

**Integrated approach to reconfigure and optimise
the control of a pump in reverse operation**

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ABSTRACT

Title: Integrated approach to reconfigure and optimise the control of a pump in reverse operation

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Energy is a major expense for industrial consumers such as direct customers of Eskom (South Africa's main energy supplier). The energy tariff has increased drastically over the last few decades despite South Africa being a coal-rich nation. A series of energy reduction methods have also been implemented, namely 'load shedding' for private consumers and 'load-curtailement' for large industries. Furthermore, Eskom has had a resistance towards renewable energy and self-generation. Recently, the government has gradually reduced the restriction of self-generation and renewable energy sources in the private sector.

Renewable energy is a growing commodity and is underexploited, especially in South Africa. An underexplored, yet powerful and inexpensive renewable energy source is hydropower, especially on large and integrated systems such as deep-level gold mines. Currently, some forms of hydropower systems exist in South African deep-level gold mines, but these systems are often implemented incorrectly, resulting in inefficient systems plagued with breakdowns. Various forms of hydropower have been implemented in the attempt to reduce energy costs. A reliable method is needed for the consistent and successful implementation of these systems, given the various challenges present in the deep-level mining industry.

This study focused on developing a solution method (in a corporate mining environment) to implement a pump as turbine (PAT) with the aid of a thermal-hydraulic simulation suite on an integrated system, following a preset group of key performance indicators (KPIs). A PAT is also known as a pump in reverse operation. With the thermal-hydraulic simulation suite, the

best efficiency point (BEP) of the PAT can be established and the PAT can be controlled accordingly whilst predicting its performance.

In this study, a PAT was identified and reclaimed from a sister mine (Mine Y) and was then implemented on Mine X with the aid of the various integrated models. Following the developed solution method, which proved successful within the pre-feasibility and feasibility studies, various simulation models were simulated by means of computational fluid dynamics (CFD) analysis. The feasibility studies yielded favourable results, where approximately 24 234 kWh was possibly recovered whilst maintaining KPI standards. This equates to approximately R10.5 million p.a. based on the non-local authority 2022/2023 Mega Flex tariff, resulting in a 6.2-month payback period (based on a reclamation capital expenditure (CAPEX) scenario).

After implementation, the PAT's actual performance was analysed and compared with the simulation results. A significantly low simulation error was observed, namely a 4.54% difference between the actual and simulation-generated energy results. This low difference validates the study as well as the developed solution method, proving its effectiveness.

During the actual implementation of the project (after completing the feasibility studies), an additional tariff increase was announced to take effect as of the 1st of April 2023 and therefore should be considered for generation capacity in terms of currency. Approximately 18.65% increase was implemented as from the 1st of April 2023 and adjusted the generated capacity to R 12.45 mil. p.a. Capital expenditure of R 5.4 million is required to realise the project, which will incur a payback of approximately 5.2 months based on the latest tariff increase.

PUBLICATION

This thesis presents work completed and presented in the conference proceedings mentioned below and is a continuation of the work.

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NOMENCLATURE

LIST OF SYMBOLS

Symbol	Description	Unit of measure
AACF	Average annual cash flow	(R)
COI	Cost of investment	(R)
η_p	Pump efficiency	%
η_t	Turbine efficiency	%
g	Gravitational constant	m/s^2
H_n	Net head	m
PF	Power factor	-
P_{Gen}	Power generated	kW
P_p	Payback period	Months
P_w	Water pressure	kPa
ρ	Water density	kg/m^3
Q	Volumetric flow rate of water	m^3/s

ABBREVIATIONS

Abbreviation	Description
AGV	Adjustable guide vane
ANN	Artificial Neural Network
BAU	Business-as-usual
BEP	Best Efficiency Point
BOM	Bill of material
BOQ	Bill of quantity
CFD	Computational fluid dynamics
DES	Discrete-event simulation
FED	Flow energy dissipation
HPRT	Hydraulic Power Recovery Turbine
KPI	Key performance indicator
Mil.	Million

NERSA	National Energy Regulator of South Africa
P.a.	Per annum
PAT	Pump as turbine
PDS	Product design specifications
PDT	Positive displacement hydraulic turbine
PRV	Pressure Reducing Valve
PTB	Process Toolbox
RPM	Revolutions per minute
REMS	Realtime Energy Management System
SCADA	Supervisory control and data acquisition system
SEIG	Self-Excited Induced Generator
SOW	Scope of work
3D	Three-Dimensional
TFL	Tip Leakage Flow
WDN	Water Demand Network
WSS	Water supply system

GLOSSARY

CAPEX	Capital expenditure - Funds required for project implementation
Calibration	A process used to configure a simulation model
Corporate environment	An environment involving a business or operation with regard to approval and capital, specifically related to mining
Digital twin	A realistic digital representation of a physical system developed to perform simulations and test different theories
Diversion	A flowing water source is diverted to a turbine
Hard ice	Solid ice pieces are supplied to an ice dam for cooling and refrigeration purposes
Hydropower system	A hydropower system is a system that is used to generate power with the aid of water as the medium
Impoundment	A dam is used to store water and release it to a turbine for power generation
Impulse turbine	An impulse force is used to create turbine movement

Integrated simulation model	A complex and interconnected simulation model with various systems modelled simultaneously
Load-curtailment	Percentage power load reduction for an industry
Load shedding	Reduction of power consumption across the South African energy grid
Payback period	The period required to achieve a return on investment
Pump in reverse operation	Pump operating as a turbine to generate power
Pumped storage	Water storage at different elevations is used for power generation
Reaction turbine	A turbine that requires water flow and pressure to generate rotation
Soft ice	Ice slurry or slush supplied to an ice dam for cooling and refrigeration purposes
Thermal-hydraulic simulation	A simulation suite or model that analyses the hydraulic flow in thermal fluids
U-Tube system	A system used in mining to supply and return chilled water
Verification	A process used to ensure the developed model accurately represents and follows the model objectives
Validation	A process used to ensure the developed model is realistically correct

1

CHAPTER 1

INTRODUCTION

1. INTRODUCTION TO CENTRIFUGAL PUMPS IN REVERSE OPERATION

1.1. Background

South Africa's energy system has been exceptionally dependent on mineral resources which have also contributed significantly to the country's economic development [1]. South Africa is a coal-abundant country due to its rich and bountiful deposits, which allow for inexpensive electricity generation [1]. Despite this, there is an evident absence in the generation infrastructure to ensure consumers have electricity [1]. As a result of the infrastructure inefficiency, South Africa has been experiencing load shedding. From the beginning of 2023 to date (9th February 2023), South Africa has experienced forty days of load shedding and a state of constant load shedding since September 2022¹.

The South African energy system is extensively carbon-intensive and has been overwhelmed by unreliable power generation as well as theft and end users' non-remittance [2]. To further complicate the situation, Eskom has a hesitancy towards signing power agreements with renewable energy generators, thereby maintaining the monopoly in the sector [2]. Figure 1 demonstrates the comparison between the main energy sources of South Africa.

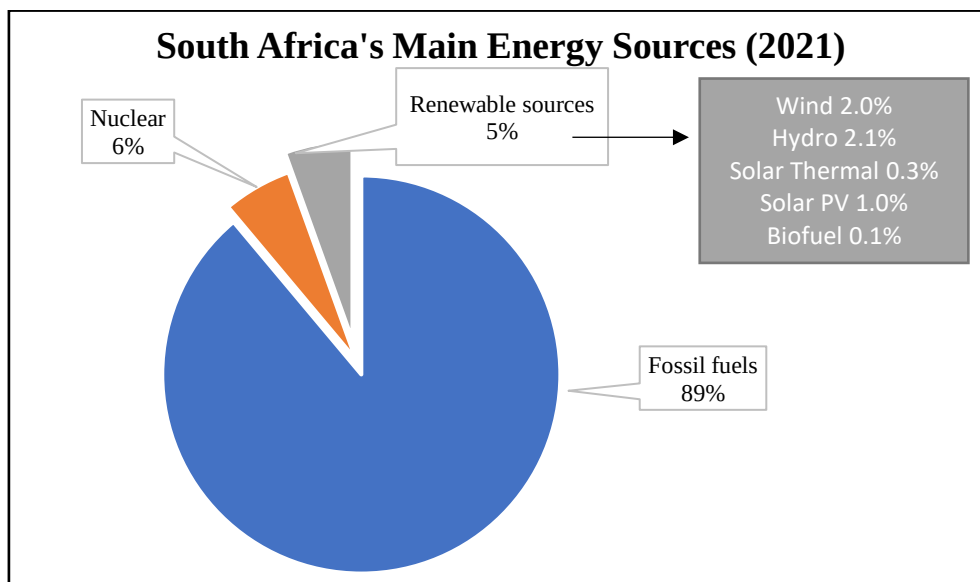


Figure 1: The energy distribution in South Africa in 2021 [3]

¹ S. Writer. 2023. Load shedding outlook for 2023 sours. <https://businesstech.co.za/news/energy/663535/load-shedding-outlook-for-2023-sours/> Date of access: 2023, Feb 9.

Eskom's tariffs have increased drastically from 2004/2005 to 2020/2021. Tariffs have increased from year to year by an average of 13% and a total of 957 c/kWh² over the above-mentioned period [4]. Figure 2 depicts the tariff increases over the entire period as the calculated percentage increase (CPI) as well as the associated Rand increase per unit of energy.

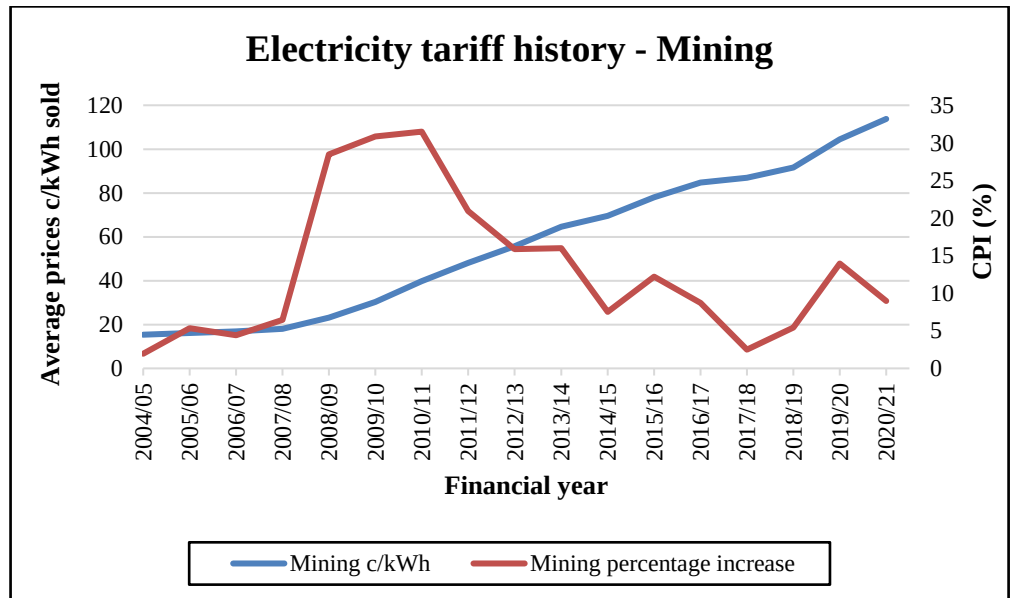


Figure 2: Eskom average tariff vs. inflation (CPI) [4]

There is a growing need for alternative energy sources within the energy sector to complement the current energy supplier and, possibly in the future, convert completely to a sustainable energy source with minimal greenhouse effects and maximum energy potential [5, 6].

Hydropower is considered one of the most popular renewable energy sources as it is convenient and reliable [7] and is growing swiftly across the globe [8]. Hydropower is responsible for 17% of the world's total power generation and is the least expensive source of energy [7].

Rising energy demand has started to engulf the coal-generative plants in South Africa [3] and Eskom has resisted the ideology of sustainable energy sources, which has led to the further demise of the current energy situation [2]. South African deep-level mines have been suffering as a result of the load shedding and load curtailment schedules, but possess generative capacities ranging from 0.5 – 1.5 GW because of the abundance of water underground [9].

² Eskom. 2022. Tariff history. Eskom. <https://www.eskom.co.za/distribution/tariffs-and-charges/tariff-history/> Date of access: Jul. 25, 2022.

Excluding Eskom's installed hydropower systems, it is projected that 60 hydropower systems have been installed by private and communal societies in the underground mining sector, which is currently being overlooked [10].

1.2. What is Hydropower?

Hydropower is a form of energy that can be harnessed from the movement of water [11]. Hydroelectric power generation is known as the process of harnessing kinetic energy from flowing water [11]. Hydropower is also considered a renewable source of energy as the water cycle repeats itself continuously [11]. Figure 3 illustrates the workings of a typical hydropower plant.

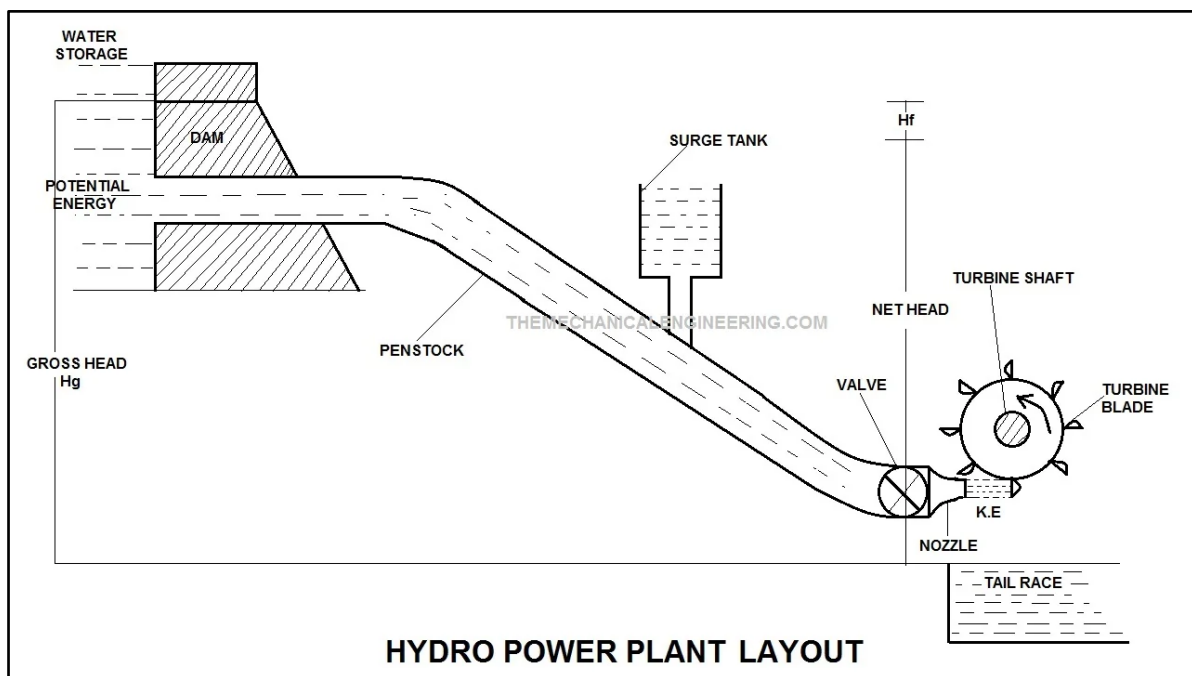


Figure 3: Typical hydropower plant layout¹

In Figure 3, the typical workings of a hydropower system are graphically demonstrated. Typically, water is stored in a reservoir (with the potential energy of having height and thus the ability to convert to kinetic energy) and then released (via a control gate) to flow into the penstock. Initially, the valve is closed to help create a high pressure with a higher water level. Once the higher pressure is obtained, the valve is opened, and the water passes through a nozzle to then strike the turbine blades.

The turbine is connected to an electric motor. When the turbine starts to rotate, it engages the turbine shaft and ultimately rotates the motor (induction motor [12] or generator) shaft where

the final energy conversion occurs³. The process of energy conversion occurs from potential energy to kinetic energy to mechanical energy and, finally, electric energy.

1.2.1. Types of hydropower systems

Hydropower is a versatile system and can be implemented in three types of configurations, namely Impoundment, Diversion and Pumped storage^{4 5}.

Impoundment is the most common form of hydropower and typically is used to store water obtained from a river or water source at a certain height (Head (m)), which is then discharged to flow through a turbine. The turbine, in turn, initiates a generator where electricity is generated^{4 5}. Figure 4 depicts the workings of an impoundment form of hydropower.

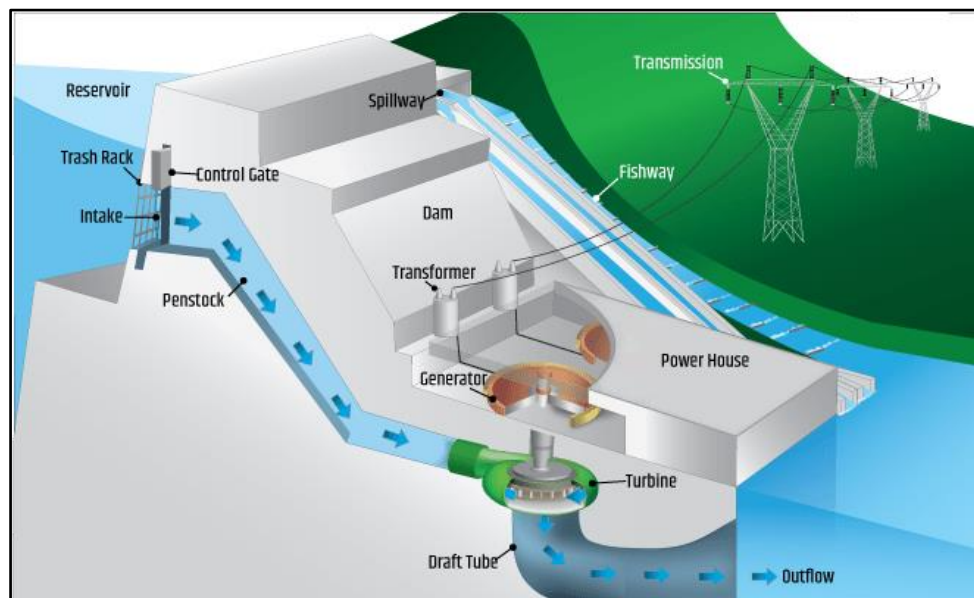


Figure 4: Example of impoundment configuration⁵

³ E. A. Kumar. 2020. Hydro Power Plant: Definition, Layout, Working Principle, Site Selection, Advantages, Application [Notes & PDF]. <https://themechanicalengineering.com/hydro-power-plant/> Date of access: 31 January 2023.

⁴ Anonymous. 2020. What are the Four Major Types of Hydropower Plants? <https://www.scientificworldinfo.com/2020/03/four-major-types-of-hydropower-plants.html> Date of access: Jul. 31, 2022.

⁵ Types of Hydropower Plants. Office of ENERGY EFFICIENCY & RENEWABLE ENERGY. <https://www.energy.gov/eere/water/types-hydropower-plants#:~:text=There%20are%20three%20types%20of,renewable%20energy%20to%20the%20grid.> Date of access: 1 February 2023.

Diversion, also known as ‘run-of-river’, diverts a percentage of the flow of the running source down a natural terrain decline to generate electricity^{4 5}. Figure 5 illustrates a typical example of how diversion hydropower occurs and the workings thereof.

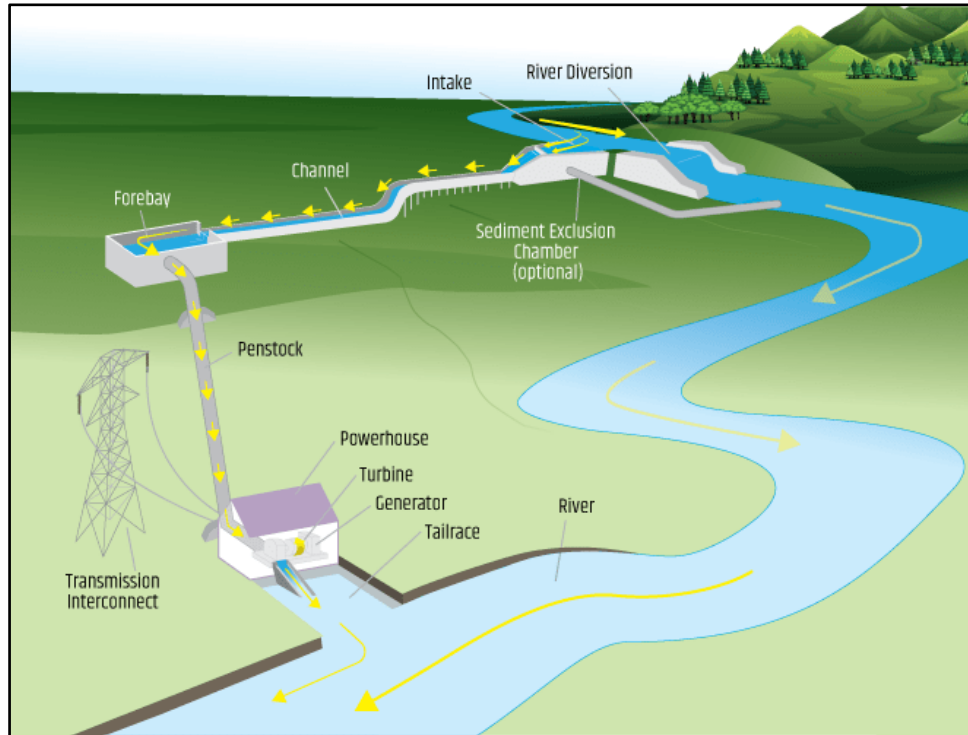


Figure 5: Example of diversion configuration⁵

Pumped storage systems primarily function as energy storage systems, using another power source (renewable energy) to pump water to an elevated reservoir during low electricity demand periods^{4 5}. The gravitational potential energy of the pumped storage is then converted to useful work via a turbine to generate electricity during high electricity demand periods^{4 5}.

