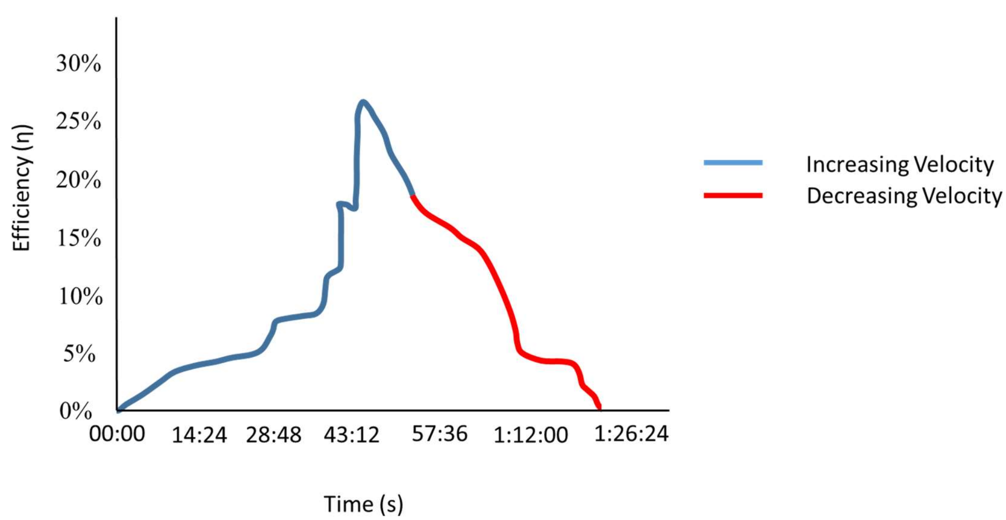


Figure 5-9: IPW2 Turbine efficiency

The graphs in Figure 5-10 present the turbine and alternator characteristics. This illustrates the system efficiency during the start-up with acceleration versus the reaction of the turbine with deceleration.

The fluid velocity determines the rotational velocity of the turbine that resulted in different power outputs of the turbine – at first it accelerated and after a while, a change in power characteristics was observed when it decelerated. These results are shown in Figure 5-10. The turbine pitch, diameter, and rotating velocity are all specific characteristics of the turbine runner influencing the turbine behaviour and power output that is illustrated in Figure 5-11. The alternator rotational speed is determined by the pulley diameter combination on the alternator and the turbine.

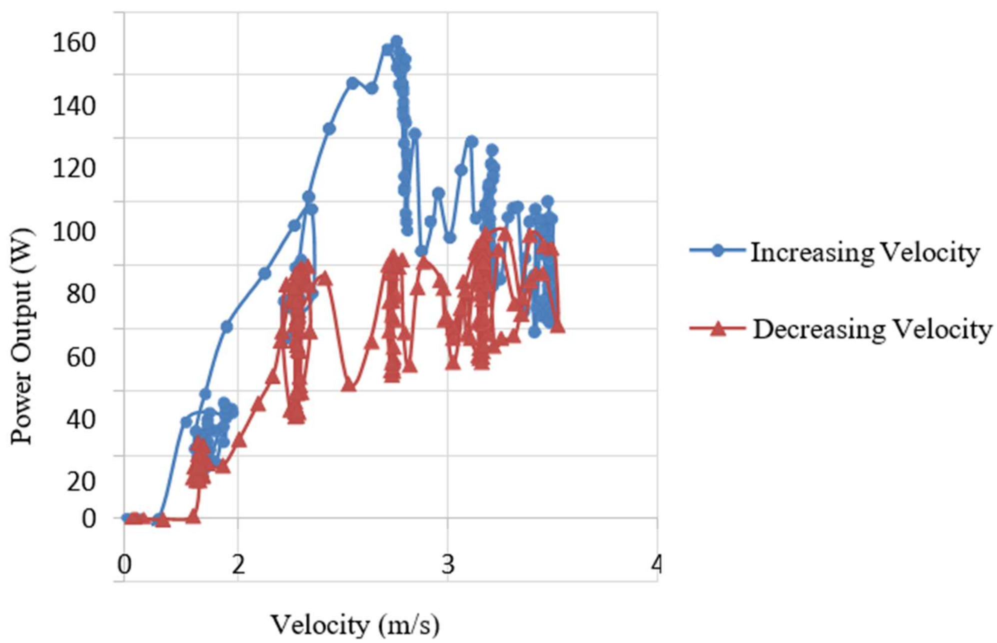


Figure 5-10: Relation between power output and fluid velocity

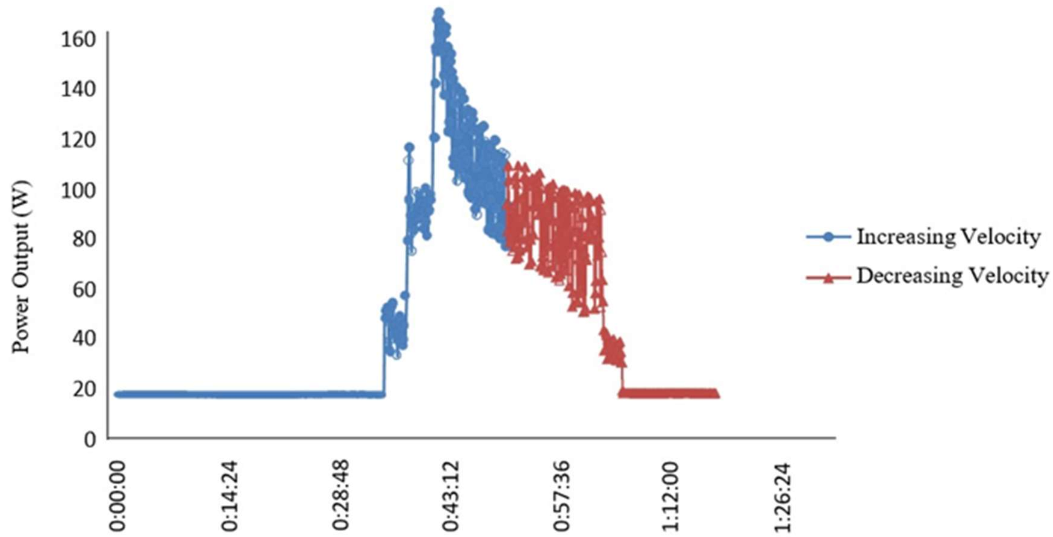


Figure 5-11: Power output in Watt over time

The turbine should produce the same power output behaviour during each test. This test was repeated a few times and the conclusion was that the turbine followed the same power and flow relation every time that it was excited. Figure 5-12 shows the power the turbine produced during the opening of the PRS system during a normal reservoir filling event.

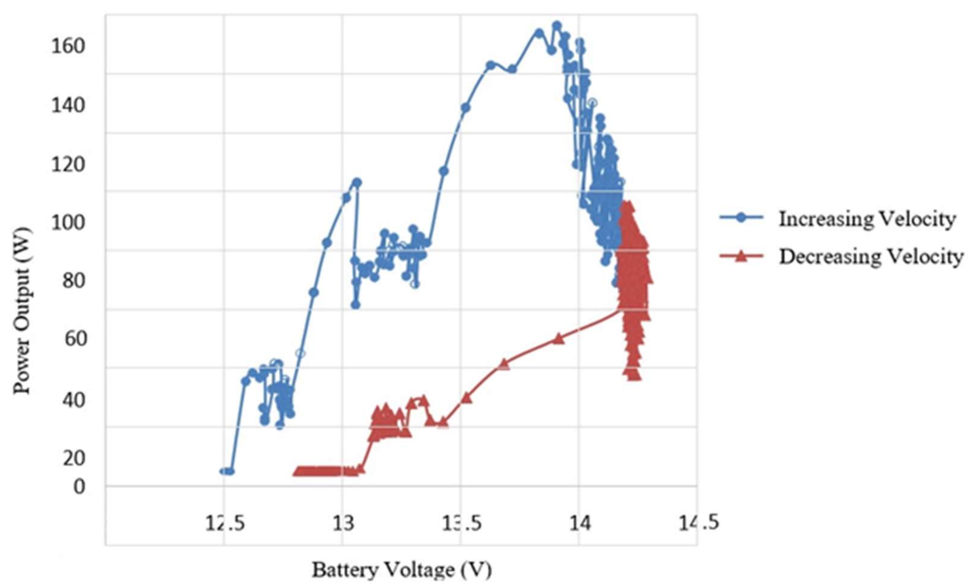


Figure 5-12: Relationship between power output and voltage (Davel, 2015)

Tests that were previously performed by Davel (2015), indicated the relationship between the power output and voltage generated (Figure 5-11) and corresponds with the data that were logged during this study. Figure 5-12 shows the repeated pattern that the turbine followed during testing and is indicative of the stability of the behaviour of the turbine. The objective of this study was to prove that the turbine will deliver reliable and sustainable power under the given flow and pressure conditions experienced in the chamber installation.