1.2.2. Turbine classification

Water turbines have different classifications, namely Impulse and Reaction turbines. Figure 6 displays the turbine classification and types.

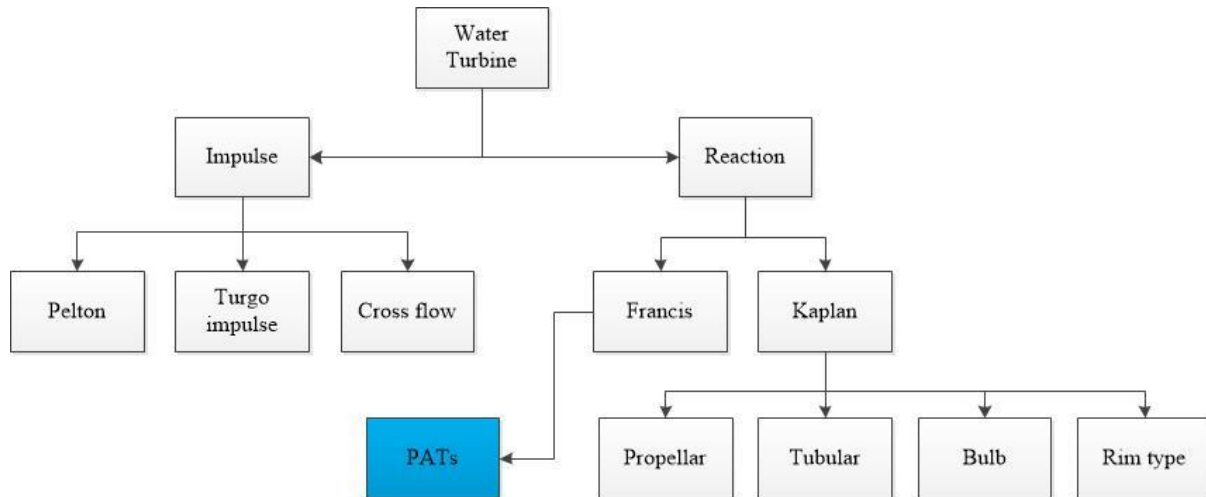


Figure 6: Water turbine classification [13]

The classification is dependent on the system configuration (head, flow, turbine efficiency, turbine configuration and cost)⁶. A hydropower system can be implemented via numerous methods, which include [13, 14]:

- **Impulse turbines** (Pelton and Turgo turbines) [13]

The impulse turbine is typically fed via a penstock through a nozzle. The nozzle converts the water pressure into kinetic energy and is considered a free jet due to the water flow. The free jet then strikes a series of buckets attached to the periphery of the runner. Typical examples of impulse turbines are Pelton turbines, Turgo-impulse turbines, and Crossflow turbines.

- **Reaction turbines** (Francis and Kaplan) [13]

A reaction turbine operates on the pressure of the water, which applies a force on the face of the runner blades and decreases as it advances through the turbine. Reaction turbines also operate mainly with the runner submerged in water. Reaction turbines can be classified further into two categories, namely mixed flow turbines and axial flow turbines. An example of a mixed flow turbine is the Francis turbine and examples of

⁶ Anonymous. Types of Hydropower Turbines Office of ENERGY EFFICIENCY & RENEWABLE ENERGY. <https://www.energy.gov/eere/water/types-hydropower-turbines#:~:text=There%20are%20two%20main%20types,over%20time%2C%20at%20the%20site> Date of access: Mar. 11, 2023.

axial turbines are Propeller turbines, the Kaplan turbine, the Bulb turbine and rim-type turbines.

1.2.3. Centrifugal PATs

A pump as turbine (PAT) is defined as a pump which operates in reverse operation as the flow has been reversed through the traditional pump configuration to generate power [15]. The traditional pump's discharge (high-pressure) becomes the inlet, and the suction side (low-pressure) becomes the outlet [15]. Figure 7 illustrates the standard workings of both modes, pump (a), and turbine (b) mode (centrifugal pump).

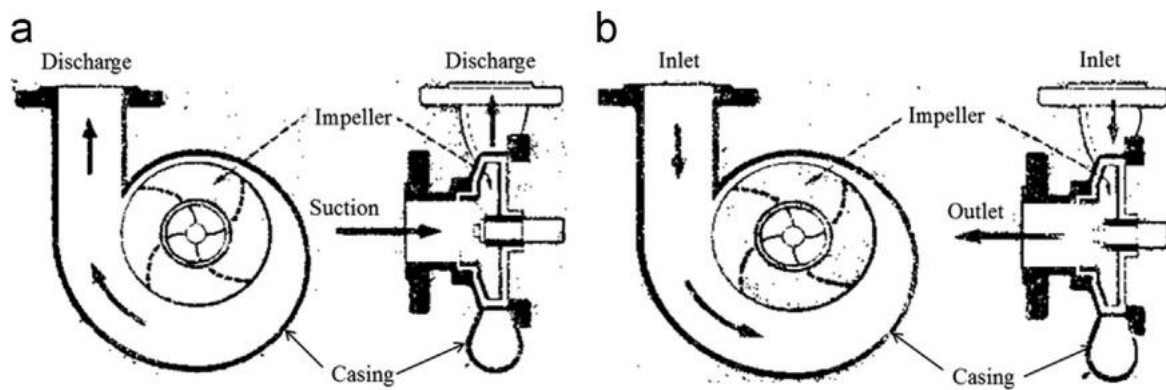


Figure 7: Centrifugal pump as pump (a) and turbine (b) [16]

As seen in the image above, the discharge of a traditional centrifugal pump develops into the inlet when in turbine mode, therefore, the flow is reversed within the pump when in reverse operation [16]. The author also mentions the importance of predicting the performance of the PAT prior to installation. However, pump manufacturers do not provide a performance curve for pumps in turbine mode [16, 17]. This lack of information is critical for water stakeholders to calculate the payback period and accurately estimate energy production [17].

The best efficiency point (BEP) parameters differ between pump and turbine modes [16]. This complicates the pump selection process even more [16]. The author also mentions that many studies (theoretical and experimental) have been completed on performance prediction as well as the method to do so [16, 17].

Many pumps exist that can be used for a variety of applications, defined by the available head and discharge [16]. Proper pump selection is critical and is generally defined by the following factors [16]:

- Available head
- Capacity range
- Back pressure at the turbine outlet
- Desired speed

According to Jain and Patel [16], all centrifugal pumps, from low to high speed, single or multistage, radial or axial type, and horizontal or vertical installations can act as turbines. All centrifugal pumps' centrifugal PATs are also classified as Francis turbines [15] and have been overlooked in the industry as a hydropower renewable energy source, but offer many additional benefits, which include [18]:

- Availability for various head and flow
- Various standard sizes
- Inexpensive
- Availability of parts
- Easy installation

One major limiting factor regarding the pumped storage is the electromechanical energy and the required equipment to regulate the speed of the system [19]. PATs are great alternative sources of hydropower compared to the typical turbine wheel systems. The PAT is an electromechanical device that is typically used in smaller hydropower plants, such as micro- and nano-hydropower plants [19]. PATs are considered reliable as well as low cost and therefore are great alternatives [19, 20]. PATs can also act as pressure reduction valves (PRVs) whilst still being able to recover energy and convert it to usable electricity [21].

The use of centrifugal PATs is a great alternative for power generation, especially in small and micro-hydro generation systems [20]. It is also advantageous as it promotes economic growth due to the minimal costs required to set up a hydropower station and it provides a sustainable energy source to further promote the socio-economic environment of involved people [20].

Hydroelectric systems do encounter different faults, failures and experience several issues. Failure in hydroelectric systems is ever-present and ongoing. These failure mechanisms lead to increased shutdown time during maintenance periods [14] and an increased frequency of stoppages. As a result, there are significant losses in revenue [14]. Dorji and Ghomashchi [14]

and Kumar and Singal [13] explain that the main failure mechanics in hydro turbines can be attributed to the following factors:

- **Cavitation**

Cavitation is the formation and bursting of vapour bubbles due to changes in flow characteristics (fluid pressure) on the machine component.

- **Erosion**

Erosion is defined as the ongoing removal of material from a machine component surface because of frequent deformation.

- **Sediment erosion susceptible turbine parts**

This form of erosion includes the presence of soil or sediment.

- **Fatigue**

Components that are subjected to repetitive alternating and cycling stress below the normal yield strength experience fatigue which results in cracking.

- **Material defect**

Material defects are sometimes caused due to cavitation and silt erosion, however, are controlled during the manufacturing process. Another cause may be due to the welding joints and coating as the metal properties may change, therefore resulting in a material defect.

There is much literature regarding the causes of failure and how to mitigate or avoid this failure. From industry application, it is known that typical turbine failures lead to high capital costs to resolve the damage and long downtime periods. Discussed below is an article supporting this statement.

NTNU [22] published an online article in which Norway's power struggle and the many challenges faced are discussed as well as a way forward is given. *NTNU* [22] mentions a compelling statement about the loss of production which led to loss of enormous amounts of money due to downtime of approximately six months, which agrees with industry opinions.

The publication, therefore, highlights the need to make use of a reliable and cost-effective turbine type to ensure that the hydropower system is stable and mitigates the possibility of mechanical failure. Complete mitigation of mechanical failure is impossible. However, the

possibility of failure can be minimised during the turbine selection process. This study focused on the implementation of a reliable and cost-effective PAT or turbine.

1.3. Hydropower simulations

According to literature, thermal-hydraulic simulation is the calculation of functional variables or thermal constraints found in a thermal system operating steadily [23, 24]. Simulation software suites have proven successful in the engineering sector, especially with the design and performance prediction thereof [25]. Research shows that computational fluid dynamics (CFD) is an efficient simulation tool for performance prediction of PATs and turbines [26]. According to Vasanthakumar, et al. [26], previous studies performed with numerical analysis did not align adequately with the experimental results and therefore questioned the validity of numerical analysis solely for performance prediction.

Completing an integrated simulation model has proven to be advantageous in numerous ways which include [23, 27, 28]:

- The simulation model acts as a form of documentation for the system's operation and layout.
- The modeller and analyst are compelled to comprehend the model and process behind the model.
- The simulation model forms a basis for component selection and design.
- The simulation model acts as a superior debugging and fault-finding tactic.

Yang, et al. [29] mentions that, based on a comparison between experimental data and CFD results, there is reason to believe that CFD may be used in the PAT prediction process. Although a simulation model is very powerful, especially if used correctly, it is important to ensure that there is a simulation procedure in place prior to modelling an integrated and complex system. The reason for this is to ensure that the initial problem, objectives and outcomes are aligned.

1.4. Literature on hydropower in industry

Based on previous discussions in this thesis, the literature has been analysed for various criteria required for a generic methodology for the successful implementation of PATs with the aid of a thermal-hydraulic simulation suite.

Much focus and effort has been put into the optimal control of PATs and turbines. However, most research only focuses on the PAT or turbine itself and does not incorporate the surrounding- and integrated network. This supports researching a hydropower system within an integrated network as well as the effect thereof on the network when optimally controlled. Within an integrated network, the surrounding systems need to be considered in terms of performance, especially with such complex and vulnerable systems. Therefore, the performance of the individual and integrated systems needs to be monitored according to a certain standard, especially to determine the effect of a newly developed system in a simulation model. Therefore, a certain group of preset KPIs needs to be identified.

As stated earlier, many researchers have developed numerous methods to predict the performance of PATs or turbines numerically and experimentally with some focus applied on thermal-hydraulic simulations. This focus is directed to existing PATs or turbines and not necessarily on the integrated network. The ideology of this thesis is to reduce initial costs, therefore locating an inactive pump, PAT, or turbine, which can be repurposed and applied to a new application was worth investigating, as this significantly reduces the capital expenditure (CAPEX) and implementation period.

Referring to the previous discussions, the criteria were selected based on whether optimal control for the PAT was established that satisfied a preset of key performance indicators (KPIs) as well as the use of a thermal hydraulic simulation software to predict the PAT or turbine performance of an integrated network. Combining these specific parameters and characteristics forms part of the novelty of this thesis.

The identified criteria used to analyse literature, were based on:

1. whether an optimal control strategy had been established that satisfied a preset of KPIs,
2. whether a thermal hydraulic software package was used,
3. whether the study performed a reclamation and reconfiguration on a pump or turbine and
4. the overall system integration within the model.

These criteria formed the basis of this study. Based on the developed criteria set before the literature analysis, sixty-eight studies were reviewed. Table 1 summarises the literature analysed within this study based on these identified criteria.

Table 1: Applications of PAT and turbine systems in literature

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
1	[30]	Variable and constant turbine speed systems can be used to recover energy and regulate pressure in deep mines.	Turbine	✓	X	X	X
2	[31]	Analysed performance of turbine under different flow conditions	Turbine	✓	X	X	X
3	[32]	Improved turbine performance with blade configuration and setup	Turbine	X	✓	X	X
4	[33]	Analysis of the basin and inlet channel of a gravitational water vortex hydraulic turbine using the surface response methodology	Turbine	X	X	X	X
5	[34]	Analysis of the flow field and performance of a small scale Savonius turbine at a low water velocity	Turbine	X	✓	X	X
6	[35]	Evaluation of power performance of a conventional Savonius turbine augmented with various deflector configurations	Turbine	✓	X	X	X
7	[36]	Analysis of a water droplet erosion-induced fatigue crack propagation and failure in turbines at low pressure	Turbine	X	X	X	X
8	[37]	Various forms of analysis were utilised to determine the best efficiency point of a centrifugal pump in reverse operation.	PAT	X	X	X	X
9	[38]	The criteria of pump selection for a pump as turbine were modified and performance improved.	PAT	✓	X	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
10	[39]	The performance of a pump as turbine was analysed in a Pico-hydropower plant and revealed an acceptable prediction (excluding very low flows).	PAT	✓	✓	X	X
11	[40]	A runner optimisation strategy was used to increase efficiency on the high-pressure side in both pump and turbine mode, especially focussing on the blades.	PAT	✓	✓	X	X
12	[41]	An analysis of internal fluid stability of a pump turbine by reducing the change rate of pressure and improving the flow regime	PAT	✓	✓	X	X
13	[42]	Decision-based support algorithm used to predict potential to recover in the system	PAT	X	X	X	X
14	[43]	A new power plant for small residential areas is presented.	PAT	X	X	X	X
15	[44]	The potential of super hydrophobicity for a very low head axial hydraulic turbine	Turbine	✓	✓	X	X
16	[45]	The study reviewed CFD analysis and future works and improvements for centrifugal pumps.	PAT	X	✓	X	X
17	[46]	This study focused on trade-off during design of turbine under constraint of dimensions for commercial steel pipes.	Turbine	X	✓	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
18	[47]	Novel impeller design for-medium centrifugal pumps and efficiency improvement	PAT	✓	✓	X	X
19	[48]	Hydro turbines were used to recover excess pressure.	Turbine	✓	X	X	X
20	[49]	Dynamic analysis of PATs and application to district	PAT	✓	X	X	X
21	[50]	A comparison among the feasible regulation systems for PAT regulations is discussed and optimal solution obtained	PAT	✓	X	X	X
22	[51]	Use of affinity laws to evaluate PAT performance at variable speed	PAT	✓	X	X	X
23	[52]	Coastal axial flow pump system experiment built to analyse internal characteristics	PAT	X	X	X	X
24	[53]	Experimental characterisation of inline tubular propeller	Turbine	✓	✓	X	X
25	[54]	Experimental data of PATs were used to predict the best efficiency point (BEP).	PAT	✓	X	X	X
26	[55]	Experimental data of positive displacement hydraulic turbine (PDT) show effect of difference in parameters and input variables	PAT	X	X	X	X
27	[56]	The effect of viscosity was tested within a PAT. It was found that an increase in viscosity resulted in increased hydraulic friction	PAT	✓	X	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
		losses and lower efficiency. At BEP a higher viscosity resulted in less mechanical losses.					
28	[21]	Integrated methodology presented to optimise pump control, pump schedule, and implement PATs in the WDS	PAT	✓	X	X	X
29	[57]	Study proposes methodology to obtain BEP of the PAT-SEIG (Self-Excited Induction Generator) under various operational speeds and loads	PAT	✓	✓	X	X
30	[58]	Conversion of adjustable guide vane (AGV) pump mode and turbine mode was analysed in terms performance and payback period	PAT	✓	X	X	X
31	[59]	Aimed to accurately predict performance of PAT for centrifugal pump	PAT	✓	X	X	X
32	[60]	Study introduces theoretical method to predict head and BEP for pump and turbine mode	PAT	✓	X	X	X
33	[61]	Study presents a one-dimensional code for performance prediction in centrifugal PATs	PAT	✓	X	X	X
34	[62]	Study outlines the development of micro-hydropower systems	PAT	✓	X	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
35	[63]	The study investigated enhancing the energy efficiency of water supply networks via technical and economic feasibility.	PAT	✓	X	X	X
36	[64]	Explains work done around PAT. CFD future works is a viable option to be explored.	PAT	✓	✓	X	X
37	[65]	Transient cavitating flows of PAT were investigated.	PAT	X	✓	X	X
38	[37]	Determined the BEP of a PAT using theoretical analysis	PAT	X	✓	X	X
39	[66]	Study reviewed state-of-art of Pelton turbine casing based on hydraulics, mechanics, and aeration	Turbine	✓	✓	X	X
40	[67]	Study investigated the pressure fluctuation intensity and vortex characteristics of PAT with a tip clearance	PAT	✓	X	X	X
41	[68]	Artificial Neural Networks (ANNs) were used to predict performance curves and BEP	PAT	✓	X	X	X
42	[69]	The entropy generation theory is introduced to analyse hydraulic losses in a PAT	PAT	✓	✓	X	X
43	[70]	A general analytical method for predicting a PAT performance in turbine mode was investigated	PAT	✓	✓	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
44	[71]	Propose a predicting model for PAT performance in off-design operating conditions	PAT	✓	✓	X	X
45	[72]	Predicted PAT performance based on pump performance curves	PAT	✓	X	X	X
46	[29]	Established correlation between PATs performance curve and impeller trim	PAT	✓	✓	X	X
47	[73]	Established correction factors to evaluate Hydraulic Power Recovery Turbines (HPRTs)	PAT	✓	✓	X	X
48	[74]	Bidirectional transitions from pump-to-turbine modes caused by power failures in PAT were investigated	PAT	X	X	X	X
49	[75]	Investigated the effect of tip leakage flow (TFL) on PAT energy performance	PAT	✓	✓	X	X
50	[76]	Different prediction models (experimental and numerical) were used for performance prediction in single and multi-stage pumps.	PAT	✓	X	X	X
51	[77]	Application of energy recovery PAT system in oil refinery	PAT	✓	✓	X	X
52	[78]	Validation of statistical model to estimate flow, head and select PAT based on BEP and payback period	PAT	✓	X	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
53	[20]	The status of renewable energy generation is identified and discussed	PAT	✓	✓	X	X
54	[26]	Study presented an experiment and numerical model to predict and conclude a comparative study	PAT	X	X	X	X
55	[79]	The feasibility and power generation performance of a PAT was investigated in a water supply system (WSS)	PAT	✓	X	X	X
56	[15]	Proposed a new concept, “Impulse PAT” with a centrifugal pump impeller coupled with a spear valve injector	PAT	✓	✓	X	X
57	[80]	Numerical simulation provides reliable prediction methods of PAT performance (transient flow and time mean characteristics)	PAT	✓	✓	X	X
58	[81]	Investigated the effect of fixed guide vanes on a PAT	PAT	✓	✓	X	✓
59	[82]	Analysed the internal flow characteristics to reveal periodic rules of flow rate distribution	PAT	✓	✓	X	X
60	[83]	Introduced a methodology based on a mathematical model of a PAT in an urban hydraulic network	PAT	✓	✓	X	X
61	[84]	Introduced a model to simulate a branch of a water demand network (WDN) to substitute a PRV with a PAT	PAT	✓	X	X	X

No.	Cit.	Main finding	Type (Turbine or PAT)	Optimal control	Thermal- hydraulic simulation suite	Reclaim and repurpose PAT or turbine	Integrated simulation model
62	[85]	Presents detailed analysis of three-dimensional (3D) flows in a PAT	PAT	✓	✓	X	X
63	[86]	Theoretical method based on the impeller-volute matching principle was proposed to predict the BEP	PAT	✓	✓	X	X
64	[87]	Theoretical model for energy performance of centrifugal machinery under turbine and pump mode was proposed	PAT	✓	✓	X	X
65	[88]	Improved the performance of a PAT by means of a new impeller	PAT	✓	✓	X	X
66	[89]	Highlights the utilities of CFD in hydraulic turbine operations	PAT	✓	✓	X	X
67	[90]	The study analysed the pico-hydro development and proposes a PAT concept as alternative	PAT	✓	X	X	X
68	[91]	Establishment of PAT performance prediction methods	PAT	✓	✓	X	X
69	[92]	Evaluation of unsteady flow of an ultra-high-head PAT	PAT	✓	X	X	X
70	[17]	Evaluate the performance of the PAT and BEP through various methods and develop a characteristics curve with the aid of a experimental analysis	PAT	✓	X	X	X
71	[93]	The pressure fluctuation and flow pattern evolution are calculated for a prototype PAT	PAT	X	✓	X	X

From the extensive literature study shown in Table 1, it was noted that the majority of the literature focuses on the BEP (optimal control) and improving the overall performance of the PAT with the aid of a simulation model. Many of the studies made use of numerical, experimental, and theoretical simulation modes. Some studies also made use of the thermal-hydraulic simulation suites. Literature shows neither the integration of networks nor the physical implementation of a PAT system in a corporate environment.