Maximum efficiency was reached at the flow at which the pressure difference was at a minimum, thus the lowest loss of pressure head measured before and after the installed turbine. The maximum efficiency of the turbine occurred at about 221 ℓ/s at 3,1 m/s with a pressure difference of 0,37 m (Figure 5-13).

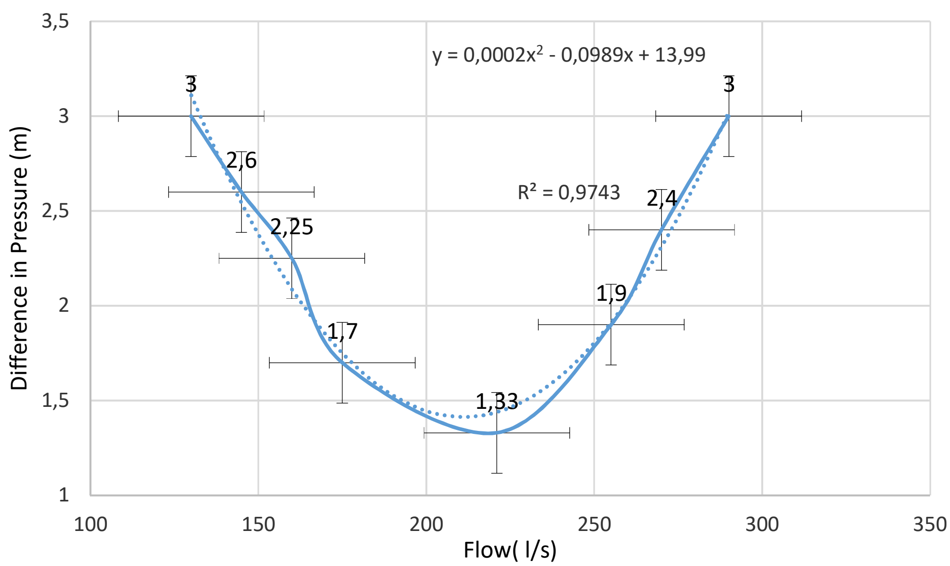


Figure 5-13: Pressure difference over the IPW2 as an indication of efficiency

Figure 5-14 illustrates the energy gradient that was discussed earlier in the document, but here the influence that the addition of the IPW had, is also indicated. The difference in pressure before and after the turbine installation reflects the energy that was dissipated by the inline turbine (Figure 5-14).

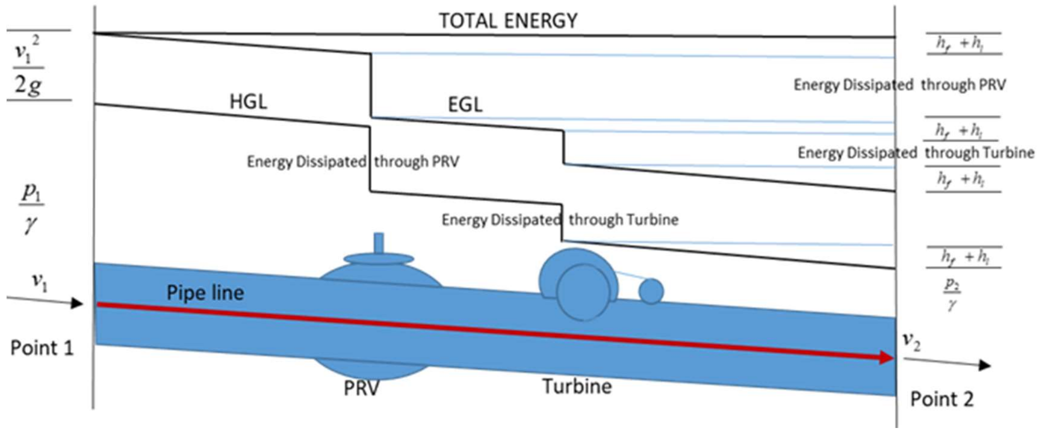


Figure 5-14: Hydraulic and energy gradient through the PRV and IPW in a closed conduit

6 RECENT RESEARCH AND DEVELOPMENT IN PICO CONDUIT HYDROPOWER DESIGN

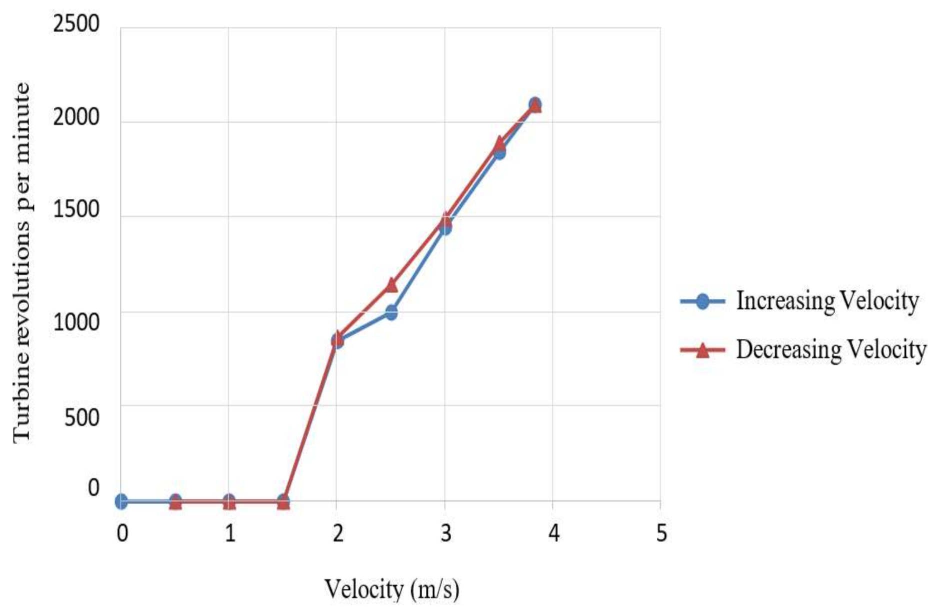
According to the results that were published in a recent article (Samora *et al*., 2016), the interest in micro-hydropower into existing infrastructure has increased, since this is a technology with low environmental impact and potential for energy recovery in different types of installations. This is in line with the research purpose of this project and the results of the laboratory tests that were performed by Samora *et al*. (2016) on their turbine have been comparable with the test results observed in this project, which was on a retrofitted field installation.

The authors performed an experimental characterisation of a five-blade tubular propeller turbine for inline pipe installation. The results of the IPW2 installation tested in this study were also comparable to theirs.

Furthermore, the hydro turbine referred to by Samora *et al*. (2016) was built and tested under laboratory conditions and the results were published in the form of various graphs. The results include graphs that show torque vs flow, head vs flow, efficiency vs flow, power vs flow and optimum efficiency. Some of their results are compared with those found in this study, below.

Figure 6-1 illustrates that both sets of tests results of the turbine rotation speed plotted against the flow velocity in the two studies, have identical graph shapes. The inside diameter of the conduits of both tests were the same, indicating that the flow velocities are comparable. The trend that can be seen is an increase from zero rotational speed of the turbine with a linear tendency. With excitation of the alternators, the gradient of the graphs changed, but remained linear after the turbines started to produce power. This was identical in both research studies.