A corporate environment, in this application and thesis, is defined as a large company or organisation that practises project governance in terms of finance and overall project approval. From my experience in the mining environment, the commercial process can be time-consuming as approval from various high-level management designations is required. Figure 8 demonstrates the company hierarchy and highlights designations required to provide approval upon submission of a project for CAPEX.

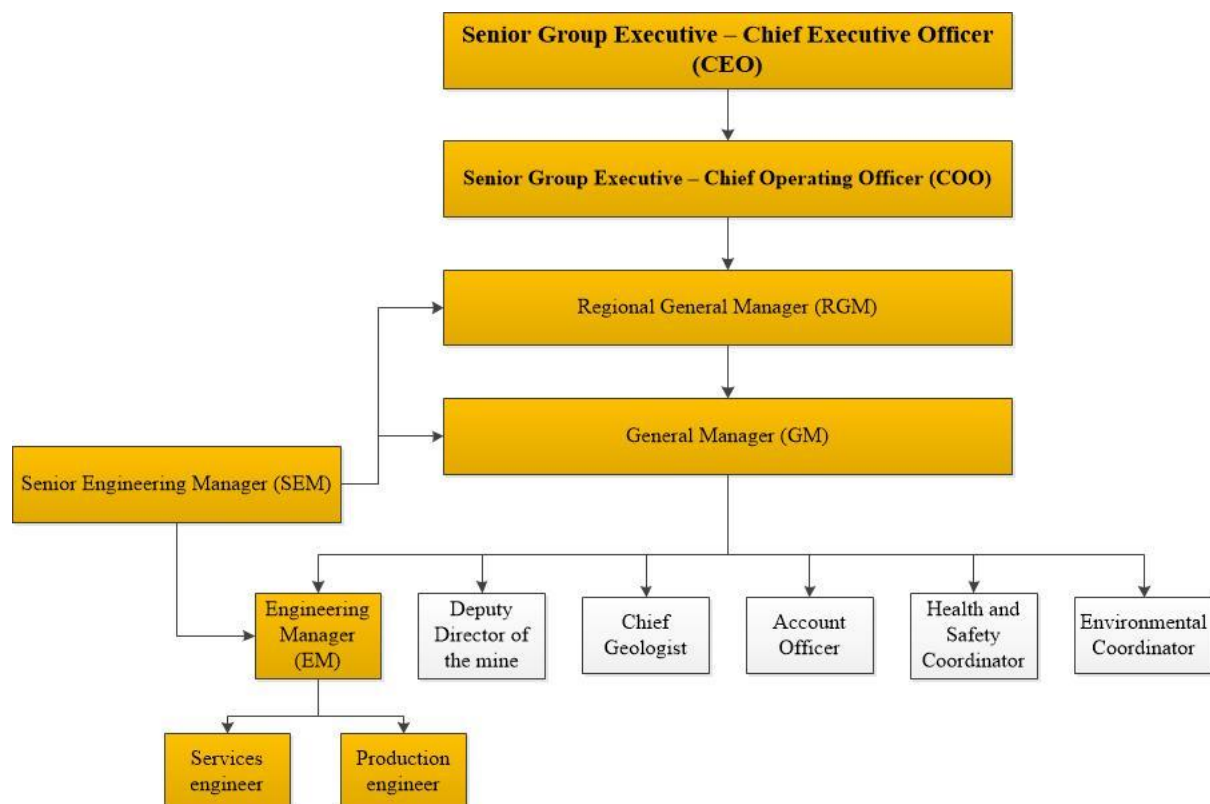


Figure 8: Typical example of a medium-sized mining organisation

Literature has shown many efforts to improve the operational efficiencies of PATs and hydropower turbines, as well as numerous testing methods via numerical, experimental, and computational trials.

Another concept to consider, especially in terms of ‘recycling’, is collecting equipment or machinery and repurposing the machinery for another use. By doing so, large amounts of capital can be saved in the long run and the period taken to set up and install the hydropower plant can be shortened.

Studies were categorised based on the type of turbine, either a PAT or turbine, and then according to the developed criteria for this thesis. Figure 9 illustrates the number of studies that satisfy the given criteria.

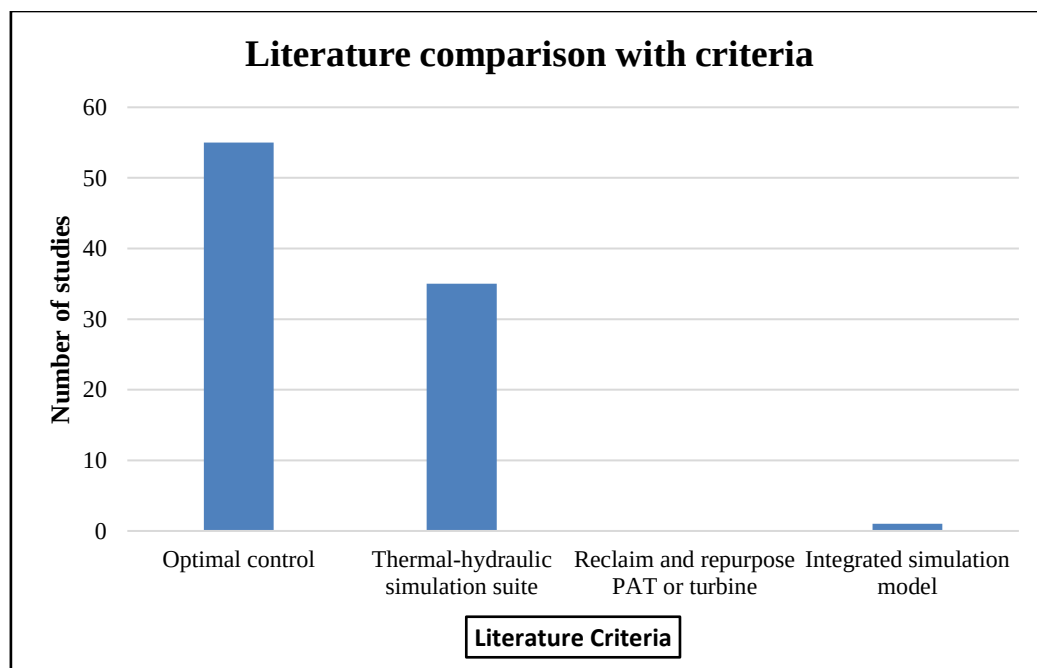


Figure 9: Literature analysis according to criteria

It can be noted from Figure 9 that minimal to no studies were performed based on integrated simulation models and reclamation of PATs which are then repurposed for a certain application. This highlights the need to perform this study to satisfy all the given criteria.

Figure 10 demonstrates the relationship between the different criteria and overlapping criteria within the different studies for PATs.

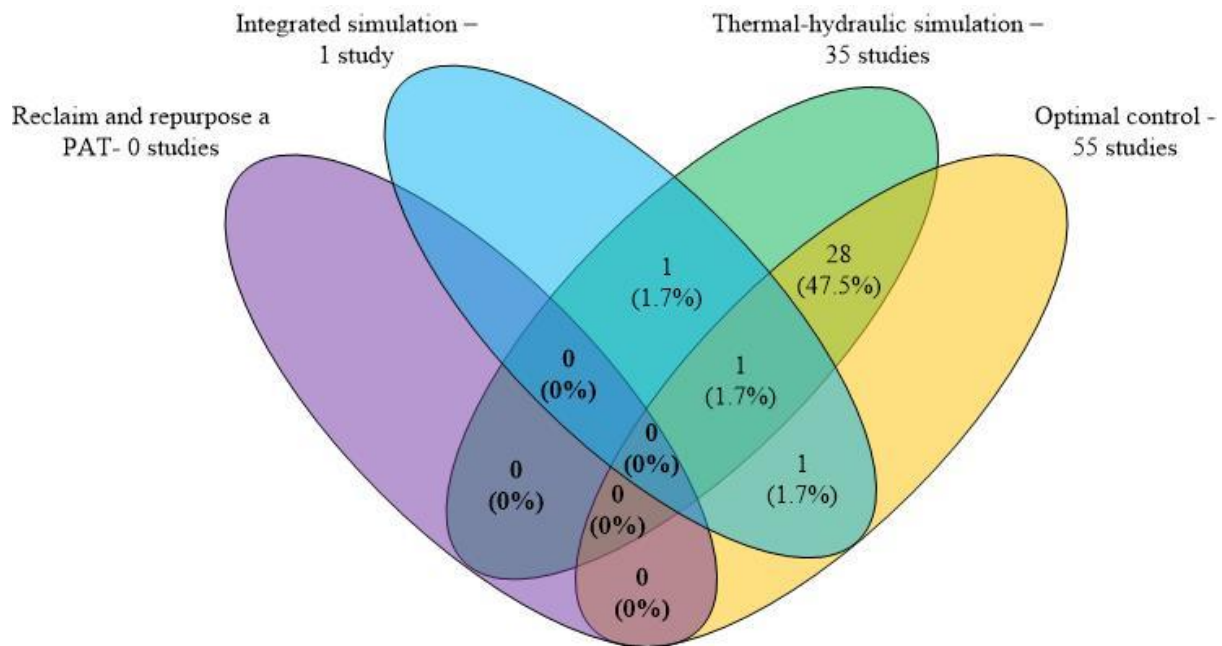


Figure 10: Venn diagram representing the literature overlap.

From analysing Figure 10, approximately forty-eight percent of the studies analysed represent a correlation between the use of a thermal-hydraulic simulation suite and obtaining optimal control. Further analysis shows approximately 1.7% of the studies analysed share a small relation with integrated simulations, optimal control, and thermal-hydraulic simulations. Although a significant number of studies made use of a thermal-hydraulic simulation, the combination of aiding a reclamation of a PAT and optimally controlling the PAT accordingly with a thermal-hydraulic simulation suite in an integrated network does not feature in the literature analysed for this study. Zero percent of studies show any correlation and results of the combination of the criterium.

This analysis exposed a shortcoming in the literature and an opportunity to investigate and research the unique combination of the above criteria. The next section discusses establishing the need for the study based on the literature analysis and the results obtained.

1.5. Need for the study

The mining sector is facing many challenges as energy prices and a constant supply of energy are being threatened. The demand for an alternative and sustainable form of energy supply is unanimous. Turbines have proven to be able to supply large quantities of power, but also have severe and expensive disadvantages. An underrated and underexplored option is the PAT. Exploring a PAT, with the abundance of technology available, is becoming simpler to do. There

exist many forms of simulation suites that can predict the performance and outcome without spending large amounts of capital and failing. The simulation model warrants a higher implementation success rate as all the possible issues that would result in failure, can be identified, and corrected beforehand.

Sixty-eight studies were analysed and proved various aspects of turbines that can be optimised, altered, experimented, and tested. However, none of the studies were able to demonstrate actual results of a turbine physically implemented into an integrated system with the aid of a thermal-hydraulic simulation software. The analysed studies also showed no evidence of a generic or simplified procedure for the implementation of a hydropower system in a complex and integrated network. Many studies made use of a thermal-hydraulic simulation software; however, the results were not validated with an actual hydropower system based on the simulated model. Although experimental results were obtained, the results were not based on an integrated and complex network.

A need exists for a method, based on engineering principles, to aid in the successful implementation and operation of PATs in deep-level mining. Furthermore, the use of thermal-hydraulic simulation software is also underexploited, especially when predicting the performance of PAT or turbine systems. Therefore, there also exists a need to predict the performance of a PAT with the aid of a thermal-hydraulic simulation software, while adhering to a certain set of criteria.

Deduced from the extensive literature analysis and need for the study, there is scope to investigate the PAT performance in an integrated water supply system (WSS) and water distribution network (WDN) with the aid of a thermal-hydraulic simulation software suite.

1.6. Objectives

Based on the major energy crisis in South Africa, the need for alternative energy sources or hydropower systems (which are underexploited), is substantiated and furthermore encourages the use of a thermal-hydraulic simulation suite to predict the overall performance. Based on the simulation model results, the financial and overall energy impact can be determined and used for the important decision-making process.

The aim of the study is to develop a new method that incorporates simulation of an existing integrated mine hydro-system and predicts the performance of a PAT (new or reclaimed and reconfigured) within a business and corporate environment.

This is achieved by the objectives of the study:

1. Recover gravitational potential energy using hydropower principles in large energy-intensive systems.
2. Recover and reconfigure an existing PAT or turbine with the aid of a thermal-hydraulic simulation software suite.
3. With the aid of thermohydraulic simulations, optimise control and test feasibility.
4. Reduce CAPEX and implement a reconfigured PAT in a corporate and business environment.
5. Predict the energy recovery outcome on a large and complex mining system with preset KPIs.
6. Evaluate PAT performance in different applications (large water storages).
7. Exploit system configurations and parameters for optimum benefit.
8. Develop a comprehensive, generic, and holistic solution procedure for implementing a hydropower system in a corporate environment.

There is extensive literature on PATs and hydropower in complex water networks. However, there is a lack in the use of a thermal-hydraulic simulation software. This shortage encompasses the entire water complex, its KPIs and developed control strategies designed to sustain production and maintain water supply at identified KPIs.

As the objectives of the study have been defined, the novel contributions can now be defined and discussed in more detail. The novel contributions of this thesis are discussed in the following section.

1.7. Novel contributions

1.7.1. A method to predict the performance of PAT in an integrated WSS and WDN with the aid of a thermal-hydraulic simulation and determine the effect of the PAT on the system configuration.

Existing approach:

Many studies have been performed on existing turbines and PATs either by means of experimental methods or by theoretical calculations and simulation models performed on the turbine or PAT itself. The main objective is mainly to improve the overall turbine or PAT performance or identify new mechanisms and strategies for increased performance.

Shortcomings and needs:

Few to no studies examined the effect of the PAT on an integrated network or system. The surrounding WSS and WDN were not examined with a thermal-hydraulic simulation software suite, thereby ensuring a sustainable and operational integrated network which is not negatively affected by the implementation of a PAT.

Description of contribution:

This study focuses fundamentally on accurately predicting the performance of a PAT with the aid of a thermal-hydraulic simulation software suite, as well as on the effect on the WDN and WSS. The study will also conclude whether the PAT does indeed affect the system negatively, especially when controlling to the optimum point.

1.7.2. An analytical approach to reclaim a PAT, test feasibility, and repurpose the PAT for a different application to recover potential gravitational energy.

Existing approach:

Studies have focused mainly on the feasibility of existing turbines or PATs and performed experiments as is. Theoretical calculations were also performed on existing turbines. Additionally, no studies were found showing the actual implementation of their research or simulation model on an integrated network.

Shortcomings and needs:

Literature has mainly focused on performing work, research and studies on existing turbines or PATs and has not yet explored the possibility of reclaiming an existing turbine and testing the feasibility thereof as well as the physical implementation of the PAT within a large and complex network to recover potential gravitational energy. There exists a lack of literature especially surrounding the idea of reclaiming an old PAT, refurbishing, and reconfiguring the PAT according to a thermal-hydraulic simulation model, and implementing the PAT in a complex and integrated WDN and WSS.

Description of contribution:

This study investigated the idea of reclaiming a PAT, testing the feasibility of the PAT in a different application, applying such configurational changes to said PAT, and physically implementing the PAT in a working system to generate energy and positively contribute to the reduction of energy loads in South Africa.

*1.7.3. Develop a generic and simplified simulation procedure for PAT implementation for a corporate environment.**Existing approach:*

Generic simulation procedures exist in literature to assist with the development of complex simulation models in an engineering environment. These generic simulation procedures are often complex and of little relevance to a corporate environment. Many procedures have been identified and discussed in literature; these procedures have been utilised in the development of a generic yet simple simulation procedure for the implementation of a PAT in a corporate environment.

Shortcomings and needs:

Generally, the procedures identified in literature lack the physical implementation of a PAT and only highlight the actual simulation part. There exists a need to develop a full and comprehensive procedure which can guide a designer or engineer from the identification of the problem to the development of a simulation model and finally the actual implementation of the PAT within an integrated WSS and WDN. Studies have also shown little to no research about the inclusion of the corporate sector within a simulation procedure.

Description of contribution:

The developed procedure in this study not only addresses the addition of the corporate sector and commerciality of the study but also focuses on the simplicity of the simulation procedure. Simulation procedures have proven to be complex. However, the objective of the study was to develop a procedure that can be easily followed yet remains effective. This procedure was developed to also be a generic yet comprehensive procedure to address all aspects of the implementation of a PAT within a corporate environment. This generic developed simulation procedure mainly focuses on the implementation of a PAT within any WSS or WDN, as well as in any type of hydropower system.

*1.7.4. Optimally control the PAT in industry based on the thermal-hydraulic model taking integrated network KPIs into account.**Existing approach:*

Typically, studies have shown that the optimal control of a PAT can be obtained via theoretical calculations as well as experimental analysis and simulation models. Generally, these PATs are stand-alone systems and do not exist within an integrated network. The optimal control point is generally obtained based on the maximum performance of the PAT via the various mechanisms mentioned. Studies have also explored various new methods of obtaining the optimal control point of a PAT, but do not incorporate the surrounding environment.

Shortcomings and needs:

Many studies have focused on obtaining the BEP of a PAT via various mechanisms but have not incorporated either the effect of the surrounding environment on the PAT, or that of the PAT on the surrounding environment, which is considered to be the KPIs. Studies have only focused on obtaining the BEP and various manners in which to improve the operational efficiency of a PAT. There exists the need to explore how to optimally control a PAT within an integrated network with the aid of a thermal-hydraulic simulation software suite to ensure that certain KPIs are maintained while still receiving the maximum benefit of the PAT.

Description of contribution:

This study focused on obtaining the optimal control point with the aid of a thermal-hydraulic simulation software suite while taking certain identified KPIs into account during the process.

The identified KPIs play an important role within an integrated and complex system and therefore need to be considered in determining the optimal control. The KPIs also need to be achieved within these certain specifications whilst still operating at the BEP. The study highlights and demonstrates how the KPIs were identified as well as sustained, within the thermal-hydraulic simulation model and still achieves the main objective of the study.

1.8. Thesis overview

1.8.1. Chapter 1: Introduction and Literature

Chapter 1 briefly elaborates on the role of Eskom within the South African energy sector as well as the corresponding challenges that are faces. Eskom, South Africa's major energy supplier, has also resisted the ideology of renewable energy and maintained its monopoly within the energy sector for decades.

Chapter 1 also discusses the fundamentals of renewable energy and its role in South Africa as well as the potential in a struggling South African economy. Various renewable energy techniques are explained in detail, while mentioning which sources are best suited for different environments and applications.

1.8.2. Chapter 2: Methodology

Incorporating the basis of renewable energy, a generic solution strategy was developed for a simplified process of implementing a hydro-power system within a corporate environment. This is discussed in detail and the methodology is explained to ensure a suitable solution is developed with the aid of hydraulic simulation software to incorporate the various factors of a large and complex system.

1.8.3. Chapter 3: Model verification through a case study

The model developed in Chapter 2 is verified in this chapter. The developed model was applied to an actual case study mine. The model's results were also compared to that of the theoretical and computational results. This comparison allows for logical and informed deductions to be made about the developed strategy as well as the possibility and potential for hydropower within the South African mining sector. Measurable results were obtained from this application and are discussed in Chapter 4.

1.8.4. Chapter 4: Conclusions and recommendations

The final conclusions are discussed in this chapter where all the main concepts and ideas are summarised. The recommendations for future work identified within this thesis are also discussed.



CHAPTER 2

METHODOLOGY

2. A METHOD FOR RECONFIGURING A PUMP IN REVERSE OPERATION FOR OPTIMAL CONTROL

2.1. Preamble

Chapter 2 discusses and outlines a generic solution strategy process which can be followed to implement a complex hydropower and potential recovery system within an existing system to recover gravitational potential energy. With the aid of a hydraulic simulation software, a validation model can be generated and used to evaluate and validate the solution strategy performance. The methodology defines the critical path required to realise a successful renewable energy system.

2.2. Research Methodology

Implementing a hydropower system can be complex and requires adequate financial, logistical, economical, and practical preparation. An appropriate solution strategy is required to adequately plan out the required steps to successfully implement a hydropower system. A solution development procedure has been developed which focuses on achieving the main objectives and ensuring the optimal and suitable solution is created and chosen for each case.

The engineering design method is a systematic approach which is used as a support mechanism to assist an engineer when working towards a solution for an identified problem [94]. Lasser [94] summarises the engineering method into six steps, depicted in Figure 11.

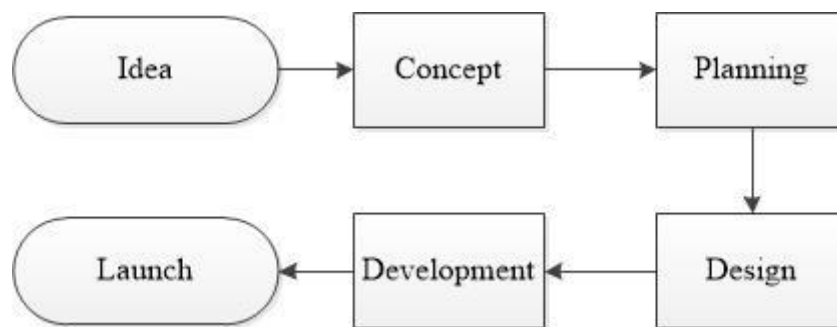


Figure 11: Engineering method process [94]

The author further describes the development step as an iterative cycle which is repeated until the desired solution is obtained by means of build, test, debug and redesign [94]. The engineering design method, in its entirety, is a repetitive process [94].

Based on the engineering method discussed, the process can therefore be simplified further to obtain a generic engineering design approach for this application.

1. Identification
2. Method development
3. Verification
4. Evaluation

2.3. Identification

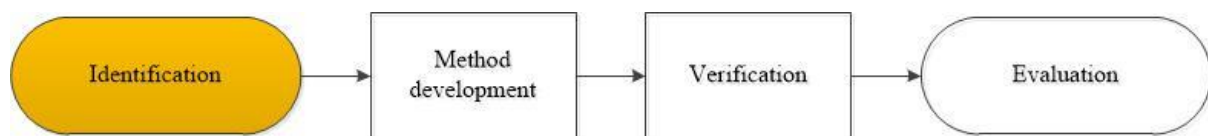


Figure 12: Methodology – Identification step

Identifying the initial problem and needs is crucial when developing an efficient and successful solution [34]. Identifying the root cause allows for the correct solution to be designed and selected.

Within “Identification”, the following topics were investigated:

- Problem statement (e.g., High energy consumption and tariffs)
- Objective of the project (recovering energy)

An accurately defined problem statement highlights the main problem at hand and defines the scope of work (SOW). This alludes to the main objective as well as sub-objectives and ensures that all objectives are aligned with the SOW. Objective numbers 1, 2 and 8 were satisfied within this step of the methodology.

2.4. Blueprint –Method development: Assess and map out regenerative strategy

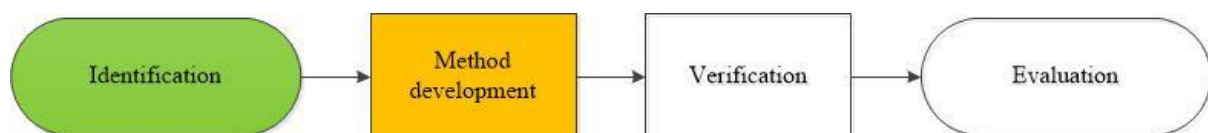


Figure 13: Methodology – Method development step

Entailing the main components of the engineering design and problem solving process, the procedure was adapted to a computational approach for a more detailed and comprehensive study [95, 96]. The solution procedure identifies the problem with a comprehensive

investigation, develops a solution with the aid of computational power (based on numerical methods favoured by engineering [68]), and verifies the solution for important decision making. The procedure is continuously evaluated throughout with iterative processes, ensuring the optimal solution is selected for the identified problem.

The method development comprises:

1. Comprehensive investigation
2. Pre-feasibility
3. Feasibility
4. Implementation

These steps are discussed below in further detail, highlighting the outcome of the respective step within the method developed.

2.4.1. Comprehensive investigation

Once the problem and needs of the study have been defined, a comprehensive investigation should be completed where all the necessary information relating to the study is assembled. This information will typically include.

- Existing information available (maps, water reticulation layouts, experiments, actual data etc.)
- Comprehensive audits on the hydro-system (water source, flow rate, system type and energy recovery type)

The comprehensive investigation is critically important (Step 1 and Step 2 are as important as the others), as the basis of the entire system is defined during this step. The foundation of the solution development, including the inefficiencies and successes, are established within this step and the first. Thus, a thorough and complete investigation is required.

2.4.2. Pre-feasibility

To develop a comprehensive solution, both a pre-feasibility and feasibility analysis are required. This allows and ensures that the solution developed is addressing the problem statement and that the objectives are met. The pre-feasibility study primarily screens possible solutions and identifies the most auspicious solutions. It entails:

1. Design
2. Theoretical calculations
3. Estimated CAPEX

The steps included in the pre-feasibility section are further explained below.

Design

When designing a new product, initiative or project, there are three typical design phases that are encountered. These three design phases can be summarised as the concept phase, the embodiment phase, and the detailed design. Although the different design phases exist in different sections of the solution development, they are discussed here for continuity and later in the thesis in more detail. Figure 14 illustrates the flow diagram of the design phases.

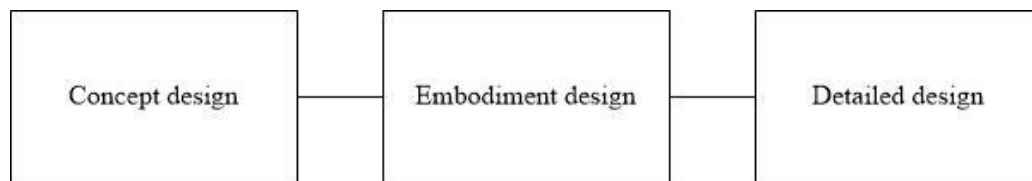


Figure 14: Design phases for a new product, initiative, or project

The three design phases are described in more detail below.

Preliminary (Concept) design

Concept design is considered the phase which focuses on the ‘bigger picture’ and where the product requirements are established⁷. The concept design is arguably considered the most important step within the design phase as it involves function, formulation, concept generation, concept organisation, concept evaluation and improvement [97]. The effectiveness of the concept design phase determines more than 50% of the cost and quality [97]. According to Zhang, et al. [97], rash decisions made during this phase are typically the basis for complications within the operation. Thus, the concept design phase is considered as one the most crucial stages of the design phase.

To further complicate this phase, the majority of the decisions are often made without supporting information and data until the detailed design is completed [97].

⁷ E. Rudeck. Concept Design: A Short Introduction [Web log post]. Retrieved from <https://www.concurrent-engineering.co.uk/blog/concept-design-a-short-introduction>

Embodiment design

The embodiment design phase is a main phase where the main engineering design concept is established⁸. This design is based upon the product design specifications (PDS) and economic conditions⁸. During this stage, the idea is conceptualised until such a point where the detailed design can directly lead to implementation and production⁸. This phase is also commonly known as the concept design and can be elaborated in further detail below⁸:

- ✓ Product architecture
Physical components are outlined and allocated to the function of the product.
- ✓ Design configuration
General dimensions and sizes are established here.
- ✓ Parametric design
Design variables are allocated values to produce the best product design.

The embodiment design phase is based upon furthering the concept design with enough details and functionality to ensure the detailed design phase is easily completed. For this application and this thesis, the embodiment design was completed within the feasibility study based on the concept design. The simulation model can be considered as the embodiment design as the finer details were determined in this stage based on the concept design.

Detailed design

In the detailed design phase of the design phase, all the final details are worked out to ensure the project or product is manufacturable. The final tolerances, clearances and customer perception are considered in this phase⁷.

The design is typically refined, and the design's plans, conditions and approximations are created here⁹. The detailed design phase also allows for 2D and 3D models to be generated, procurement plans, and the full cost of the project or product to be identified.

⁸ 2022. Embodiment design. Engineering product design. <https://engineeringproductdesign.com/knowledge-base/embodiment-design/> Date of access: Sept. 8, 2022.

⁹ Projen. Why is detailed design & engineering important? <https://www.projen.co.uk/info-centre/why-is-detailed-design-engineering-important/#:~:text=Detailed%20design%20ensures%20that%20the,detailed%20design%20and%20engineering%20solution.> Date of access: 13 September 2022).

The detailed design is not able to exist without the conceptual thinking. However, most of the mathematical corrections and modelling is completed during the detailed design⁷. The detailed design phase in this study was completed within the feasibility section based on the embodiment design (simulation model), although it is discussed in the pre-feasibility for continuity.

Theoretical calculations

Theoretical calculations needed to be performed initially to determine the estimated power that can be generated from a chosen application. This was the backbone of the study as without enough power generation, this study would be unfeasible. Therefore, the theoretical calculations were performed within the pre-feasibility step to determine the initial generative capacity.

The theoretical calculations were based on the water characteristics within the system as it would pass a turbine. Typically, a turbine converts accumulated water pressure or gravitational potential energy (Head) into mechanical energy through the turbine shaft [98]. The turbine shaft rotates as a result and is attached to a generator [98]. The turbine shaft rotates the generator shaft and electricity is then generated [98]. For the theoretical calculations, the power factor was assumed as 0.9. The electricity generated via the hydropower system can be calculated through Equation (1) [98, 99]:

$$P_{Gen} = \rho * g * H_n * Q * \eta_g * \eta_p * PF$$

Equation 1

Here:

P_{Gen} = Power generated (kW)

ρ = Water density ($1\,000\,kg/m^3$)

H_n = Net head (m)

Q = Water flow rate (m^3/s)

g = Gravity ($9.81\,m/s^2$)

η_g = Generator efficiency (%)

η_p = Pump efficiency (%)

PF = Power factor

Equation 1 represents a linear equation used to determine the amount of power generated with the listed parameters. The reasoning for this choice of equation type is to ensure that the relationship between flow and head directly impacts the power generated¹⁰. Another justification for the choice, is that the pre-feasibility is supposed to give an indication whether the turbine system is feasible to warrant further investigation, thus the simpler answer is sufficient, thereafter, more detailed analysis such as simulation models can be explored.

Water pressure can be calculated with the following equation¹¹:

$$P_w = \frac{\rho * g * H_n}{1000}$$

Equation 2

Here:

P_w = Water pressure (Pa)

Thus, the final equation can be deduced to:

$$P_{Gen} = P_w * Q * \eta_t * \eta_p * PF$$

Equation 3

Important decisions can be made based on the generative capacity results as well as the CAPEX required to realise the ideology. It is important to bear in mind that the theoretically generated power is not completely accurate as it does not consider losses within the system and optimal

¹⁰ I. E. Team. 2023. Linear vs. Nonlinear Equations: Definitions and Examples. <https://www.indeed.com/career-advice/career-development/linear-vs-nonlinear#:~:text=A%20linear%20equation%20forms%20a,view%20nonlinear%20equations%20as%20complicated>. Date of access: Oct. 11, 2023.

¹¹ Anonymous. Water Pressure Formula with Examples. <https://byjus.com/water-pressure-formula/> Date of access: Jun. 2, 2022).

control of the system. Thus, it is important to build a simulation model which reenacts actual conditions and provides more accurate results, as discussed in Section 2.4.3.

The number of theoretical calculations performed is solely dependent on the designer as several iterations can be selected dependent on the desired outcome and variables. This does, however, need to align with the simulated model iterations to ensure a fair and comprehensive comparison with the expected outcome. This is also explained further in the next section (Section 2.4.3).

Estimated CAPEX

The return on investment (ROI) will play the vital role in determining whether a hydropower project is viable. Ideally, capital intensive projects are subsequently avoided with an ROI of more than a year [100]. Therefore, reducing the CAPEX and maintaining a similar output will allow for an improved ROI and higher profitability.

A cost study should be completed based on the concept design, including machinery and equipment required as well as labour, to determine the total cost to implement the project from start to finish. Once the final cost has been obtained, the ROI period can be determined with the following equation¹²:

$$P_p = \frac{COI}{AACF} \times 12 \text{ months}$$

Equation 4

Here:

P_p = Payback period (Months)

COI = Cost of investment (R)

$AACF$ = Average annual cash flow (R)

¹² J. Kagan. 2022. Payback period. Investopedia. <https://www.investopedia.com/terms/p/paybackperiod.asp#:~:text=The%20payback%20period%20is%20calculated,by%20the%20annual%20cash%20flow>. Date of access: Aug. 5, 2022).

With the aid of Equation 4, the pre-feasibility step of the solution development can be completed. With the calculated value, important decisions can be made to determine whether the project is viable enough to implement on a financial basis.

2.4.3. Feasibility

The feasibility study analyses the solution more extensively and permits a suitable solution to be selected for implementation. Within the feasibility section, a simulation software needs to be selected based on the needs of the project, required machinery and equipment need to be sourced (with specifications), required CAPEX lists need to be compiled and final CAPEX approval is required from the organisation.

Figure 15 illustrates the feasibility process that can be followed:

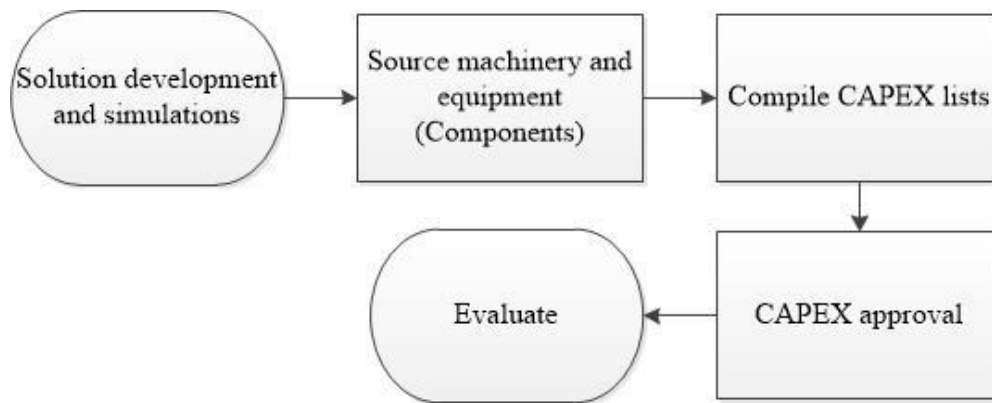


Figure 15: Feasibility process flow diagram

In summary, the feasibility of a project can be summarised as follows:

1. Select a simulation software and build detailed simulation with design specifications for various scenarios based on the concept design.
2. Source machinery and equipment with specifications
3. Compile CAPEX list for scenarios and obtain pre-approval.
4. Obtain approval from committee members for capital and project implementation.

Once the feasibility study is completed, it will contain a list of possible solutions detailing the process and KPIs of models. From this list, the most suitable is chosen for the application. The ideal solution will also be optimised and improved to obtain the maximum benefit.

1. Solution development and simulation procedures:

When constructing the detailed model, it is beneficial to follow a structured process. It is also beneficial to follow a simplified process. Therefore, a simplified, generic, and deduced

simulation procedure was developed for this application and type of study. A brief process that can be followed is depicted in Figure 16.

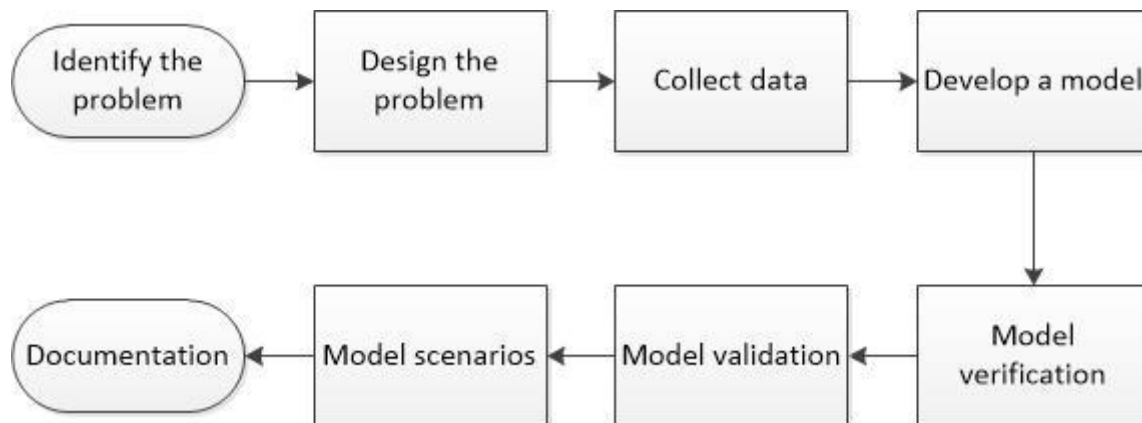


Figure 16: Simplified simulation procedure modelling integrated systems.

This process allows an initial problem statement to be formed, the problem to then be designed with all the factors, and data to be collected surrounding the problem¹³. Detailed models can then be constructed and validated accordingly with actual results prior to modelling the problem¹³. Once the problem and solution have been modelled, appropriate decisions can be made based on the simulation results¹³.

Identify the problem

Identifying the problem in the commencement phase is probably the most crucial stage as this is where the entire problem complex needs to be defined in as much detail as possible. The problem statement gives context of what the current issue is and what provoked the study [101]. The identification of the problem also highlights the objectives to be achieved [102]. Problem identification is typically associated with the “what” aspect of the process [103].

Along with the problem statement, there is generally a goal and objective statement that follows in the next step. Ensuring a well described and comprehensive understanding of the problem is key, especially as the following steps build on this. If the problem and objective are inadequately defined, the following steps will incorrectly and inadequately attempt to find a

¹³ Anonymous. Modelling & Simulation - Quick Guide. https://www.tutorialspoint.com/modelling_and_simulation/modelling_and_simulation_quick_guide.htm Date of access: Jun. 8, 2022).

suitable solution which may only be realised too late. This will result in a waste of time, resources, and money.

This emphasises the importance of appropriately and clearly defining the problem and warrants enough time and effort is spent on the problem statement. A clear and concise problem statement will allow for accurate and appropriate objectives to be established.

Design the problem

Designing the problem can also be referred to as formulating the problem. Problem formulation allows for a solid foundation to be established and the “how” aspect of the problem to be formulated [103]. Figure 17 defines the “design the problem” step-by-step guide which can be used to define the problem comprehensively and outline the required information.

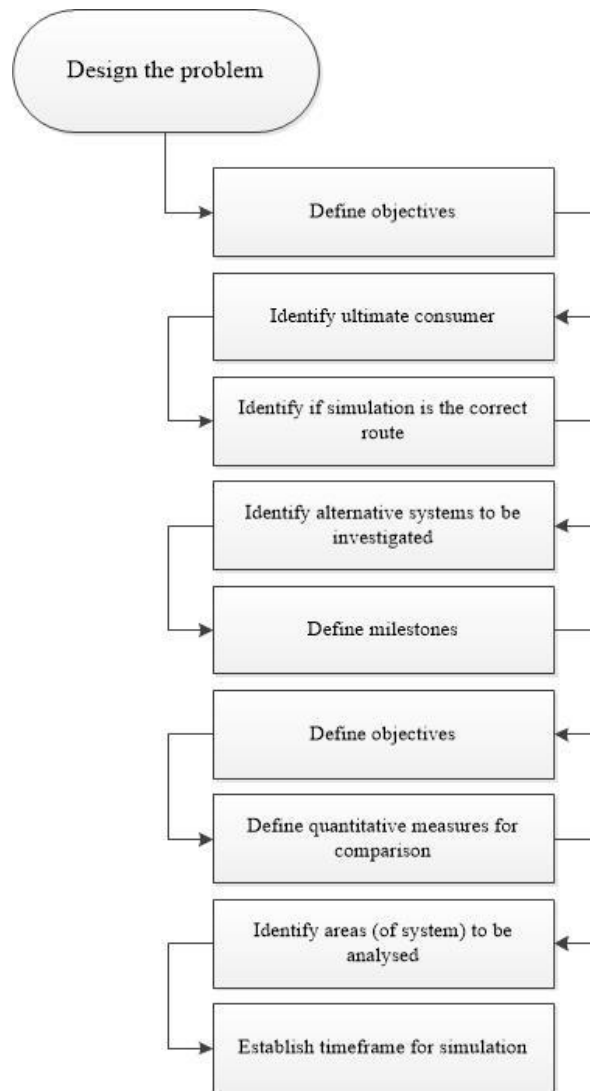


Figure 17: Design the problem flow diagram¹⁴

Collect data

Collection of data is typically completed for the simulation model to accurately model the current operations. An online blog argues that the data collection phase of the simulation process is a critical step in the process¹⁴. Maré [23] defines the data acquisition process as follows:

1. Attain system data.
2. Attain system designs.
3. Outline system components and specifications.

¹⁴ SoftwareSim. (November 20, 2021). The 9 phases of a simulation project [Web log post]. Retrieved from <https://softwaresim.com/blog/the-9-phases-of-a-simulation-project/>

4. Determine the current control philosophy.
5. Attain future initiatives and
6. Attain current operative budgets.

Figure 18 is a visual representation of the data collection flow diagram process that can be followed and was followed in this thesis.