(a)



(b)

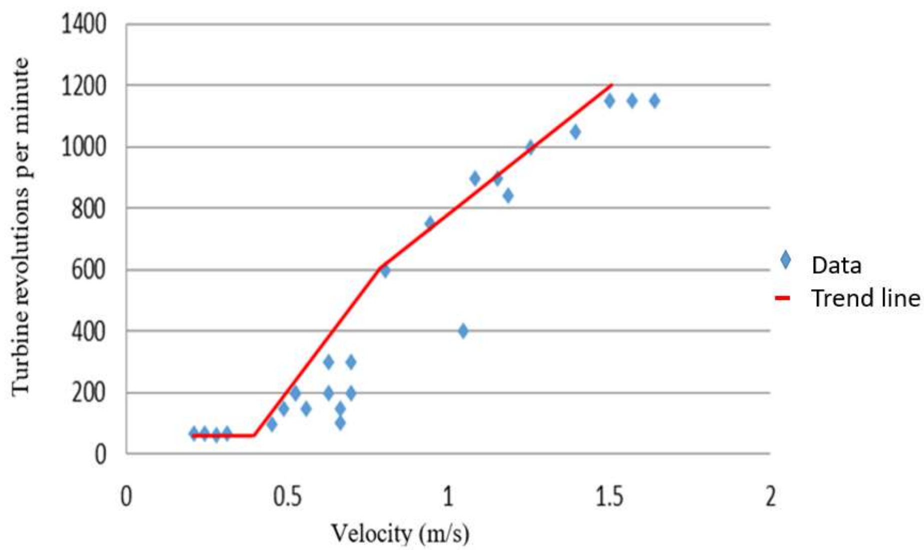
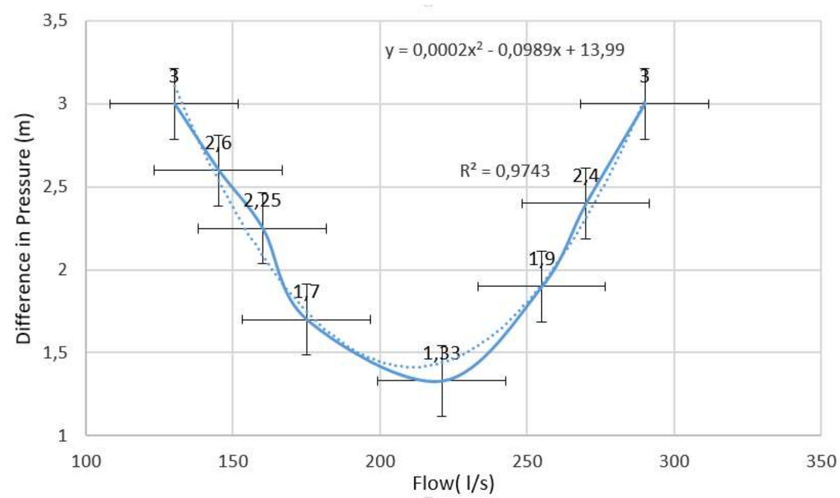


Figure 6-1: A comparison between turbine revolution and water velocity between (a) the IPW2 Turbine and (b) results from Samora *et al.* (2016)

Correlations of the efficiency of the turbines are given and compared in Figure 6-2. In Figure 6-2a, the efficiency was calculated as the point where the pressure difference before and after the turbine was plotted against the flow. The second graph (Figure 6-2b) is presented almost as a mirror image, to allow comparison of the graph trends of the two graphs. In the second instance, the efficiency was plotted against the flow, resulting in nearly the same trend of graph shape.

(a)



(b)

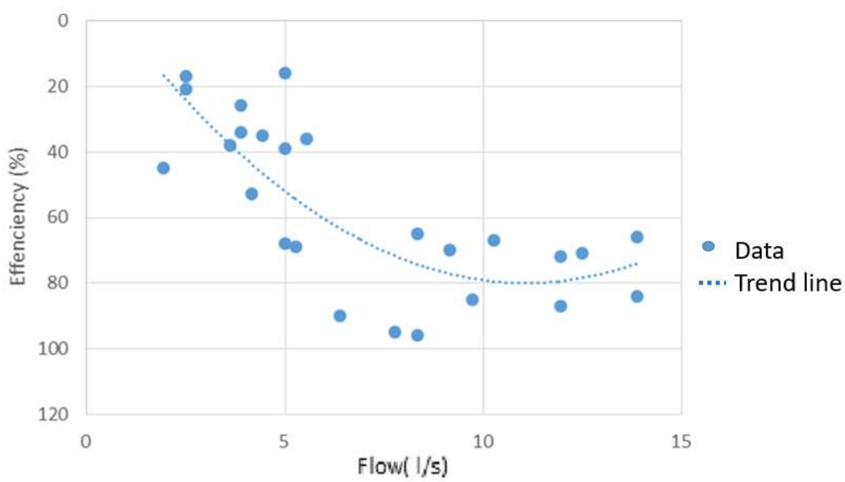


Figure 6-2: A comparison between the efficiency tendency of (a) the IPW2 turbine and (b) results from Samora *et al.* (2016)

In the last comparison between the two sets of results, the graphs of the power produced are plotted against the flow velocity and the flow (Figure 6-3). The first graph (Figure 6-3a) illustrates the power output against the increase, as well as the decrease of the turbine. According to Samora *et al*. (2016), power output only reflects the turbine relationship in the acceleration phase. From the graphs, it is clear that the trend line reflecting the results of the two turbines have nearly the same shape.

(a)

(b)

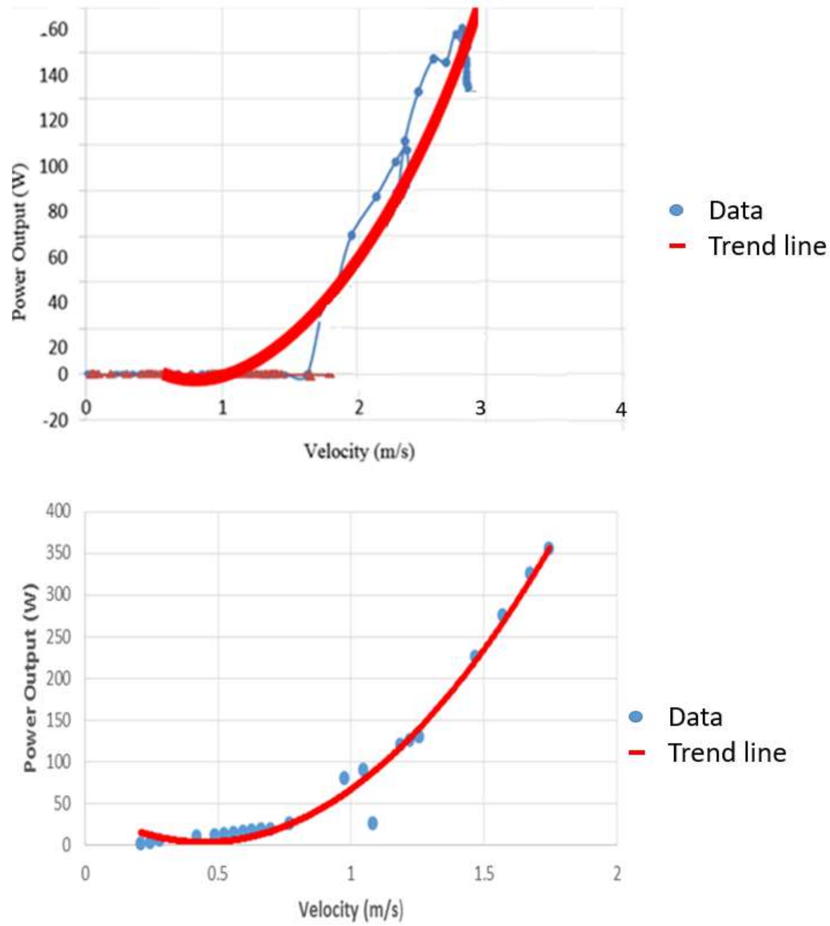


Figure 6-3: A comparison of power against velocity between (a) the IPW2 turbine and (b) results from Samora *et al.* (2016)

It can thus be concluded that the turbine that was developed in this study, although operational on a smaller scale, produced comparable results to those found by Samora *et al*. (2016). The results observed with the IPW2 turbine is even more significant, due to the fact that it was tested in the field, as opposed to laboratory testing performed by Samora *et al*. (2016). It could be suggested to test the IPW2 in the same laboratory conditions as the turbine tested by Samora *et al*. (2016), and compare the data again in a further study.