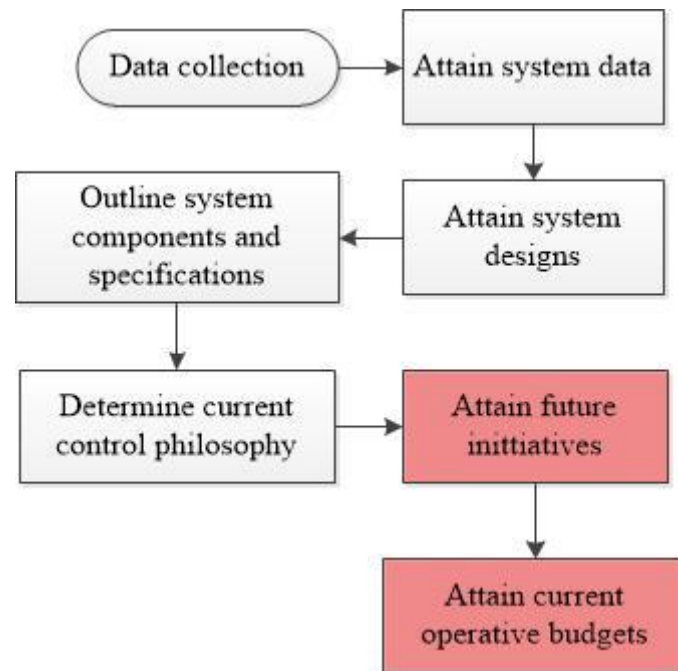


Figure 18: Data collection procedure followed [23]

For this application, Steps 5 - 6 (highlighted in red) were not applicable, as budgets and future initiatives were not modelled in the simulation and prediction outcome. Steps 5- 6 were not applicable for this case and were omitted from the procedure as they did not fall within the scope of this thesis.

Develop a model

Simulation procedures in engineering –

This section of the thesis briefly discusses the simulation procedures found in literature to substantiate the complexity and importance of ensuring a thorough yet simplistic simulation procedure is developed and in place. The developed simulation procedure will form part of the solution development and novel contributions of the study. The developed solution strategy i.e., simulation procedure, is discussed and explained in more detail in section 2.4.

Maré [23] discussed the entire process of a new simulation approach that can be used when developing a simulation model. The author also incorporated the different mining systems and budgets which do not feature in this thesis. In the author's simulation approach, they discuss various procedures and sub-procedures that have been followed during different steps of the process for the different mining systems.

In some cases, much of the required simulation information and inputs will not be available [23] depending on the technology available at the site, as well as the type of simulation model being modelled. Some simulation models require extensive inputs that are not readily available for the user. The simulation characteristics are reliant on the application and convenience of system data. The type of simulation model being developed also determines the information availability (assuming updated technology on site). A prediction model will typically not allow for a wide array of data availability as specifications need to be determined by the model in the embodiment and detailed design phases (discussed in the previous sections).

Maré [23] incorporated the various large mining systems (refrigeration, air cooling systems, water supply, water reticulation and dewatering) in their simplified transient response procedure. However, the procedure developed by Maré does not apply to this study. Although of significance, their procedure incorporates baselines, budgets, the various mining systems and is mainly focused on transient response.

The purpose of this section is to identify a generic simulation procedure that can be applied to any application regarding hydropower, not only on mines. These types of procedures are discussed below.

Bouwer [104] also developed a procedure that was aimed at verifying the integrated simulation developed within the method. The procedure developed focuses on providing a guideline on simulation approach [23]. The procedure is depicted in Figure 19 as a flow diagram.

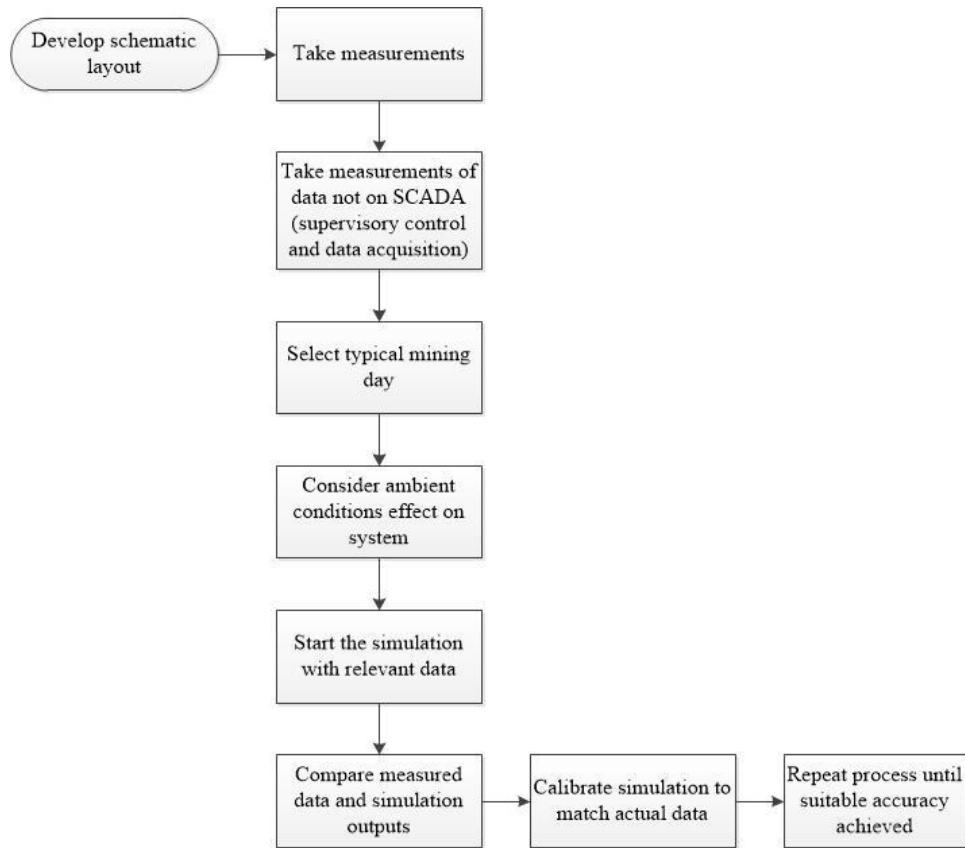


Figure 19: Simulation process procedure A [23, 104]

The procedure developed by Bouwer [104] was identified as part of the literature study and can be summarised as follows:

1. Develop schematic layouts to establish the configuration of the model and measurement points.
2. Conduct comprehensive audits and collect the data of the systems required within the simulation model (dams, temperatures, flows, electricity consumers and consumption etc.).
3. Collect relevant data of systems and sub-systems not recorded on the SCADA system (Supervisory control and data acquisition system).
4. Select a normal operational day for simulation and calibration purposes.
5. Ensure ambient conditions are considered within the simulation model.
6. Complete the simulation setup with the suitable data and initiate the simulation.
7. Create a comparison between the measured and collected data with the simulation results.
8. Calibrate the simulation until measured and simulation data correspond. This is an iterative process.

Discrete-event simulation (DES) is becoming more popular as it is used as aid for important decision-making [105]. By making use of modelling, analysis, and system design, parameters of a system can be altered and the impact of these alterations measured on the output performance [105]. The majority of the DES projects are deconstructed into three stages, namely conception, implementation and analysis [105].

F. Pereira, et al. [105] describe the conception phase as the problem definition where objectives are identified, and the conceptual model is discussed. The concept phase is also considered the most important phase of the three, as the main objectives are defined here [105]. The implementation phase includes translating the conceptual model into a computational variation (with suitable simulation software) and the analysis phase, where various simulation scenarios are run [105]. The input parameters are altered accordingly to generate a certain output or mirroring a current system and the outputs are then used to aid critical decision making [105].

Figure 20 graphically demonstrates the three phases of the simulation procedure.

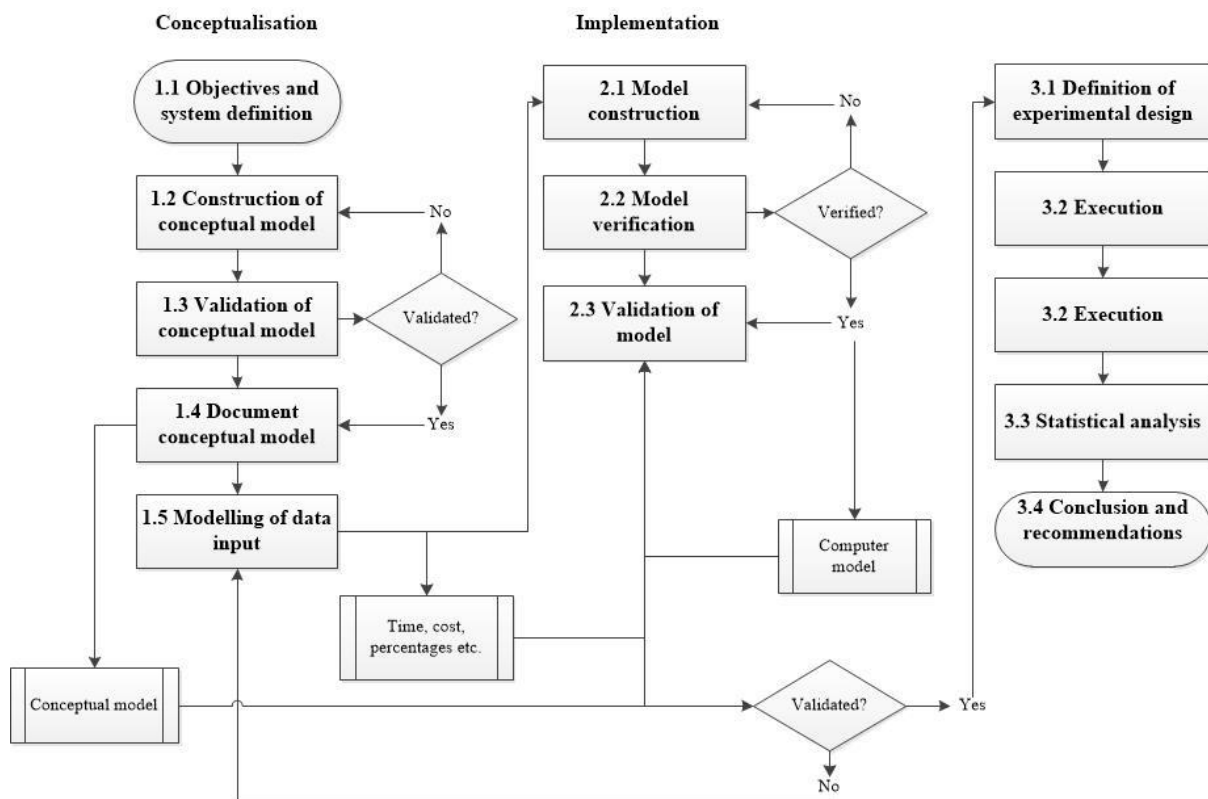


Figure 20: Procedure B – Project simulation phases and steps [105]

Another simulation procedure of significance to this thesis is by Rabya [102], who developed a nine step process. The nine steps include defining the problem, project planning, defining the system, model formulation, data collection and analysis, model translation, verification, and

validation, experimental and analysis and finally, documentation as well as implementation [102].

Figure 21 depicts the procedure and summarises the most important steps required to fulfil the criteria mentioned by Rabya [102].

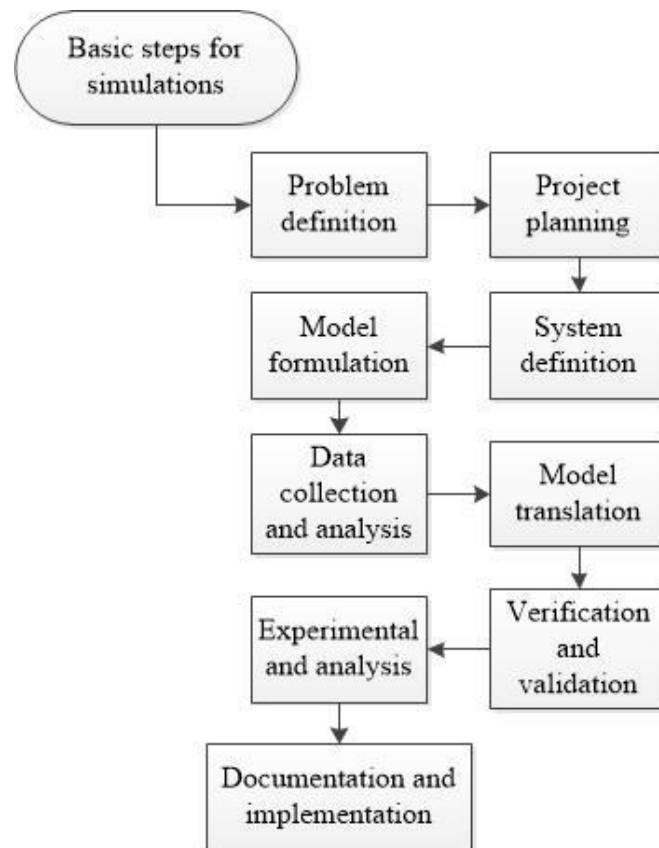


Figure 21: Procedure C – Basic simulation steps [102]

In summary, all the above-mentioned simulation procedures (Procedures A-C) have many similarities. The most common aspect of these procedures is adequately identifying and defining the main problem. This, in turn, allows the user to define the main objectives of the simulation. Once the main objectives have been defined, the simulation model may be generated according to the concept idea.

This thesis also assists with a procedure to follow when developing a simulation model. By using the simulation procedures obtained in literature, a generic simulation procedure was formulated customised for this application and generic for further cases with the aid of thermo-hydraulic computational methods.

Prior to the model being developed, it is also important to consider which simulation software is to be used, as different software programs achieve different outcomes [23]. The software must be tailored for the specific purpose.

One of the many benefits of using a simulation program is that the model developed acts as a form of documentation, thus reducing the time and effort to document the results on a separate document. This is explained in further detail later in this section.

Simulation models available in industry

Various simulation software programs exist that can be used for different outcomes of the project. Therefore, selecting the correct software is critical. This selection process highlights the importance of initially defining the problem. With a well-defined problem and goal, the selection process is made simpler as the most suitable software can be chosen for the project's outcome.

Traditionally, simulations, especially energy simulations, were utilised as an inexpensive manner to identify new energy efficiency and cost saving methods [23, 104, 106]. There does, however, exist a need to use thermo-hydraulic simulations for PAT performance prediction as shown by the lack in the literature study. Maré [23] and Bunse, et al. [107] also mentioned the need for energy efficiency and KPI visualisation and a simulation tool to integrate the energy efficiency performance.

REMS

Realtime Energy Management Systems, otherwise known as REMS¹⁵, is an energy management software, mainly focused on dewatering and cooling systems, that can be used to simulate, optimise, and control these systems [23]. Unfortunately, REMS is not able to complete predictive modelling in terms of energy generation [23].

¹⁵ Developed by TEMM International Pvt. (Ltd.). Contact Jan Vosloo; jvosloo@rem2.com; 087 980 3620

Process Toolbox (PTB)

The integrated mining system software known as Process Toolbox¹⁶ (PTB) can be used to model integrated mining networks and systems for a comprehensive model according to Maré [23] and Holman [27]. PTB is a thermal-hydraulic simulation software which is able to simulate integrated and complex networks simultaneously. Maré [23] also mentioned that there exists a need for further software development. However, the basic functionality is sufficient for novel simulations. PTB makes use of transient modelling, which benefits predictive simulations [23, 108].

ANSYS

Ansys has a variety of different products that can be used for modelling certain applications. For this comparison, Ansys Fluent is discussed. Ansys Fluent can be used to model advanced physics models and analyse fluid phenomena¹⁷. The study conducted by Alvear Pérez, et al. [109] focused on simulating the performance of a pico-hydraulic turbine to generate power specifically in residential suburbs and focusing on small waterfalls and streams. The simulation was not integrated with a complex network but was simulated singly. The study also focused on the rotation speed of the turbine and the outlet pressure.

Another study conducted (Lu, et al. [110]) made use of Ansys Fluent, whereby the flow energy dissipation (FED) was compared at two different typical guide vane angles (pump and turbine mode) based on computation fluid dynamics (CFD) and the entropy production. This study, however, did not record the electricity generation and consumption at the different guide vane angles.

Yu, et al. [111] made use of Ansys CFX 18.0 to analyse the energy evolution features in the PAT. This study also did not integrate the surrounding systems and did not simulate a possible digital twin but focused on the energy evolution throughout the turbine cycle and effect of the turbine blades.

¹⁶ Developed by TEMM International Pvt. (Ltd.). Contact Jan Vosloo; jvosloo@rems2.com; 087 980 3620

¹⁷ Anonymous. Ansys Fluent Fluid Simulation Software. <https://www.ansys.com/products/fluids/ansys-fluent> Date of access: 28 January 2023.

A fair number of studies have been completed with the aid of ANSYS. However, many of these studies focused on the internal water flow and dynamics within the turbine. For this study and application, the focus needed to be on the turbine performance as well as on the integrated network performance under new conditions. The purpose of the simulation is to predict how the integrated network (current network) will perform when subjected to an additional component or sub-system.

SimScale

The SimScale suite of software is a cloud-native software and was mainly designed for engineering simulation tools for propeller, fan, compressor, pump, and turbine applications¹⁸. This advanced physics solver allows designers and engineers to analyse and optimise pressure drops and force behaviour, assess fluid flow patterns, and reduce cavitation¹⁹.

One study used ANSYS and SimScale to analyse the PAT characteristic curves, specifically focusing on the off-design operating conditions [112]. The study focused on recreating or reconstructing the performance curves with limited operational data in turbine mode at the Best Efficiency Point (BEP) [112]. From this study and previous studies discussed in the previous sub-section (ANSYS), it was noted that predictive simulations are possible. However, integrating systems into the simulation was not performed.

Autodesk CFD

Key features of this simulation suite include the analysis of rotational machinery surrounded with a static frame of reference²⁰. This CFD software suite also simulates flow control applications, motion simulation (where the interaction between solid objects in motion and a fluid is modelled), thermal prototyping and other applications which are not of relevance for this case.

¹⁸ SimScale. "Turbomachinery, Propellers, & Pump Simulation." [Online]. Available: <https://www.simscale.com/industries/turbomachinery/> Date of access: Jan. 28, 2023.

¹⁹ SimScale. "Turbomachinery, Propellers, & Pump Simulation." [Online]. Available: <https://www.simscale.com/industries/turbomachinery/> Date of access: Jan. 28, 2023.

²⁰ AutodeskCFD. Key features of Autodesk CFD. <https://www.autodesk.com/products/cfd/features> Date of access: 30 January 2023).

One study modelled and simulated, with the aid of Autodesk CFD, an estimate error caused by power decrement and the reason therefore [113]. The study and simulation software did not simulate an integrated system. Figure 22 illustrates the simulation results obtained from the Autodesk CFD simulation.

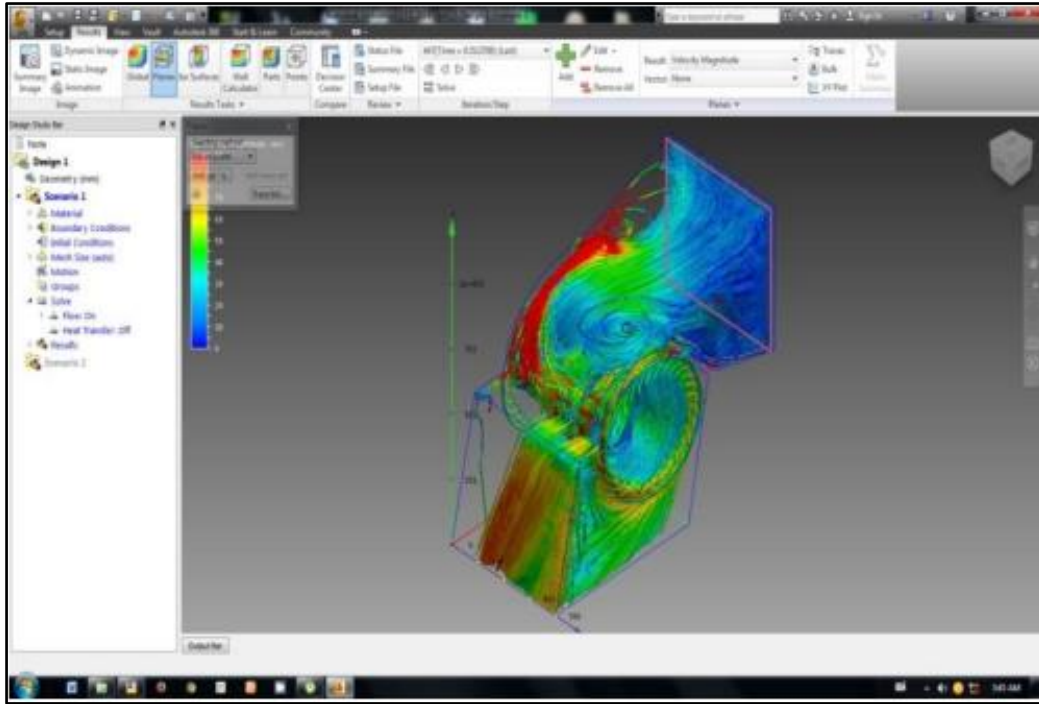


Figure 22: Simulation results (Autodesk CFD)[113]

It is clearly noted that only the turbine itself is simulated and does not represent an integrated thermal-hydraulic system. Other CFD software suites include:

- CFD Module
- OpenFOAM
- Simcenter
- Flowsquare
- SOLIDWORKS

These software suites are not common in literature but are used for engineering problems and computational simulation methods. These simulation suites possess the same capabilities as most. However, they do not possess the capability specifically required for this application such as modelling an integrated network system and developing a digital twin of a large system. A digital twin is defined as a simulated imitation of a real object or system and is also part of Industry 4.0 [114]. The capabilities compared can be summarised to the following questions:

- Can the software suite model a digital twin (system)?
- Can the software complete transient calculations (predictive modelling)?
- Can the software suite perform integrated network modelling?
- Does the software suite allow to optimise the model and control?

When comparing the simulation capabilities and study objectives, there were relative correlations with objectives number 2, 3, 5, 6 and 7. The correlation is dependent on the capability of the simulation as a result of the study objectives. Based on these parameters, the simulation must be capable to perform and satisfy the questions mentioned above, which in turn will assist in fulfilling the crucial study objectives.

Table 2 tabulates the software capabilities and compares them across a series of requirements for this study.

Table 2: Simulation software comparison

	Simulation software capabilities			
Software	Digital twin	Transient calculations	Integrated network modelling	Optimisation and control
REMS			✓	✓
PTB	✓	✓	✓	✓
ANSYS		✓		✓
SIMScale		✓		✓
Autodesk CFD		✓		✓
CFD Module		✓		✓
OpenFOAM		✓		✓
Simcenter		✓		✓
Flowsquare		✓		✓
SOLIDWORKS		✓		✓

Based on the software comparison, PTB was chosen for this application as it possesses the capability to complete models with transient calculations, whereas most of the software available use steady-state calculations [23, 108]. Transient calculations also allow for predictions to be made, which was required for this study [23, 108]. This thesis is based on the prediction of a PATs performance, therefore PTB's capabilities and functions align with the research outcome and was the most suitable choice.

Literature has shown the benefits of using an integrated simulation software, which has become an essential commodity when conducting an engineering research project. The various benefits of using computational models are summarised below as [23, 27, 28]:

- The model serves as a form of documentation of the project.
- The specialist and modeller comprehend the project modelled.
- The model forms as a basis for component selection, design, and specification.
- The model serves as a “faultfinder” and can eliminate faults on a digital platform.

Liu, et al. [31] also recommended the use of 3D numerical simulations when predicting the performance of turbines and PATs to ensure all the losses are considered in the outcome calculation. The authors also mentioned that 2D simulations miscalculate the power coefficients for both wind and hydro systems, therefore the use of 3D simulations is substantiated.

Once the software has been selected, the simulation properties need to be defined according to the following criteria [23]:

- Establish simulation time periods
- Establish the number of simulation time steps
- Establish the time-period size
- Consider the number of iterations

The detailed model can then be developed based on the information collected and validated by modelling various actual scenarios under different conditions, which are documented for future use²¹.

Minor adjustments can be made to the control strategy to optimise control and obtain the maximum benefit from the energy recovery system. To ensure the optimal solution is modelled, the solution should be dynamic before progressing to the next step of the methodology, thereby ensuring an iterative process.

²¹ Anonymous. Modelling & Simulation - Quick Guide. https://www.tutorialspoint.com/modelling_and_simulation/modelling_and_simulation_quick_guide.htm Date of access: Jun. 8, 2022).

Model verification

Verification is the process of ensuring that model behaves as intended and is a comparison of data to ensure accuracy, especially between the model's implementation, associated data with conceptual design and specifications²¹ [102, 103]. For this study, computation thermal-hydraulic simulation models were used to verify the developed strategy as well as the application of a PAT in an integrated WSS and WDN. Ideally, a minimal simulation error of below five percent is strived for [115, 116].

A detailed simulation model is able to predict the performance of a possible system without actually physically adjusting any system configurations. This is advantageous as it can be completed iteratively until the desired outcome is obtained [117]. This will typically be completed within the feasibility section described in Chapter 3.

Model validation

Model validation specifically refers to ensuring that the developed model reflects reality and that there is no major difference between the model and the real system that the model is reflecting [102, 103].

It is therefore important that a model be critically evaluated to ensure that the model is verified and validated prior to implementation. This step acts as the quality control step, confirming the required objectives are being met and supplying accurate data. If either step of the process fails, the model should be re-developed, and the procedure repeated until suitable and favourable results are obtained.

The model validation was done once the model scenarios were completed to validate the entire developed strategy.

Model scenarios

Ideally, when simulating models of PATs, the typical simulation would drift towards the BEP to determine the maximum efficiency of the system. The BEP can be determined from the curve, and then point selected and modelled in the simulation suite. It is also important to take the input parameters collected in the comprehensive investigation into account as a starting point. The number of model iterations is normally also determined in the pre-feasibility section

where several theoretical calculations are completed. The quantity of model iterations generally aligns with this number.

Documentation

Documenting the entire process from start to end to ensure all critical steps, data and information are stored for records purposes needs to be completed. Depending on the purposes and origin of the project, the relevant documentation needs to be completed. For this application, which is discussed later, a business case report was compiled and submitted for corporate funding. Although this was more high-level for funding purposes, another engineering report was also written for documentation purposes.

2. Source machinery and equipment with specifications:

Based on the model built in the simulation software, the required specifications can be compiled in a BOM (Bill of materials) and BOQ (Bill of quantities). With both the BOM and BOQ, the required machinery and equipment can be sourced from various companies. Depending on the company's procurement procedure, certain items need to be sent out on tender while other items below a certain value can be procured directly with the correct motivation. This equipment list can then be used later for the detailed design, as discussed in Section 2.4.4. The equipment specifications, sizes and quantities are then used for the final design of the project.

3. Compile CAPEX lists and requirements:

A CAPEX list can then be compiled for the initiative, which then forms the basis of the business case. The business case reports are then compiled with both the theoretical values, simulation results and CAPEX requirements. In the business case, the project is presented on a high-level, mainly for management purposes, where the project can then be analysed and the final approval decision can be made, provided all the criteria is met.

4. CAPEX approval:

The business case (as discussed in the above section) is then compiled and submitted to management and the various committees for final capital approval. Once the project is approved and capital available, the project can be implemented based on the detailed design. As depicted in Figure 8, this is the typical hierarchy that needs to be followed for a CAPEX project to be approved. Each level (highlighted) within the hierarchy is required to approve the

project on both a fundamental and capital basis. This process can be both time consuming and problematic due to the availability of the stakeholders as well as technical analysis. This process complicates the entire commercial process and can easily delay the project.

5. Evaluate

Evaluating the solution development during the process ensures the quality of prior stages and that the ideal solution has been selected to be implemented. The ideal solution will also be optimised and improved to obtain the maximum benefit.

The updated models are then compared with the theoretical models to distinguish the better option prior to implementation. This step in the process allows for the more suited solution to be selected with a higher quality data set. “Evaluate” acts as a method of quality control. The process of evaluation will determine whether the developed solution is optimal and can further be enhanced. If the process is optimal, further enhancement is void and the solution developed is suitable. If the suggested solution is viable and has been validated by means of CFD analysis, the project may be implemented.

2.4.4. Implement – Implement the solution

The implementation of the strategy is the physical installation and construction of the designed idea once all the required approvals have been obtained from the various parties, such as the acting engineer. The implementation step can be summarised as depicted in Figure 23.

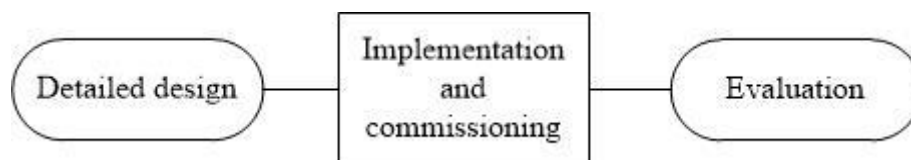


Figure 23: PAT implementation strategy

This stage consists of four main steps which include detailed design, implementation, commissioning, and evaluation. This is explained in further detail below.

1. Detailed design

The detailed design forms the crux of the initiative as the theoretical and simulation model results are combined to achieve a collective effort of knowledge and calculations. The detailed design is based on the concept design as explained earlier in this thesis (Section 2.4.2). Within this stage of the process, the project is implemented according to the detailed design (as signed

off by the appointed engineer), which is drafted by the on-site appointed draughting department.

2. Implementation and commissioning

Depending on the resources available for the project (capital, manpower and time) certain tasks can then be delegated and allocated to teams to complete. By doing so, especially when involving contractors to complete certain tasks, this assists with the completion of a project by a certain date and can be held to a higher standard. This is especially helpful when resources are limited, which would inevitably delay the project.

Commissioning of the project normally occurs once the implementation is completed. Commissioning of the project generally ensures that the system that has been implemented is started and operational according to what has been stipulated during the problem statement, objectives, and concept design.

Typically, the implementation and commissioning of a project is performed in conjunction with one another. For this strategy, the implementation and commissioning were performed within this step.

3. Evaluation

Evaluation of the implementation stage is done to assess and analyse the performance of the two above-mentioned steps, which includes investigating whether the problem statement has been addressed, whether the objectives set out have been achieved, as well as checking the physical standard of the work performed. The onsite engineer will be involved in this step as the final sign-off will be performed by the appointed site engineer.

Another part of this step and the final step (discussed in 2.6) is to analyse the overall performance of the PAT implementation. Therefore, this step and the final step of the procedure coincide with each other.

2.5. Verification – Verify strategy’s operational efficiency

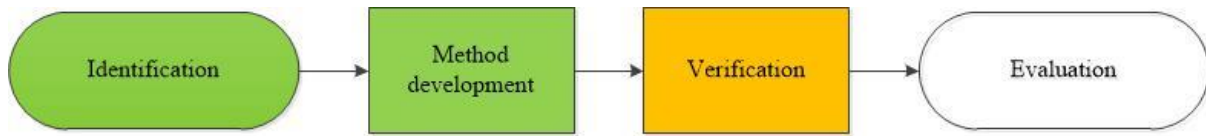


Figure 24: Methodology – Verification step

To adequately verify the strategy’s operational efficiency, it is best to compare the theoretical, computational, and actual results obtained to determine the operation accuracy of the strategy, as well as the methods applied to predict performance. It is also important to consider computational results validation (when comparing to theoretical results) due to the technological capabilities in this century. Actual implemented results are considered as further validation and confirmation of the solution strategy.

Once this comparison has been completed, a comprehensive post audit should be completed to ensure safety standards are adhered to as well as the final design parameters. This post-audit should focus mainly on the PAT performance, compared with the expected results (theoretical and simulation results). There should be a strong correlation between the results. If the results do not correspond with each other, it should be investigated as to what the cause may be and documented to ensure it may be considered for future works and projects.

2.6. Evaluation – Evaluate the strategy’s overall operational performance

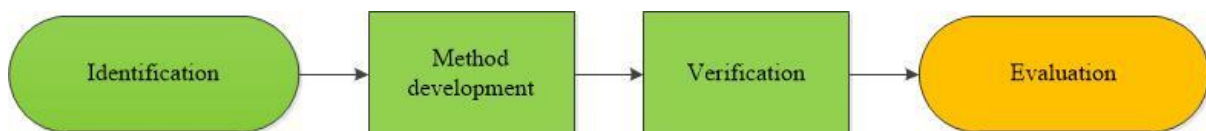


Figure 25: Methodology – Evaluation step

Typically, when evaluating the strategy’s overall performance, the performance and actual results will be compared to that of the simulation and theoretical results. This comparison will allow an in-depth analysis of the performance prediction and actual results obtained. From the comparison, detailed information can be used to make important decisions, whether it may be corrections or future regenerative projects.

The overall system and, moreover, the PAT efficiency can be determined and cross-checked with the PAT characteristic performance curves. The performance of the PAT can also be manipulated, if need be, to optimise parameters that may benefit the PATs overall performance

operating point. This can be an iterative process until the desired or most optimum operational and regenerative capacity is obtained.

It is best to always document findings and performances of projects, therefore it is not included as the final step. It is beneficial to ensure a final engineering report is written, summarising the main ideas of the project as well as results.

2.7. Conclusion

This chapter has focused on the development of a method to implement a PAT in a large and energy-intensive system, based on recovering gravitational potential energy that exists in WSSs and WDNs. The methodology also includes a corporate and commercial aspect to account for the budgeting cycle and CAPEX cycle of a corporate environment.

The main purpose of the method, which also forms part of the novel contributions, was to test the pre-feasibility (theoretical) and feasibility of a PAT in an application (either reclaimed or new, dependant on circumstances) and accurately predict the performance of a PAT with the aid of a thermo-hydraulic simulation suite whilst sustaining the condition of certain KPIs identified. This falls within the integrated network simulation model and ensures the network is not negatively affected and ultimately hindering the operational capacity of the integrated system.

Table 3 represents the respective locations of where the objectives are achieved within the methodology process.

Table 3: Generic methodology correlation with criteria and content

Step #	Criteria numbers	Correlation
Step 1	1, 2 & 8	Within this step, it is recommended to first conduct a comprehensive investigation of the entire system to ensure it is completely understood. A need is identified and forms part of the energy recovery process. This enables the proper solution to be identified as well as establishes the problem statement. This also forms the basis for the solution development of the hydropower system and is critical for the correct formulation of a strategy.
Step 2	1, 2, 3, 4, 5, 7 & 8	This step focuses on developing a concept design based on the previous step to satisfy the problem statement developed previously. Based on this, a series of theoretical calculations can be determined, which form the crux of the pre-feasibility analysis. Once the estimated capital requirements have been determined, the ROI can be determined to prove the initial feasibility of the hydropower system. Based on the findings of the pre-feasibility analysis, proven profitable, an in-depth feasibility study can be completed to test this analysis with a CFD study. Accurate capital requirements need to be determined and the ROI is then based on this information. The project's business case is then submitted to management for approval and capital is set aside based on approval. The completed feasibility step needs to be evaluated to ensure the main problem statement is satisfied and objectives align with the solution. The project is then implemented (dependent on capital and resource availability) by contractors or site representatives. Upon implementation and commissioning, the hydropower system strategy is to be evaluated.
Step 3	6 & 8	This step focuses on the verification of the strategy as well as the results compared to the theoretical and simulation findings.
Step 4	6 & 8	The final step focuses on evaluating the overall hydropower system performance and objective satisfaction.

Figure 26 displays the detailed developed procedure, also mentioned, and discussed in Chapter 2.

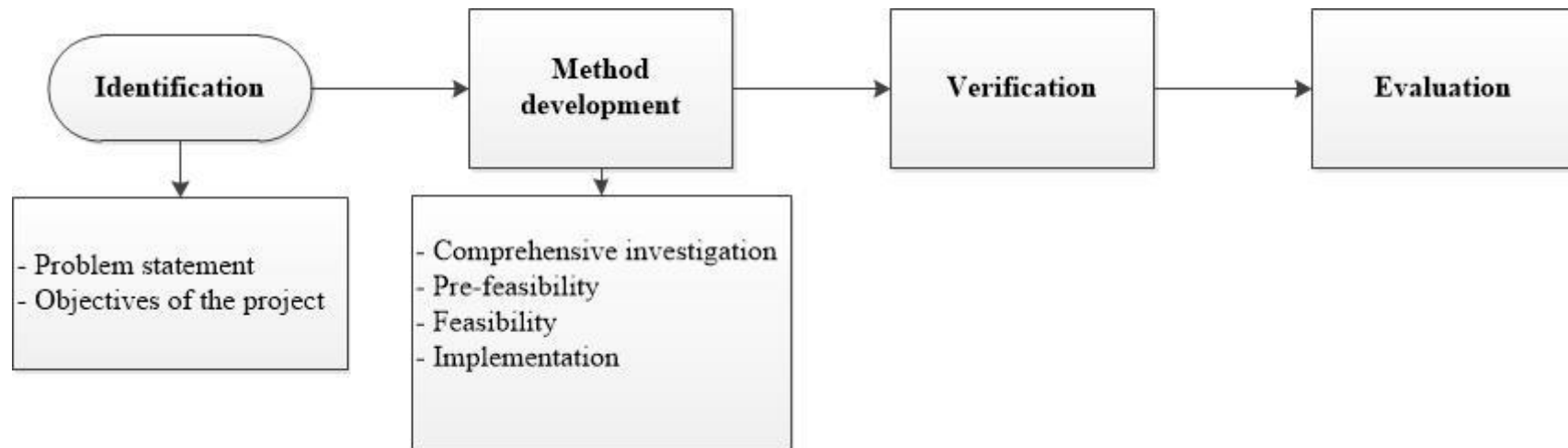


Figure 26: Generic and novel method for reconfiguring a PAT



CHAPTER 3

IMPLEMENTATION & RESULTS

3. IMPLEMENTING A WATER DEMAND MANAGEMENT AND THERMO-HYDRAULIC MODEL ON A LARGE COMPLEX SYSTEM

3.1. Preamble

Chapter 3 describes the application of the newly developed generic solution method discussed in Chapter 2 on a case study, namely Mine X and Mine Y. Mine X and Mine Y will be considered together within this case study. For confidentiality reasons and ongoing agreements, the names both Mine X and Mine Y will be withheld from this thesis to conform to said agreements. The objective of the chapter is to demonstrate the steps taken and procedures followed to implement a successful hydropower system and generate energy that can be used in a large energy-intensive system. The entire process was implemented from start to finish and results from the simulation models, theoretical results and actual results are discussed and compared. Once the results have been discussed, appropriate conclusions are made.

3.2. Background information

Mine X is situated in South Africa and is commonly known for deep-level gold mining. Mine X consumes approximately 47.14 GWh monthly, equating to R61.4 million. Mine X is a large and energy-intensive system with several underground turbine applications which currently generate power from gravitational potential energy recovery. There exists scope to investigate the current underground infrastructure and improve and increase the possible regenerative power from the WSS.

3.3. Identification

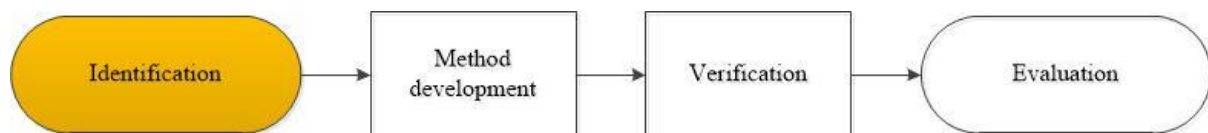


Figure 27: Methodology – Identification step

The objective of the study was to implement a developed solution on Mine X where energy can be recovered by means of renewable measures to assist with the ever-increasing electricity costs.

Problem statement:

Mine X, a large energy-intensive system, has a high monthly energy bill from Eskom, possesses some underground hydropower systems and is facing the challenge of reducing energy consumption. Mine X needed to be further investigated to determine whether there was scope to recover more gravitational potential energy from the current systems and implement another hydropower system.

Objectives:

The main objective was to reduce the high energy bill by implementing a sustainable, renewable hydropower energy system directly connected to the current energy grid with minimal CAPEX, resulting in an energy reduction, i.e., cost saving.

Another objective of the study was to accurately predict the PAT performance (recovered, repurposed or new) and feasibility within a different application with the aid of a thermal-hydraulic simulation software suite, and optimally control the PAT for maximum cost saving benefits. From this study, theoretical and simulation results could be compared to determine the best and most suitable way the PAT performance predictions can occur.

This first step assisted in addressing objectives number 1, 2 and 8, by identifying a possible gravitational potential energy recovery, and formed part of the first step in developing a generic and holistic solution procedure for energy recovery with the aid of a thermal-hydraulic simulation software. The identification process allowed for a need to be identified, and based on the need, certain objectives were identified and formed the basis of the study, therefore aiding with the process of energy recovery.

3.4. Blueprint – Assess and map out regenerative strategy

Mine X was used in this project as the case study to demonstrate how the above-mentioned solution development was used to identify inefficiencies and effectively develop an adequate solution proposal as well as implementation. The power generation of the PAT as well as performance indicators will be evaluated, for this application, power losses on the cables will be considered as negligible as it does not fall within the scope of the thesis. The procedure developed in Section 2.4, in other words, Figure 11, was applied to the case of Mine X to achieve a generative system which is sustainable.

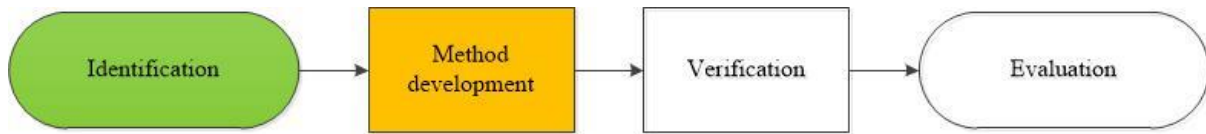


Figure 28: Methodology – Method development step

3.4.1. Comprehensive investigation

Mine X

Mine X has a total depth of approximately 3 900 m with three sets of turbines operating at various levels to recover potential energy and convert it to electricity. The electricity is then rerouted within the grid to the dewatering system, reducing the overall load. Upon completing the comprehensive audit, extensive information regarding the mine was collected to understand the current system systematically.

Comprehensively investigating Mine X led to the retrieval of the following:

1. Underground level layouts (all major layouts of the WSS and WDN)

Water quantity was adjusted for the desired outcome. Figure 29 displays the level layout for 110L (110 Level). With the aid of the layout, the concept design could be drawn according to the actual layout.