The reliability and durability of the IPW2 turbine will be discussed in the following chapter.

7 RELIABILITY AND DURABILITY OF THE TURBINE INSTALLATION

The short-term behaviour, or reliability, test was performed on the turbine installation in the chamber during 2015 and 2016. The turbine was retested until August 2017 to investigate the behaviour in terms of the long-term reliability, or durability, of the turbine. The repeatability of the results was also investigated to establish the behaviour of the turbine in a permanent installation.

7.1 Turbine data recorded

To illustrate the long-term behaviour, the data of turbine installation was logged in detail for a month. A total of nearly 160 000 readings of all the monitoring points were logged and analysed. The alternator voltage and amperes delivered to the battery were selected to reflect the alternator's long-term behaviour.

The logging system was set up to take a reading of all the monitoring points of the turbine installation every 3 seconds, as described in section 3.6. From Figure 7-1 it can be observed that the upstream pressure before the PRV varied between 222 and 350 kPa, but it also indicates a pressure spike to 600 kPa. This was when the PRV was closed and a maximum pressure of 600 kPa was measured.

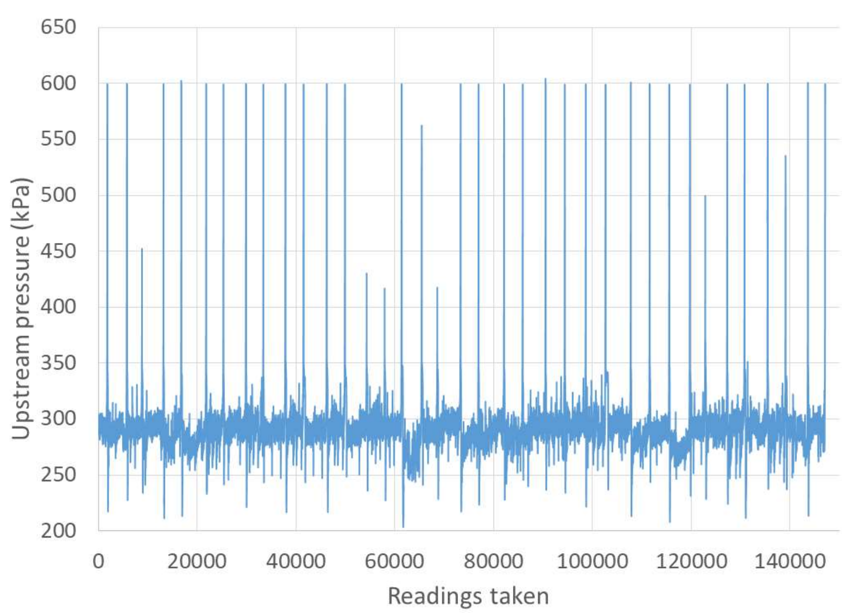


Figure 7-1: Pressure upstream of the PRV

The ampere readings given in Figure 7-2 indicate that the alternator produced consistent power of about 10 to 14 A with the start-up, which lowered to just above 1 A. It can also be seen that the power used during the turbine off-periods, was very small during the test period.

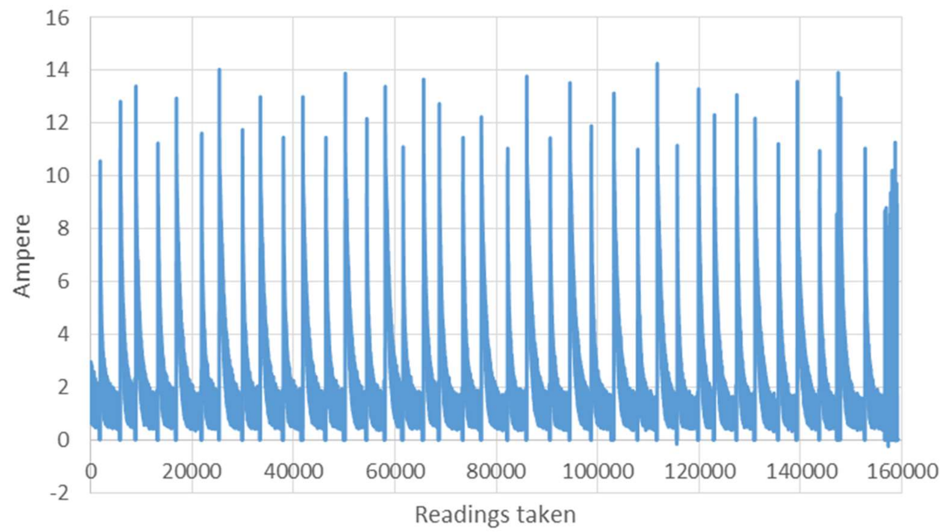


Figure 7-2: Battery amperes measured

Displayed below in Figure 7-3 is an enlarged view of the power generated during the start-up of the turbine.

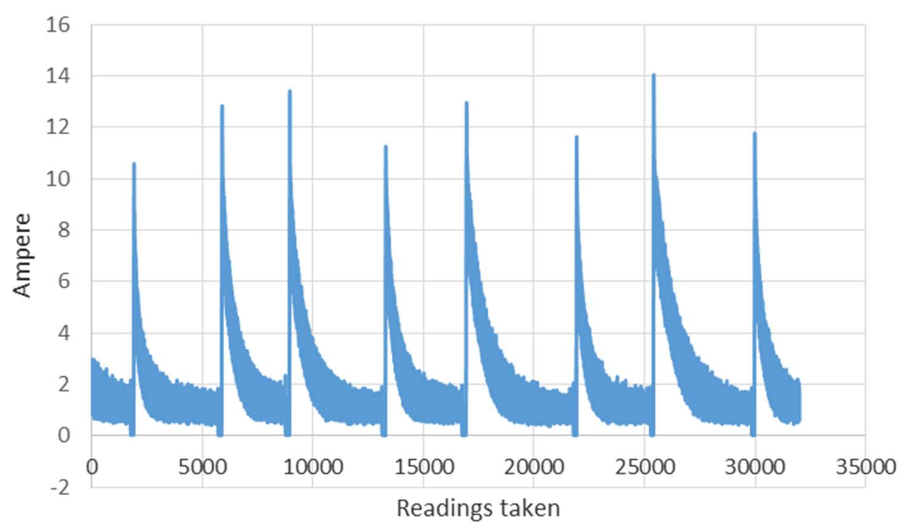


Figure 7-3: Battery amperes measure – enlarged view

The pink line in Figure 7-4 shows that the PRV opens at about 80 kPa and closes at about 120 kPa. These are the limits that were set on the altitude sensor controlling the PRV to fill the reservoir. The blue line indicates the upstream pressure. It is also clear that the closing time of the PRV is too short and that it creates a spike in the pressure from about 300 to 600 kPa.

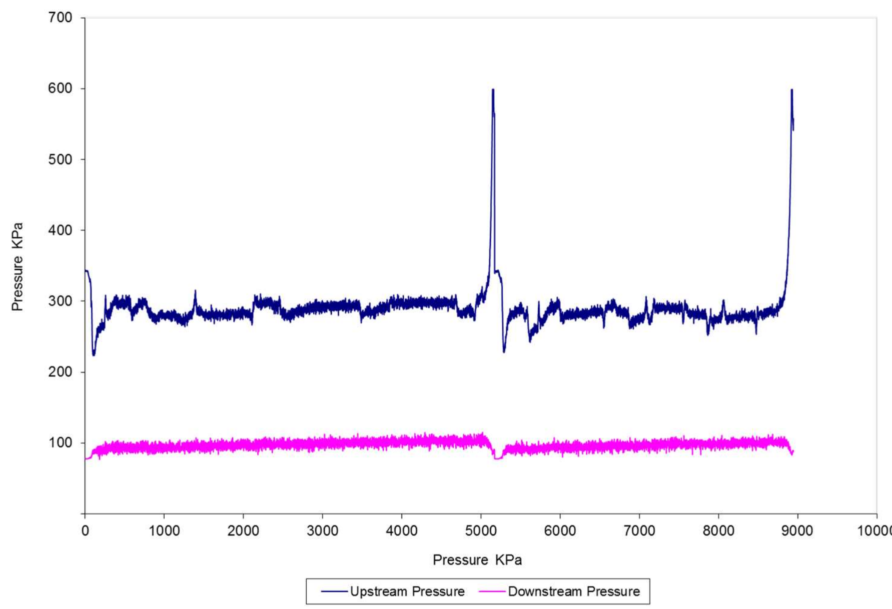


Figure 7-4: Up- and downstream pressure of the PRV– enlarged view

Furthermore, it should be noted that a direct decrease in voltage occurred at the moment when the PRV closed and this also coincided with an abrupt termination of water flow. This abrupt termination of water flow can explain the water pressure spike illustrated in Figure 7-4. As a result, the water pipeline and installation possibly experienced the effects of water hammer each time the PRV closed. This could damage the installation and should be improved.

One definition of reliability is "the measure of unanticipated interruptions during customer use" (Bajaria, 2000). Unexpected failures happen as a result of unanticipated interruptions. One of the objectives of the reliability test was to maximise the opportunities for observing these unexpected failures. These failures also highlight the shortcomings of the product and can be seen as an opportunity to improve the product.

According to Bajaria (2000):

> The fewer the opportunities we have to observe unpredictable failures, the greater the chance that we are not testing to measure reliability. A test may appear to be a reliability test and actually be a durability type test when opportunities for discovering unscheduled interruptions are minimized unintentionally.

7.2 Turbine reliability and sustainability

Figure 7-5 illustrates the period over which this study was conducted and indicates the total turbine down time during this period. The turbine working hours are also presented in Table 7-1. It is important to note that during the course of the study period, the down time that was experienced, decreased. This is an indication of the increase in the reliability of the unit.

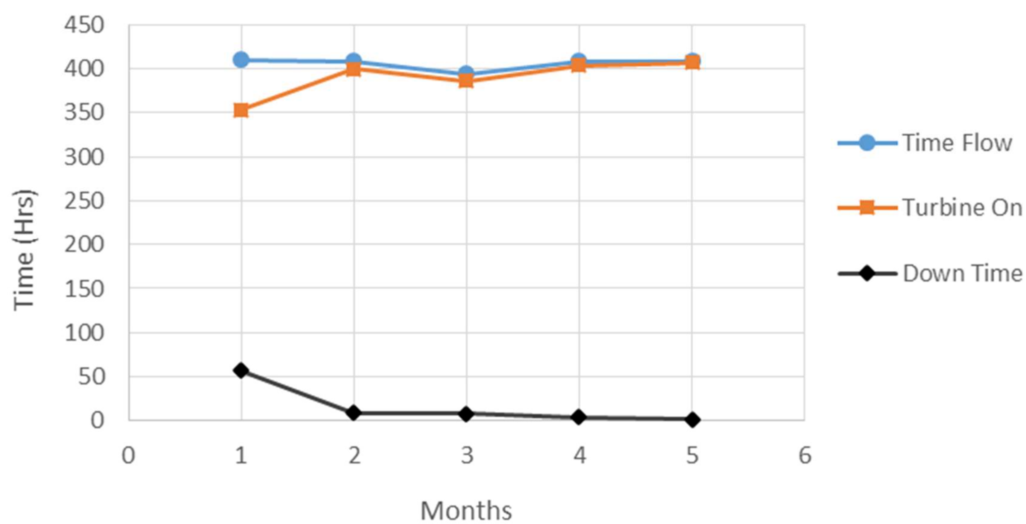


Figure 7-5: Down time of the IPW2 turbine

The table below indicates the amount and types of failures experienced during the test period.

Table 7-1: Functional and down time hours of the IPW2 turbine

Failures experienced	Time flow (hrs)	Turbine on (hrs)	Down time (hrs)	Reason for down time
1	410,0	353,1	56,9	Turbine shaft grips crew failure. Turbine shaft mechanical water seal failure.
2	408,7	399,6	9,1	Turbine shaft grips crew failure.
3	394,5	386,4	8,1	Turbine shaft grips crew failure.
4	408,2	403,8	4,4	Turbine shaft mechanical water seal failure.
5	408,5	406,8	1,7	Object damaged the turbine wheel.
TOTAL	**2029,9**	**1949,7**	**80,2**	

These results contribute to the objective of this study, namely to produce sustainable and reliable power with these turbine units.

The frequency of down time experienced with the turbine during the testing period is presented in a bar chart in Figure 7-6. It is evident from the bar chart that the biggest concentration of down time was experienced during the initial installation. This included the commissioning phase followed by the installation and testing phases.

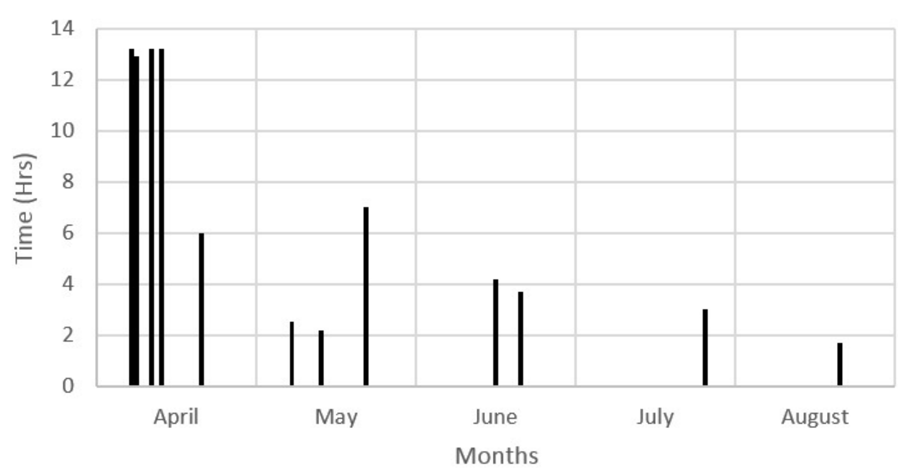


Figure 7-6: Distribution of down time during the test period

7.3 Durability of the installation

The repeatability of the results and the reaction of the turbine and alternator when the PRV was opened, are presented in Figure 7-1 to Figure 7-3. The voltage of the battery repeatedly increased from about 12,2 to 14,5 V. This repeated behaviour can be seen on the graphs. It is thus evident that the turbine reacted basically identically each time that the PRV was opened and water flow increased in the pipe system in which the turbine was installed in. According to the description of reliability and durability, both sufficient reliability and durability of the turbine are thus evident from the results.

7.4 Turbine reliability test

Table 7-2 below was used to evaluate the testing circumstances of the turbine that was installed in the PRV chamber.

Table 7-2: Reliability testing practices (adapted from Bajaria, 2000)

Reliability test description	Actual industry practice	Best practice	Turbine installation – tested and evaluated*
The test should reflect a true customer. Actual likely users in an actual environment should be testing products.	In most instances, industry uses expert or well-trained employees to simulate customers' feedback. Well-trained employees are not a true reflection of potential customers. Employees have vested interest and therefore, one cannot consider the data as 100% valid.	Use actual users and actual environments for tests whenever possible.	Turbine installation was tested in an actual environment. Data were logged and analysed.
If testing must be done in a laboratory, it should reflect a true user environment.	Many tests are conducted in a laboratory under a simulated, single environment. The outcome of such tests most likely represents durability rather than reliability.	If only laboratory tests are possible, measure customer environments and design tests accordingly, so that all environments and the operating profile are included simultaneously.	The turbine was installed in a true user environment.