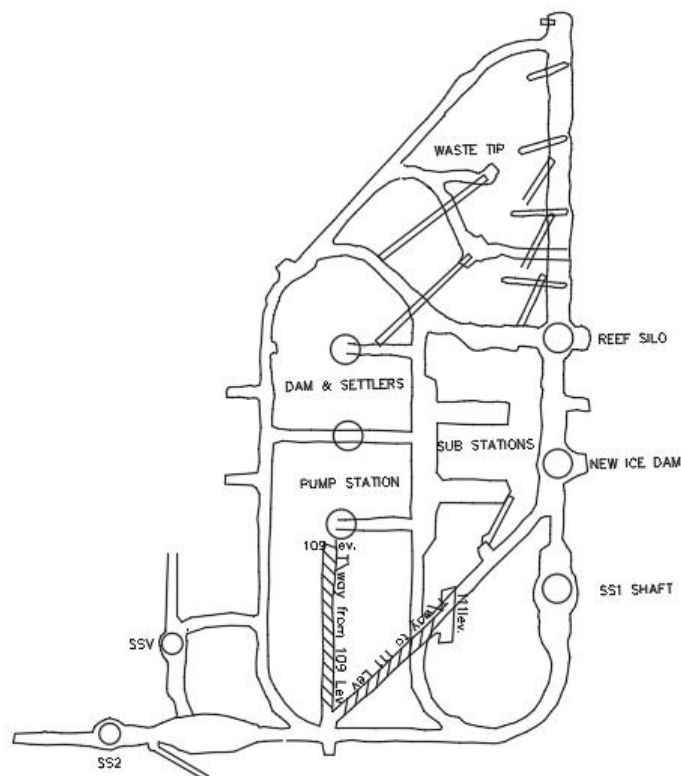


Figure 29: 110L level layout

2. Current underground infrastructure (turbines)

Identified from the extensive investigations, Mine X possesses an impoundment system where a turbine may be installed between the 84L and 110L's ice dam. Figure 30 illustrates the current underground chilled water supply where it undergoes various stages of energy recovery due to the large depth of Mine X.

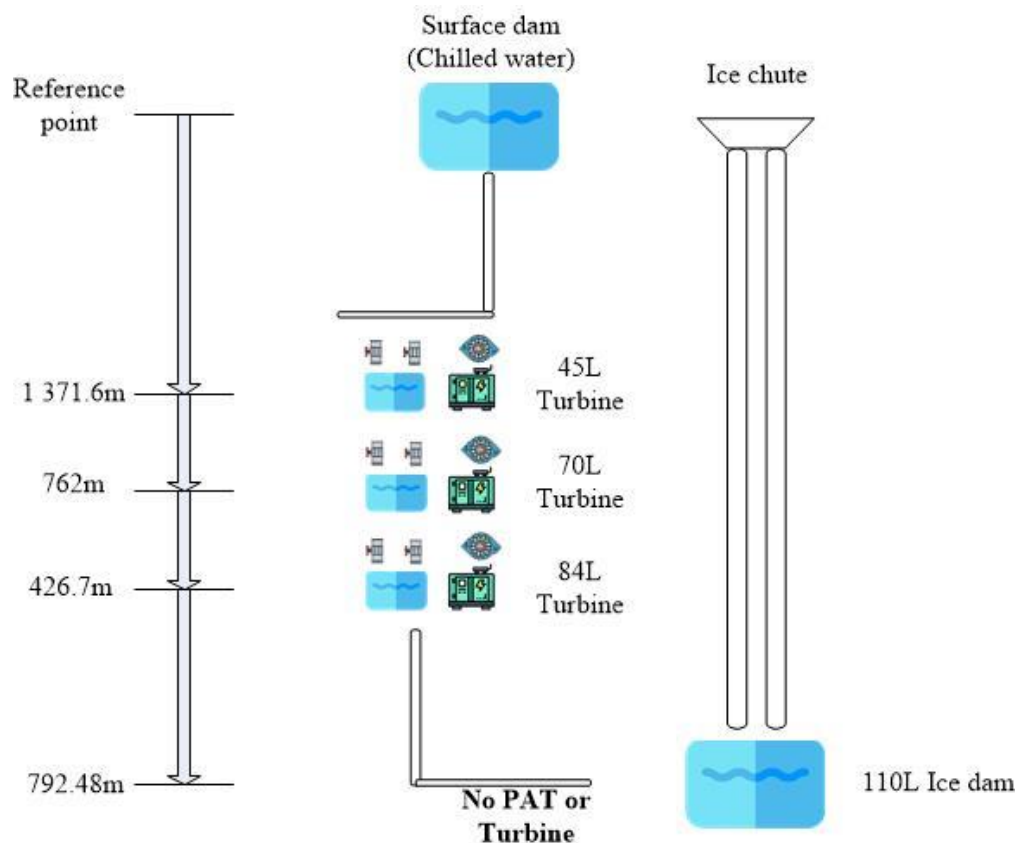


Figure 30: Mine X Chilled water supply and underground infrastructure^{22 23 24 25}

3. Dewatering supply, demand, and re-circulation

Further analysing the 110L ice dam showed several sources of chilled water being supplied to various consumers and some water returning to the ice dam. Two sources of ice are also being

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supplied to the 110L (temperature regulation) ice dam as well as the chilled water feed from 84L. A schematic of a mass balance was drawn to define the water sources being supplied to and returning to the ice dam. Figure 31 depicts the mass balance schematic.

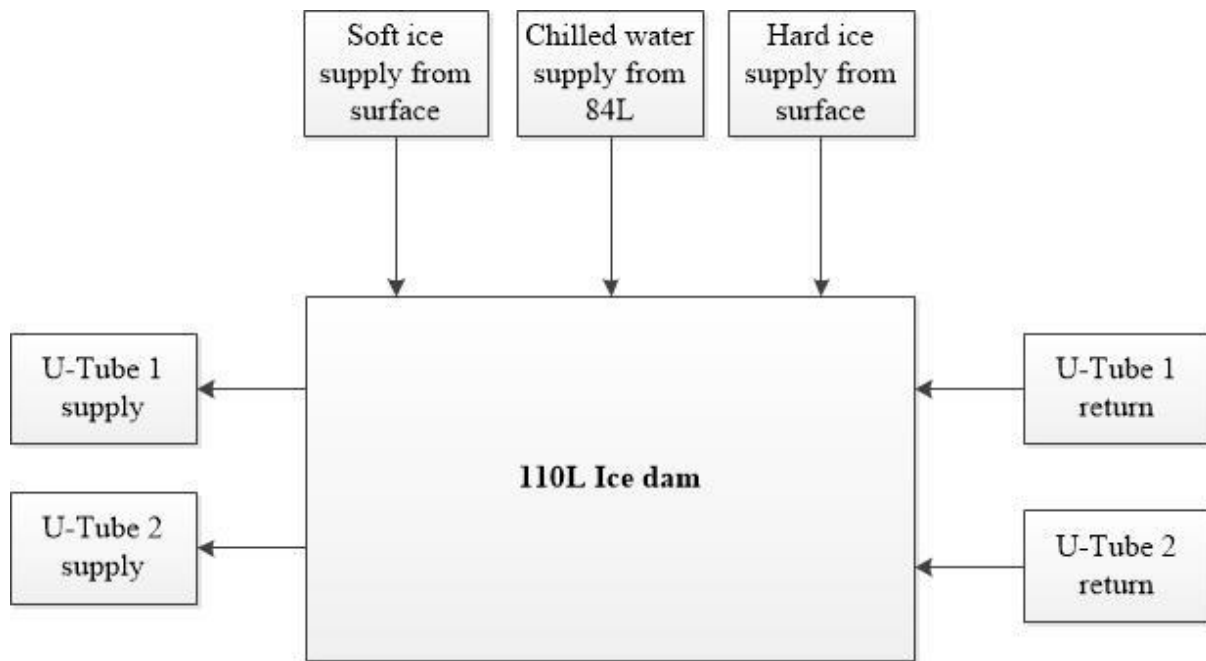


Figure 31: 110L Mass balance

This mass balance is a closed loop system; however, the system does not retain all the water as water within the system diminishes due to mining inefficiencies and consumer supply. This water then gathers and travels to the dewatering system, where the water is exhausted to the surface processing systems. It is important to note the amount of water being supplied to and from the ice dam. For this application, the dewatering system was of no relevance. The chilled water is supplied to the mining sector via the 'U-Tube' system, which is depicted Figure 32.

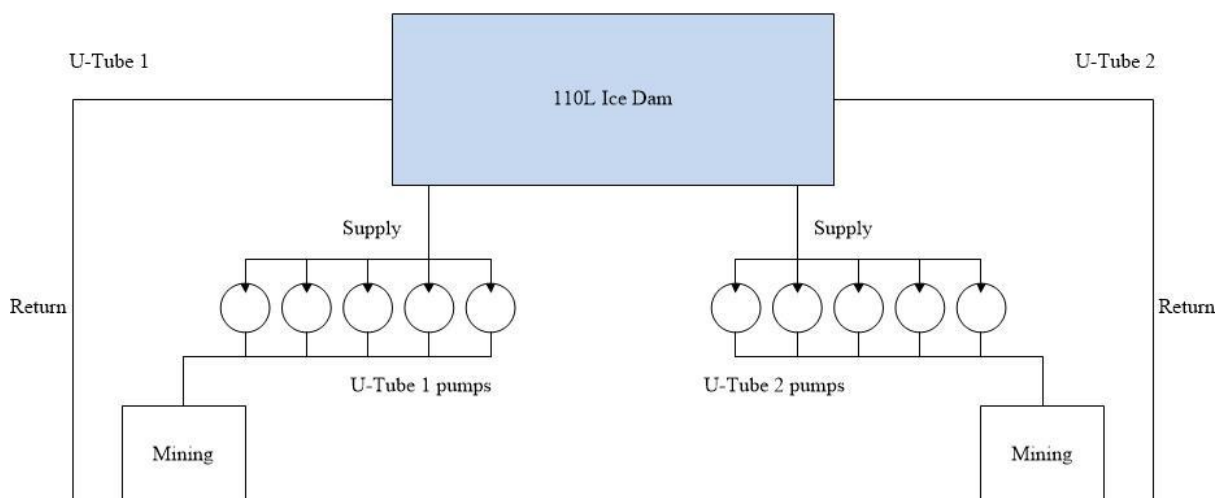


Figure 32: 'U-Tube' system layout

A set of pumps in series pumps water to the mining sector (lower levels) and due to the pressure added to the chilled supply by these pumps, the supplied water is able to return to the ice dam via a series of piping networks and control valves. Depending on the demand, the number of pumps is altered to match the demand and ensure the pressure is sufficient to return. Appendix B lists the water flow in the ‘U-Tube’ systems as well as the soft and hard ice supply.

4. Current underground energy recovery system (Impoundment system)

a. *Flows to turbines*

Figure 33 represents the average flow profile to all the turbines including the flow to the 110L ice dam.

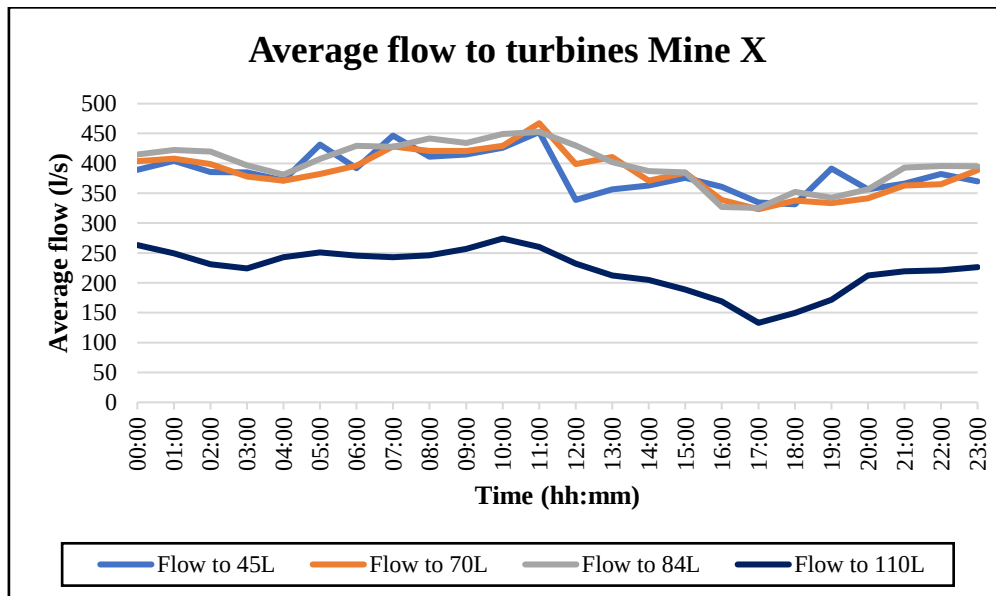


Figure 33: Average flow profiles to underground turbines

An average flow of 220 l/s, across a twenty-four-hour period, to the 110L ice dam was obtained. In the figure above, the other flows depicted are significantly higher. The reason for the difference is due to chilled water consumers on the mining levels between 84L and 110L. Therefore, the chilled water flow is reduced when entering the 110L ice dam.

b. *Power generated by turbines*

Figure 34 illustrates the typical performance of the Pelton turbines on the various levels across a twenty-four-hour period and a typical business-as-usual (BAU) day.

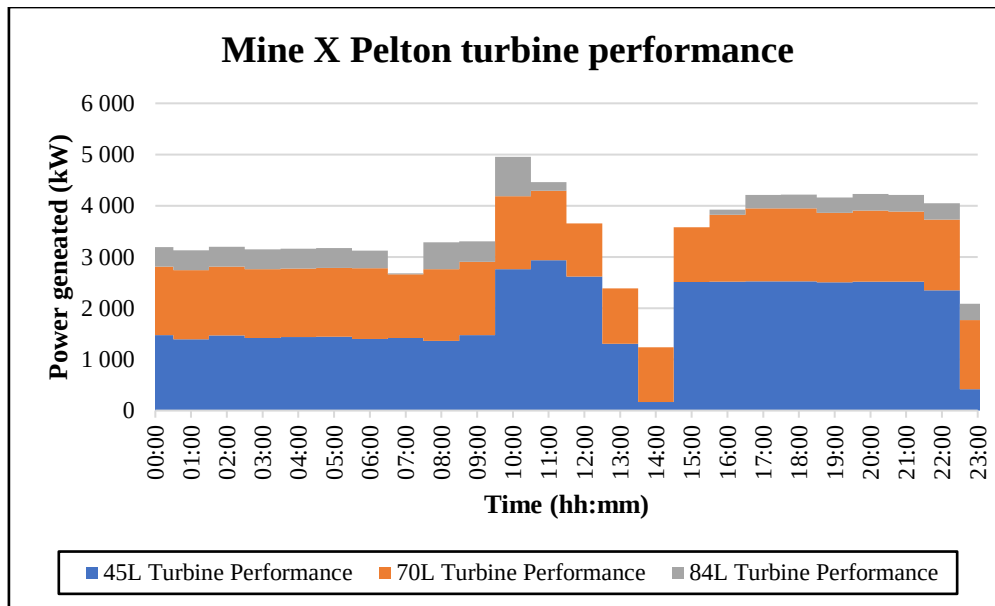


Figure 34: Mine X Pelton Turbine Performance

It is noted in Figure 34 that from approximately 09:00, underground activities and drilling commences. In conjunction with this commencement, the chilled water supply is increased to underground levels (maintain demand) and turbine performance is increased.

Throughout the day the turbine performance varies. The power generated fluctuates due to an inconsistent flow, dissipator valve control and the ice dam's level control. As the ice dams start to fill up, supply to various dams is reduced and surface chilled water production is reduced. Chilled water is then bypassed through the dissipator valves for temperature purposes. As the dam levels decrease and reach a certain point, chilled water production and supply is increased to the different ice dams to increase dam levels and maintain supply to end users.

c. Turbine specifications (Pelton turbine)

The comprehensive investigation section focused on the turbine system of Mine X. Table 4 tabulates the existing turbine performance specifications obtained in the investigation.

Table 4: Mine X turbine design specifications

Area	Station Function	Units	Power Capacity per Unit
45 Level	Turbine	1	3 700 KW @ 400 l/s
70 Level	Turbine	1	3 800 KW @ 500 l/s
84 Level	Turbine	1	1 950 KW @ 500 l/s

The turbines performance in terms of average flow and power generated are illustrated in Table 5. The performance indicated in the table below, describes the head between the turbine levels

as well as the average flow to the turbine and the daily energy generated as a result. Table 5 displays the actual and current generative capacity on Mine X depicted in Figure 30.

Table 5: Turbine performance

Level (L)	Head (m)	Average flow (l/s)	Energy generated daily (kWh)
45 Level	1 371.6	384	77 135.7
70 Level	762.0	385	46 913.7
84 Level	426.7	398	14 882.4

Due to the high head difference and efficiency of the turbines and generators, the power generated varies significantly. Flow between the turbines remains consistent, but the high head difference allows for more power to be generated as more pressure is then sustained, as depicted in Equation (2). The three turbines collectively generate approximately 139 000 kWh within a day, which averages 5 790 kW.

d. Identified PAT location for implementation

Scope to implement the hydropower system between 84L and 110L exists as depicted in Figure 35.

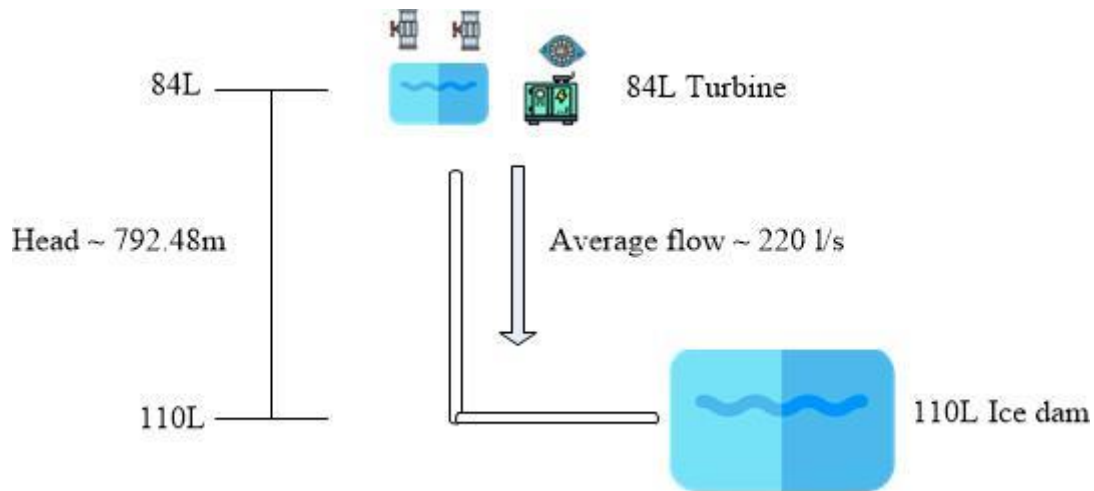


Figure 35: Turbine placement on Mine X^{26 27 28 29}

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As illustrated above, a head of 792.48 m exists as well as an average flow of 222 l/s. Potential existed to reclaim the abandoned equipment and machinery at Mine Y and install a hydropower system at Mine X, which addressed the main object, which was to recover more gravitational potential energy from the current WSS.

Figure 36 depicts the current 110L infrastructure and operational way that chilled water is transported to the ice dam.

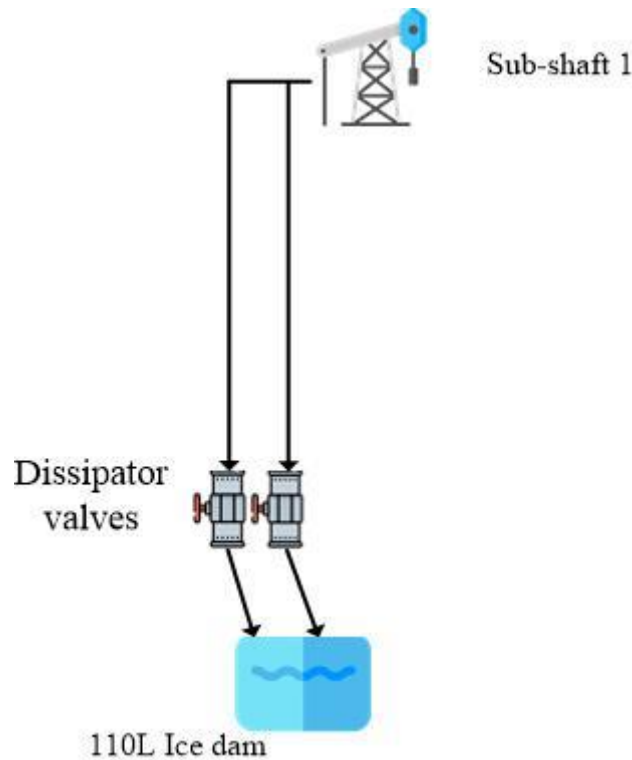


Figure 36: Current 110L Infrastructure^{30 31 32}

The chilled water is passed through a set of dissipaters before being exhausted into the ice dam. On this configuration, no energy recovery methods exist on 110L as on the upper levels.

Mine Y

Mine Y's comprehensive investigation yielded a variety of machinery and equipment that was abandoned due to a failed turbine project (mechanical failure). The abandoned turbine project

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possessed all the major components required for a successful turbine. Mine Y's turbine initiative was implemented for an approximate flow of 230 l/s and a head of 882 m. The feasibility study, completed by a contractor at the time, revealed a possible generation capacity of 1.1 MW of power.

Table 6 tabulates the equipment that can be reclaimed from Mine Y for this application. The table also offers a description of the equipment, the quantity, the current condition, and a photo.