Reliability test description	Actual industry practice	Best practice	Turbine installation – tested and evaluated*
The test should reflect a sample coming from a true production environment.	In many instances, prototype parts are used for the test. Prototype parts may exhibit the validity of physical principles but may not necessarily reflect reliability.	Define reliability at two levels: 1) Hardware level D (design level) and 2) Hardware level P (production level). Design engineering is considered complete only when both the D level and P level are proven.	Turbine design was completed and a few units were built to test. The design level (D) was successful and the production level (P) was executed for a few units.
Random samples should be tested.	Industry practice is to use pre-qualified test samples. That means that the test samples are inspected and assured to be within specifications before they are subjected to testing. This, in turn, reduces the chances of observing premature failures. Pre-qualified samples most likely measure durability, not reliability.	Use random samples. Or, if pre-qualified samples have to be used, make the pre-qualification scheme a part of the production control plan.	These tests can be performed when more units are produced.
The test should be a validation test, not just a verification test.	Most tests are designed to verify design requirements. These requirements are supposedly a translation of customer requirements. Such tests can be labelled as verification tests. The outcome of such tests most likely measures durability rather than reliability. In addition, the tests do not reflect the fact that some customer environments may be inadequately translated or omitted altogether.	Perform verification tests on a smaller sample. Perform validation tests on a larger sample.	These tests can be performed when more units are produced.

*The test turbine installation was evaluated against the reliability testing practices as described by Bajaria (2000).

7.5 Test results

The latest test results on the turbine installation demonstrated the reliability and durability of the turbine design. The reliability characteristics of the turbine design were proven with the first tests conducted during 2015 and 2016. The installation was still operational at the time when the report was completed in November 2020.

The difference between reliability testing and durability testing is key in reducing design or development expenses (Bajaria, 2000). The diagram below in Figure 7-7 illustrates the differences between durability and reliability.

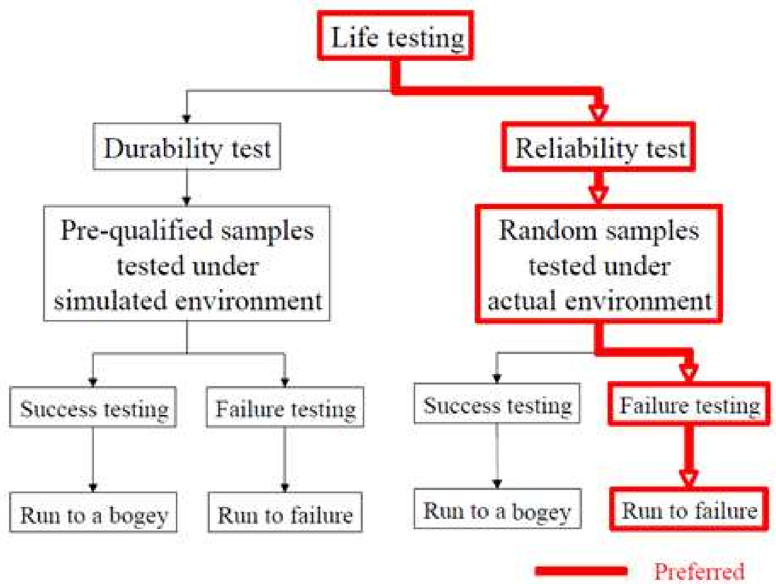


Figure 7-7: Differences between reliability testing and durability testing (Bajaria, 2000)

7.6 Commercial IPW2 unit for Klipgat Hospital Reservoir

Recently, the CoT Municipality started the process to install a SCADA system at the Klipgat Hospital Reservoir complex. The aim of this installation is to perform remote monitoring and to control drinking water flow rates in the main supply line. The IPW2 unit is needed to supply the electricity demand on this site. This is a typical example to illustrate the application of the Types 2 and 3 installations to power the required instrumentation at PRSs. According to available information, although the site is located near existing power lines, no connection is available on the site. The photo below (Figure 7-8) shows the IPW2 unit that is in the process to be manufactured for the Klipgat reservoir. The characteristics of the IPW2 unit that was ordered for the reservoir site are listed in Table 7-3.

Figure 7-8: IPW2 unit for Klipgat Hospital Reservoir

Table 7-3: Klipgat Hospital Reservoir pico hydropower unit specifications

Klipgat Hospital Reservoir site – 0,3 kW IPW2 turbine	
Total power rating (expected electrical output)	0,3 kW
Design flow	0,02m³/s
Design head (differential pressure drop across turbine)	1,05 m
Turbine type	Inline pressure wheel – model IPW2
Generator (alternator)	
Nominal max power in continuous operation	0,5 kW
Nominal voltage	13,8 V DC
Generator connection	Single phase
Frequency	50 Hz
Nominal current	25 A
Nominal speed	1500 rpm
Bearings	Lubed-for-life ball bearings
Battery bank	65 Ah

The cost estimate for the order that was placed for the IPW2 to be installed at the Klipgat reservoir site in CoT, is provided in Table 7-4. The potential generating capacity revenue for this installation is 0,3 kW × 24 hours × 365 days = 2 628 kWh × R 1,01/kWh = R 2 654 per annum.

Table 7-4: Typical cost for a commercial unit

Klipgat Hospital Reservoir site – 0,3 kW IPW2 Turbine			
Cost for supply and installation	**Cost ID**	**Comments**	**Cost**
Civil works			
Preparation on site and support block	C1		R 3 000
Pipework with turbine access slot (400 mm Ø, 1 000 mm long)	C2		R 1 2000
Electro-mechanical Equipment			
Turbine (1 x IPW2)	E1		R 48 000
Generator (1 x alternator)	E2	Included in E1	R 0
Control unit	E3		R 17 000
Battery bank (65 Ah)	E4		R 4 300
Implementation cost			
Commissioning, erecting, and project management	I1	1 week	R 12 000
Training and manuals	I2		R 2 000
Integration of system components (telemetry etc.)	I3		R 6 000
Total cost (excluding VAT)			**R 104 300**
VAT (15%)			**R 15 645**
Total cost (including VAT)			**R 119 945**

From these values above, it is evident that the benefit of such a turbine does not lie in the amount of generated power, but in the subsequent benefits of having a localised power source. Final conclusions and recommendations for future studies will be provided in the next chapter.

8 CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

This project reflected the test results of a pico closed conduit inline hydropower turbine. From the analyses of the data, it is evident that the turbine is sustainable and reliable for the purpose it was designed for and that such a turbine is of subsequent benefit to the local municipality.

The practicality and feasibility of modifying a spool piece and to retrofit an IPW turbine into the pipe section were proven to be successful. This installation was performed on a bypass feeder line and not on the main supply line. This implies that the retrofitted unit did not jeopardise or risk the water supply to the reservoirs, which could have caused water interruptions to the reservoir. It remains important to note that the power generation from the water distribution system should preferably be done on a secondary supply line and, if possible, in the water distribution system and not in the main water supply line. This is to limit the risk of possible water interruptions to the water distribution zones as a result of hydropower functioning.

Data were collected during the testing phase of the turbine over a period of about three months. These data were analysed for turbine efficiency, energy produced, and sustainability. Statistical analyses showed that the hydro turbine will be reliable and that the generated energy will be sustainable. The output of the 130 Watt that was generated had a low efficiency. The efficiency is, however, less important, as the demand for required energy was less than the generated supply and the pressure decrease across the turbine (Δh = 0,37 m) was acceptable. Pressure decreases across the turbine (ranging from 0,2–0,4 m) indicate that this turbine could easily be installed anywhere along the pipeline.

The research results that were published by Samora *et al*. (2016), not only reflect a large degree of similarity in the test result tendencies between the two studies, but it also confirms the need for this type of research and development. The fact that the field installations covered in this research study proved to be sufficiently reliable and efficient, already motivates further research to increase efficiency. The article by

Samora *et al*. (2016), documenting a laboratory experiment, reports much higher efficiency. This is an indication that the data collected during this research project, and the conclusions that were drawn, reflects a more conservative statement of the turbine behaviour.

Hydropower represents a nexus of water and energy in municipalities and water utilities. There are several locations in SA and worldwide where a feasible pico conduit hydropower scheme could be implemented. A technically feasible pico closed conduit hydropower turbine could assist municipalities in reducing high operational costs. These turbines provide a sustainable and reliable on-site power solution while having a positive environmental impact. A number of water utilities have started to take the initiative of developing this type of hydropower and it is believed that there is significant potential for this in SA.

The specific benefits for developing conduit hydropower in CoT's water distribution network include:

- Conduit hydropower uses the available water distribution infrastructure, and as long as there is a demand for water, hydroelectric energy can be generated.
- Conduit hydropower "piggy-backs" on existing water infrastructure, resulting in a minimal environmental impact.
- The feasibility studies indicate short payback periods.

It is believed that conduit hydropower is the "low-hanging fruit" in terms of viable renewable energy that could be exploited. CoT is in the fortunate situation that excess energy is currently being dissipated and this could be utilised to generate clean sustainable energy. The municipality has taken a further bold step with a Council resolution that no new reservoirs or PRSs can be constructed, without investigating the potential opportunity to use the site for the generation of hydroelectric energy.

The series of tests performed on the turbine during the testing period proved the reliability of the turbine. The fact that the turbine was still functioning in November 2020 further proved the reliability and durability of the turbine design.

8.2 Recommendations

The following recommendations are proposed for future research:

- Design and development costs can be reduced by understanding the differences between reliability and durability.
- The research conducted in this study should be continued and the turbines should be tested under laboratory conditions.
- The effect of different blade designs should be investigated further to determine the effect and influence on the efficiency of the turbine.
- The effect of the installation of deflector plates in the spool piece to guide the water flow onto the runner blades should be modelled under laboratory conditions.

Computational fluid dynamics (CFD) modelling should be performed on the turbine.

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APPENDIX A

First Commercial Inline Pressure Wheel 2.0 (IPW2)

This turbine is currently in the process of being installed at Klipgat Reservoir (Pretoria, South Africa).

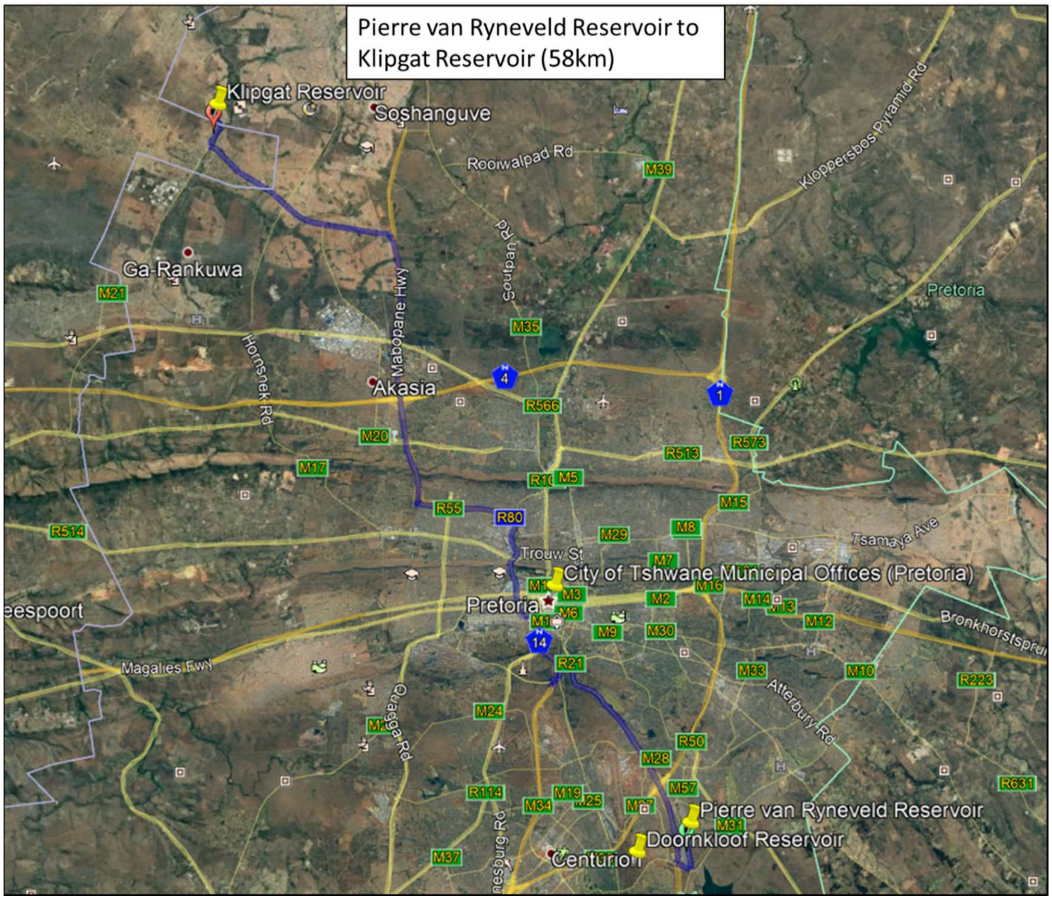


Figure A-1: Photograph: Location of the Klipgat Reservoir in the City of Tshwane

A1 Klipgat Hospital Reservoir pico hydropower unit

A1.1 Configuration and specifications

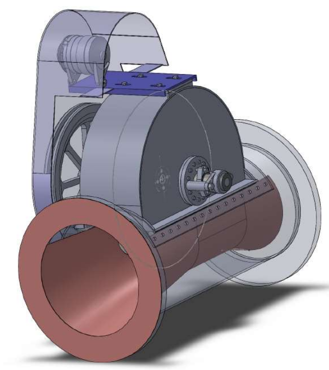
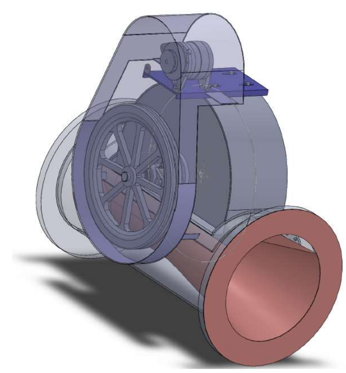
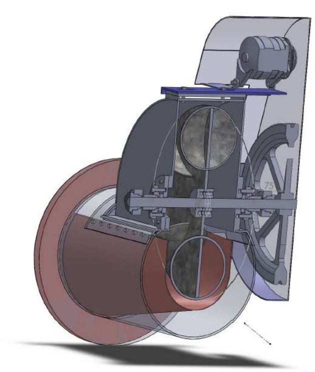
- Power rating 0.5 kW
- Generator Generator (Alternator)
- Driven by Pulley system and V-belt driven
- Pipe Diameter 400 mm Ø
- Turbine Diameter 400 mm Ø
- Peak flow 256.9 ℓ/s

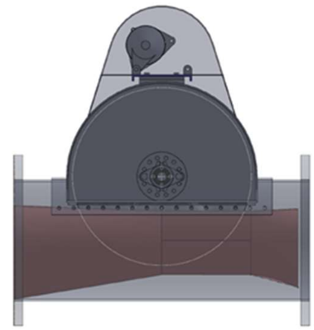
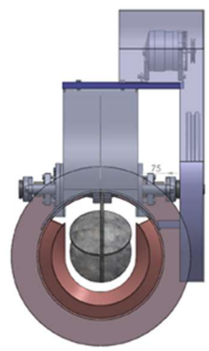
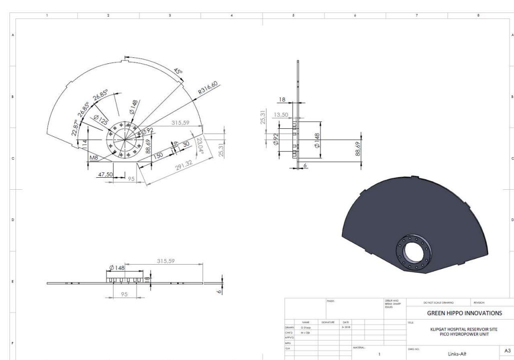
- Static pressure 165.1 m
- Pressure at peak flow 29.8 m
- Velocity at peak flow 2.08 m/s
- Nominal voltage 13.8 V DC
- Nominal current 25 A
- Nominal speed 1500 rpm
- Bearings Lubed-for-life ball bearings
- Installation will be between PRV and reservoir
- There is a strainer upstream of the PRV for protection of the equipment.
- Nominal max power in continuous operation
- Generator connection

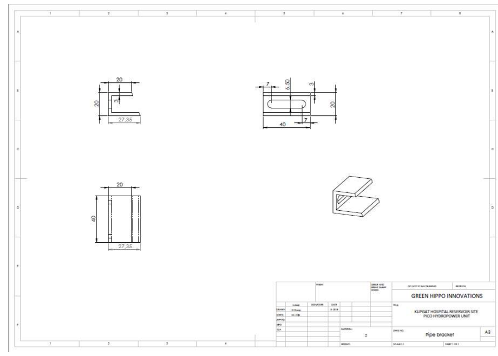
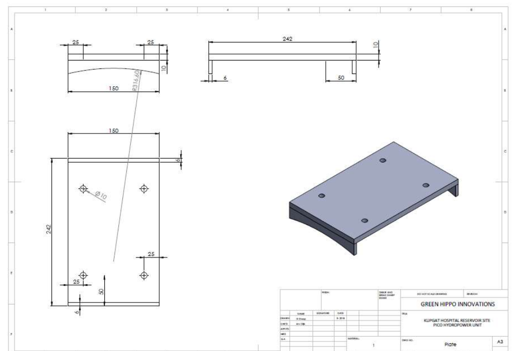
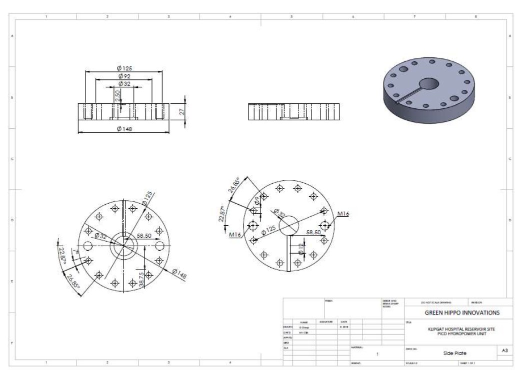
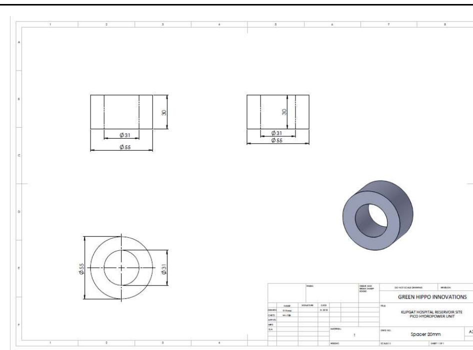
A1.2 Description and design of the IPW2

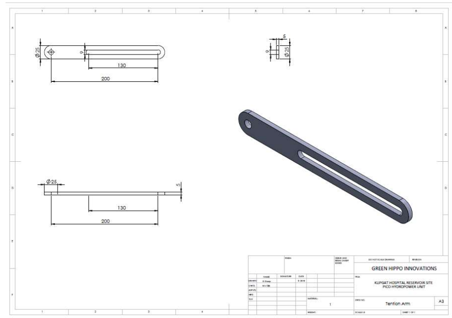
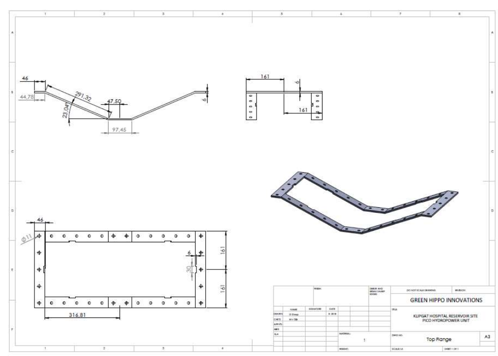
The turbine is an IPW with an expected power output of 300 W and a pressure differential over the turbine of about 1.05 m. The spool piece pipe's diameter inside the pressure wheel housing was narrowed, in order to increase the flow velocity at the runner contact zone and thereby increasing the power output of the turbine. The turbine runner is similar to the runner that was installed at Pierre van Ryneveld, as discussed in section 3.6.4 in the main report with upgrades to the buckets, position of the alternator, dimensions, safety cover, axel size, and mechanical water seal composition. Component descriptions and images of the respective components of the IPW2 are provided in Table A1 below.

Table A1: Descriptions and images of the IPW2

Description	Image/references
A 3D view of the turbine unit showing the configuration layout. The alternator is installed on top of the runner casing. An optional reducer spool piece insert is inserted to reduce the area and subsequently increase the velocity on the runner.	 Three-dimensional image – rear view
A 3D view of the safety guard covering the moving parts, V-belt and pulley system, as required by safety regulations.	 Three-dimensional image –front view
A 3D cross-section focussing on the runner shaft compositing.	 Three-dimensional image – cross-section

Description	Image/references
The transparent side view illustrates the inserted flow guide in the spool piece with the position of the runner housing.	 Three-dimensional image – side view
This transparent rear view illustrates the runner blade's position inside the inserted flow guide in the turbine configuration.	 Three-dimensional image – rear view
The image illustrates the detail design drawing for the manufacturing process of the side panel with the bearing mounting adapter.	 Detail design drawing – wheel housing side panel

Description	Image/references
This detail design drawing shows that special attention was given to the smallest details in the design process.	 Detail design drawing – bracket
The alternator mounting plate was designed with a universal application in mind to accommodate various type of alternators that are available off-the-shelf.	 Detail design drawing – alternator mounting plate
The bearing spacer mounting plate shown in the detail design drawing strengthen the thinner runner housing at the position where the shaft and water seal assembly meet.	 Detail design drawing – bearing spacer mounting
The mechanical seal shaft spacer illustrated in the drawing is needed to meet the design and application specifications of the seals used in the turbine.	 Detail design drawing – mechanical seal shaft spacer

Description	Image/references
An adjustable alternator V-belt tensioner bracket was included in the alternator mountings list to accommodate re-tensioning of the V-belt during maintenance of the unit.	 Detail design drawing – alternator tensioner bracket
Special care was given to the runner housing flange design to ensure alignment of the mounting holes of the runner cover and base flanges to produce a watertight unit.	 Detail design drawing – runner housing flange
This photo illustrates the runner, runner shaft, and bearing assembly – ready for the assembling process.	 Photograph – runner on shaft with bearing mounting
This photo in illustrates the completed product of the runner housing with the alternator mounting plane after the painting process.	 Photograph – runner housing assembly

Description	Image/references
The tolerances of the runner wheel inside the runner wheel housing was verified before the runner was painted.	 Photograph – runner with housing assembly
This figure demonstrates the modifications made to a spool piece to accommodate the IPW2 turbine. It was also fitted with two pressure test points to fit pressure sensors to measure the pressure difference over the turbine.	 Photograph – IPW2 spool piece and mounting flanges
The driving pulley used to rotate the alternator is depicted here. The pulley is an off-the-shelf product ordered according to the rotating speed required to generate power from the alternator and turbine configuration.	 Photograph – driving pulley with V-belt cover
The turbine spool piece insert was designed in such a manner that the manufacturing and installation of the insertion processes are simplistic of nature.	 Photograph – turbine spool piece insert

Description	Image/references
This illustration of the runner wheel assembling and spool piece turbine housing is evident of accurate and precise manufacturing processes of the different components of the turbine unit. The unit was also painted with an epoxy type paint that proves to be durable and long-lasting.	 Photograph – IPW2 complete housing assembly
The safety guard was attached to cover the moving parts, the V-belt and the pulley system, after being painted.	 Photograph – V-belt cover
The interior layout of the chamber and the pipework that was used during the construction phase on site.	 Photograph – PRV chamber
The modified spool piece or housing and base assembly in position. The turbine is to be installed once the construction of the reservoir and chamber is completed.	 Photograph – IPW2 housing base Assembly in installed position