Table 6: Equipment to be reclaimed from Mine Y

Description	Photo
HPH-54-25/7 SIG Impeller Diam.: 530 mm	
Generator Volts: 6 600 V RPM: 1 490 RPM Make: Siemens kW/HP: 1600 kW AMPS: 166 A SN.: K4896-48 Cycles: 50 Hz (Fixed) Phases: 3	 

Dissipater open/ close valve (Pilot solenoid controlled)	
Hand wheel Isolation Valve	
Hydropower Equipment: Dissipater open/ close valve (Pilot solenoid controlled)	
Isolation valve – Actuated (550V, 3 Phase)	

Isolation check valve	
Turbine piping surge relieve valve	
Pressure reducing valve (Mechanical pilot system controlled)	
PLC panel and touchscreen display	

The equipment and machinery identified at Mine Y had minimal running hours. However, due to the conditions where they had been stored and the duration, it was advised to refurbish all major components that were required. The main reason for this was to ensure that there was no mechanical nor electrical malfunction when the project was commissioned.

The purpose of the investigation performed at Mine Y was to identify possible machinery and equipment that could be reclaimed for this project, as suggested by the site engineer. The identified equipment, as tabulated in Table 6, was further investigated in the feasibility step of this project. The financial impact of reclaiming was compared to that of purchasing new, and from this comparison, the appropriate decision could be made based on the financial and performance indicators.

With the average flow profile in Figure 33, the pre-feasibility and feasibility studies could be completed. The flow profile could be used to determine an estimated power generation and was used within the thermo-hydraulic simulation to determine optimal control for the entire turbine system.

3.4.2. Pre-feasibility

According to section 2.4.2 of the developed simulation, the pre-feasibility follows a certain process to ensure all the important aspects of the project are contained within this sub-procedure. The first step was to complete a concept design.

Concept design

A preliminary design with the aid of the design office and team of engineers was modelled according to the identified location. The following equipment was required for a complete pump in reverse operation setup:

- a. PAT (Multi-stage pump in reverse operation)

The purpose of the PAT is to convert the kinetic energy into mechanical energy. The number of stages was determined with the pump curve in the following section of this thesis (section 2.4.3).

- b. Generator (11 kV)

The generator, which is connected to the PAT via a rotating shaft, converts the mechanical energy into electrical energy.

- c. Dissipator valve

The dissipator valve dissipates the energy of the water and breaks the pressure when required.

d. Mechanical isolation valve

The purpose of the mechanical isolation valve is to isolate the entire high-pressure line when maintenance is required on the hydropower system. This also diverts the flow to the existing dissipator valves.

e. Flow control valve

The flow control valve allows accurate and optimal control on the turbine water inlet flow to reach optimal control and the BEP. It also acts as a failsafe to ensure the pump is mechanically safe and does not exceed the maximum flow allowed.

f. Piping (High-pressure and low-pressure piping)

The different pipes transport the chilled water to either the pump - Inlet (high pressure) or to the 110L ice dam – Outlet (low pressure).

g. Instrumentation (Pressure probes, flow meters, PLC etc.)

The instrumentation allows for adequate monitoring of the performance of the pump as well as predictive performance and possible failures.

Based on the required equipment and machinery for this application, the concept design developed is depicted in Figure 37.

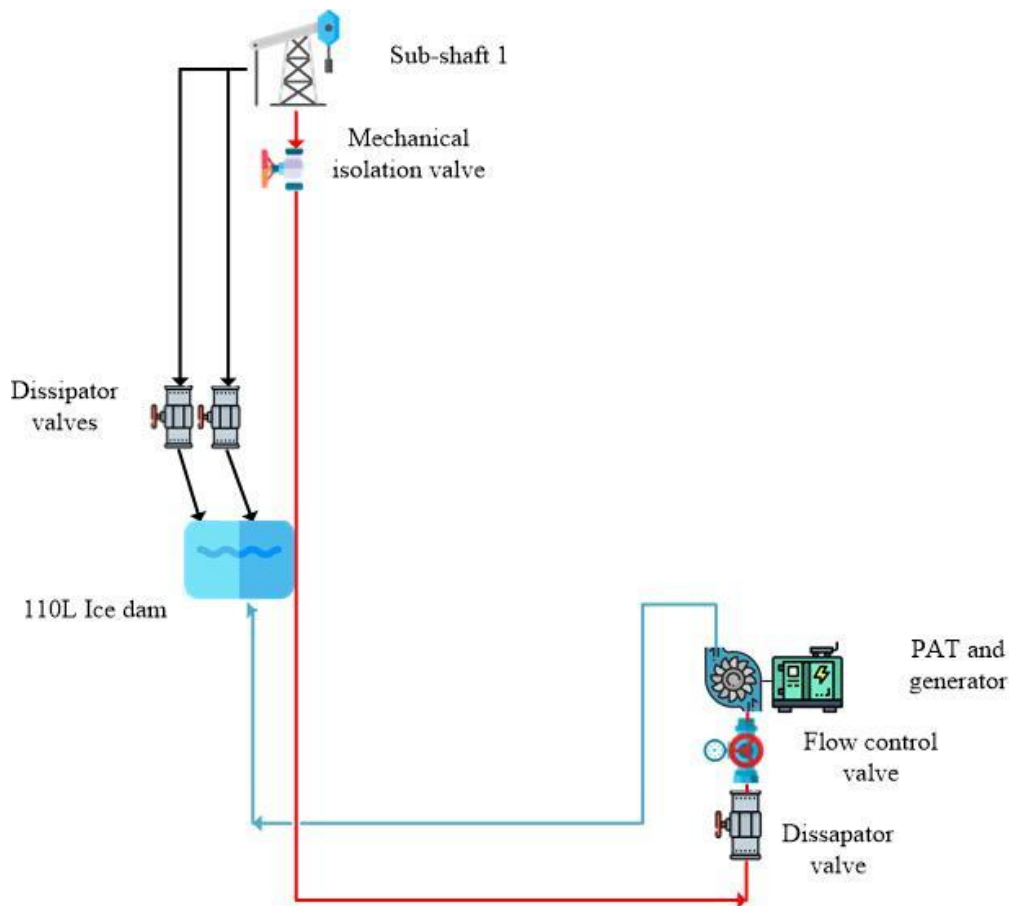


Figure 37: Initial solution design (concept design) on 110L^{33 34 35 36 37 38 39}

In this figure, it can be noted that the existing infrastructure was maintained, and the hydropower system was only added as an upgrade on the system. The concept design still made use of the current infrastructure as a possible failsafe for the newly designed hydropower system.

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Bypassing the 110L ice dam to the pump station, a new high-pressure pipeline (red) was planned to the existing pump station and newly designed PAT. The low-pressure or discharge (blue) was then fed to the 110L ice dam. The required equipment for the design was a mechanical isolation valve, flow control valve, dissipator valve, PAT, and generator.

Theoretical calculations

The theoretical calculations could be completed based on the data collected within the investigation stage and using Equation (1). In the attached article (Appendix E), an approximated value obtained from suppliers was used for the pump and generator efficiencies. A pump efficiency of 81.4% and a generator efficiency of 99% were used to calculate the theoretical generation capacity. For this application, the respective turbine efficiencies were used based on the performance curve depicted in Figure 38. Figure 38 depicts the performance curve of the PAT as obtained from the supplier.

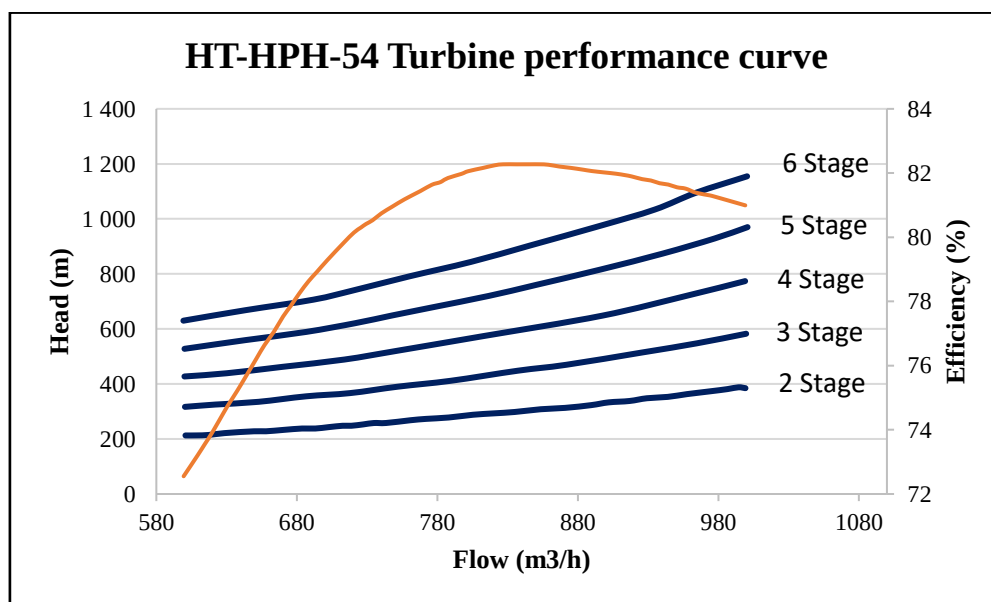


Figure 38: HPH-54 Performance curve

Table 7 tabulates the parameters and inputs used for the theoretical calculations. The generator efficiency constant was obtained from mine personnel as this is a generally accepted value to be used to determine the power generation.

Table 7: Theoretical calculation inputs

Parameter	Value
H_N	792.48 m
g	9.81 m/s^2
ρ	$1\,000 \text{ kg/m}^3$
Q	$0.171 \frac{\text{m}^3}{\text{s}}, 0.200 \frac{\text{m}^3}{\text{s}},$ $0.219 \frac{\text{m}^3}{\text{s}}, 0.245 \frac{\text{m}^3}{\text{s}}$
η_p	75%, 80%, 82%, 82%
η_g	90%
PF	0.9

Four scenarios were numerically simulated with the formula. Flows of 171 l/s, 200 l/s, 219.7 l/s and 245 l/s were used based on the average flow between 84L and 110L (obtained from the average flow determined in the comprehensive investigation). The selected flows were ten percent increment increases of the average flow to show the optimised and maximum flow that the hydropower system can generate. The results of the calculations are reported in Table 8.

Table 8 accounts for the water pressure at the inlet of the turbine, the total amount of generated energy within a twenty-four-hour period, the average daily power generated and the value of said generated power based on the Eskom Non-local Authority MegaFlex 2022/2023 tariffs⁴⁰.

Table 8: Generative capacity (Theoretical)

Flow (l/s)	Total daily energy generated (kWh)	Average daily power generated (kW)	Power generated (R)
171	21 536	897	9.74 mil. p.a.
200	26 868	1 119	12.16 mil. p.a.
219.7	30 252	1 261	13.69 mil. p.a.
245	33 736	1 406	15.27 mil. p.a.

The theoretical results revealed a linear trend in the amount of power and energy generated. The inlet turbine flow and power generated were directly influenced by one another. This

⁴⁰ Eskom. 2022. Schedule of Standard Prices for Eskom Tariffs 1 April 2022 To 31 March 2023 for Non-Local Authority Supplies, and 1 July 2022 To 30 June 2023 for Local Authority Supplies. https://www.eskom.co.za/distribution/wp-content/uploads/2022/03/Schedule-of-standard-prices-2022_23.pdf Date of access: Jun. 10, 2022).

means, that as the flow increases, the generated power increases as a result. This linear relationship is clearly visible in the theoretical results. It is noteworthy that as the BEP is surpassed, the efficiency of the PAT then decreases with increasing flow as depicted in Figure 38.

It is noteworthy that the theoretical calculations did not incorporate any frictional losses and additional losses within the calculations. The pre-feasibility was simply to give an indication of the potential available within the proposed system and should be further investigated with more accurate prediction methods (feasibility section).

Appendix A describes in more detail, for each scenario simulated theoretically, how the power generated is converted to Rands (R) as well as the different tariffs and charges used for the total power generated.

As a result of reduced average flow rate and a lower head, the calculated power generated was considerably lower than the current turbines at Mine X. However, there was a potential of 1.4 MW of energy to be recovered, which equates to R15.27 million p.a. based on the Eskom Non-local Authority MegaFlex 2022/2023 tariffs⁴⁰ and theoretical calculations.

Estimated CAPEX

The capital requirements were completed for two scenarios for the solution. The first solution was procuring new equipment for the project, while the second scenario focused on reclaiming the equipment from Mine Y, refurbishing the equipment to a perfect working order, and re-configuring some equipment to suit the application.

Table 9 tabulates the equipment required as described in Scenario one. Quotes were obtained from suppliers for a complete new set of machinery as if Mine X possessed none of the required materials and equipment. The reason for this was to determine the total cost of the project from start to finish and adequately and accurately compare costs. Both scenarios discussed below also includes an additional ten percent adjustment on the budgeted CAPEX amount to account for unforeseen changes and amendments within this project.

Table 9: Scenario one: Acquiring new machinery

Description	Cost
Generator (1.6 MW)	R 2 433 000
Turbine (Pump in reverse operation)	R 3 700 000
High-pressure pipes	R 991 000
High-pressure pipe installation	R 240 700
Pipe supports manufacturing and installation	R 345 000
Low-pressure pipes and installation	R 228 000
Instrumentation	R 505 000
Valves (Control valves)	R 1 000 000
Valve refurbishment	R 354 000
Total	R 9 796 700
Total including 10% adjustment	R 10 800 000

Table 10 tabulates the CAPEX required to execute the second scenario. Quotes were obtained from suppliers to refurbish the equipment reclaimed from Mine Y. The only equipment not used from Mine Y and thus newly installed included the high- and low-pressure pipelines, pipe supports (installation and manufacturing) and the instrumentation.

Table 10: Scenario two: Reclaiming equipment from Mine Y

Description	Cost
Generator rewind (6.6 kV to 11 kV)	R 570 000
Pump refurbishment and derating to a 5 stage (2 Dummy stages)	R 750 000
High-pressure pipes (10 inch)	R 991 000
High-pressure pipe installation	R 240 700
Pipe supports manufacturing and installation	R 345 000
Low-pressure pipes and installation (10 inch)	R 228 000
Instrumentation	R 505 000
Valve refurbishment	R 354 000
Actuator retrofit	R 920 000
Total	R 4 903 700
Total including 10% adjustment	R 5 400 000

An additional ten percent was added to the CAPEX to account for inflation and possible changes to the proposed systems. To conclude the CAPEX analysis and estimates, there was a significant difference between the two scenarios. Scenario one amounted to R 10.8 million rand, which was R5.4 million more than scenario two. Scenario two amounted to R5.4 million

CAPEX required to implement the hydropower system. Typically, it is difficult to recover equipment and machinery from an already existing system that is not functioning. Therefore, for most applications, scenario one will apply. However, for this application, the majority of the equipment and machinery already existed in a sister mine.

Recovering this equipment and machinery dramatically reduced the amount of CAPEX required, approximately R5.4 million, and improved the payback period significantly. For this thesis, the comparison was completed to compare the initial costs required, but the second scenario was the more logical option to implement as it required less CAPEX, reduced the waiting period significantly and produced the same generative capacity as scenario one.

With the completed concept design, theoretical calculations and CAPEX analysis, the payback for the different flow and CAPEX scenarios could be compared to determine the most suitable and applicable scenario for this application. This concluded whether the hydropower station was feasible. Table 11 compares the various theoretical flow generative capacities with the amount of CAPEX required from the two CAPEX lists.

Table 11: Payback period comparison

Payback period (Months)			
	Flow (l/s)	Scenario 1	Scenario 2
1	171	7	13
2	200	6	11
3	219	5	9
4	245	4	8

From the above table, it can be noted that as the flow increases, the generative capacity also increases. Therefore, the payback period decreases with increasing generation of power. The ideal scenario would be the fourth option in Table 11. Ideally, generating the most power would result in the shortest payback period possible. However, this option is significantly higher in flow than the average flow obtained and would drastically affect the surrounding systems. Therefore, this emphasised the need for an integrated thermal-hydraulic simulation model to determine the effect on the integrated network and test the feasibility of the extent of generative capability.

3.4.3. Feasibility

From the previous section, it was known that the hydropower system was provisionally feasible based on the theoretical calculations and substantiated further analysis and investigation. The theoretical analysis also determined that the initiative would yield a payback period of less than a year for both CAPEX scenarios. In the corporate environment, it is beneficial to invest in energy projects with low payback periods. A more in-depth study and analysis may be completed based on the premise of a probable pre-feasibility investigation. Adhering to the simulation processes explained in the methodology, the following process was followed to achieve an integrated and accurate model.

1. Solution development and simulations:

Identify the problem

The identified problem related inflated electricity costs, especially for large energy consumers such as Mine X. An identified solution was to implement a PAT on 110L (between 84L and 110L) as discussed in the pre-feasibility section of this thesis, without affecting Mine X's production or the KPIs. The PAT was required to operate sustainably and indirectly from the main system. The operation of the PAT should in no way affect the chilled water supply.

As the 110L ice dam is the main supply of chilled water for underground refrigeration and mining operations, the ice dam needs to be maintained at an average dam temperature and level to ensure that production is unaffected. A low and constant dam temperature is the current BAU and needs to be maintained after a possible PAT operation. This is key during further investigation and determines the extent of success of the PAT installation as well as feasibility.

The chilled water supply to the 110L ice dam needs to be maintained for both energy generation and underground chilled water consumers. As a result, optimal energy generation would be beneficial for Mine X, but any altered flow (reduced flow) would affect the underground conditions negatively. Ideally, sustained underground conditions are required, and thus this formed part of a KPI for this study.

The KPIs act as a form of quality control to ensure certain standards within the network are maintained. The identified KPIs were as follows:

- 110L dam level (Average of 60%)
- 110L dam temperature (Average of 10 °C)
- Flow to 110L
- Power generated from turbine

The identified KPIs were based on a daily average. An average greater than this would allow for a greater tolerance on the KPIs, and production would be negatively affected.

The identified KPIs were based on the success of the implementation of the PAT system, including the 110L ice dam which is critical for underground cooling and production. Based on Section 22 of the South African mine health and safety act [118], an underground working place may not exceed a temperature of 32.5°C wet bulb and 37°C dry bulb.

The 110L ice dam needs to be kept at a designated temperature (identified by the engineering department and ventilation occupational hygienist) as it is transported to the working places for adequate cooling to maintain sustainable working conditions and adhere to the legal limits as defined above.

Design the problem

In the previous section, the problem was adequately defined allowing for a set of KPIs to be established and the foundation of the solution to be defined and set for the in-depth solution development.

A concept was generated in the pre-feasibility section and was used for the embodiment design and as a blueprint for the simulation model. The concept design included a water pipeline from the sub-shaft, routed to the PAT, and the low-pressure side was then exhausted into the current ice dam. The generator was placed with the PAT. The design also included a series of valves, performing a variety of functions.

The valves included were as follows:

- Mechanical isolation valve
- Dissipator valve
- Flow control valve

The mechanical isolation valve isolates the entire water pipeline for various activities such as maintenance or failure. The dissipator valve on the current infrastructure is to remain as a failsafe to ensure the system is still able to operate independently of the possible PAT. The

flow control valve controls the flow for the desired output in terms of energy generation, 110L dam level (%) and temperature manipulation.

Later in the process, after the right managerial approval, the level layout was used for the final design of the initiative. It is important to base concept and initial designs on actual layouts to ensure accuracy.

Collect data

The comprehensive investigation completed earlier in the study allowed for the majority of the required information to be collected to complete the feasibility study. Additional information and data that was required could be collected from the SCADA (actual system performance and parameters used within the model). The additionally collected information was required for the simulation model. Most of the information collected in this section acted as inputs for the simulation model. These inputs are listed in Appendix B.

Develop model

The model's aim was to confirm the application of the turbine on 110L. A detailed and complex model was developed to simulate the performance of the turbine as well as the 110L dam to ensure there was no negative effect on production (chilled water supply and temperature). The developed model, as described in the identified objectives, fulfilled the objective and requirement of the study by predicting the performance of a PAT with a preset of KPIs. Optimal control of the PAT was established, the performance of the PAT was analysed in different applications and configurations were exploited for optimum benefit.

Select a suitable simulation software

Various thermal-hydraulic simulation suites were evaluated based on capability and previous studies in the literature analysis. From the literature analysis, it was determined that PTB was the most suitable and practical suite for this application since PTB can complete transient models and simulate an integrated model and model thermal hydraulics, which was one of the main determining factors to complete this study.

For this specific application, as stated by Maré [23], PTB is able to simulate the control of integrated systems and energy management specifically relating to mining refrigeration and dewatering systems. PTB has proven to be the most suitable software package for this

application as it encompasses the integrated network and possesses the functionality of predicting the PAT performance.

Developed model as control (Embodiment design)

For further design of the concept design, the simulation model was considered as the embodiment design. The simulation model embodies the main concept identified in the concept design, but contains more detail in terms of the pipe sizes, lengths, pipe layouts etc. The embodiment design also assists with the formation of the detailed design by the relevant department.

For the developed model, the initial chilled water flow from 84L to 110L ice dam was added to the model to mimic the amount of water pressure generated due to the head difference. The two existing dissipators were also added to the system and were maintained in the embodiment design as a failsafe. The mass balance identified earlier in this thesis for the 110L ice dam was used to ensure the model gives a sense of a digital twin of the current system. This included the chilled water supply and return ('U-Tube' system) as well as the soft and hard ice supply from surface operations.

Figure 39 illustrates a small screenshot of the developed verification model developed in PTB. Included in this model was the initial WSS and infrastructure. Based on the developed control model, the model was built according to the concept design and simulated accordingly. This model was used as the model validation and verification in the next steps of the feasibility procedure.

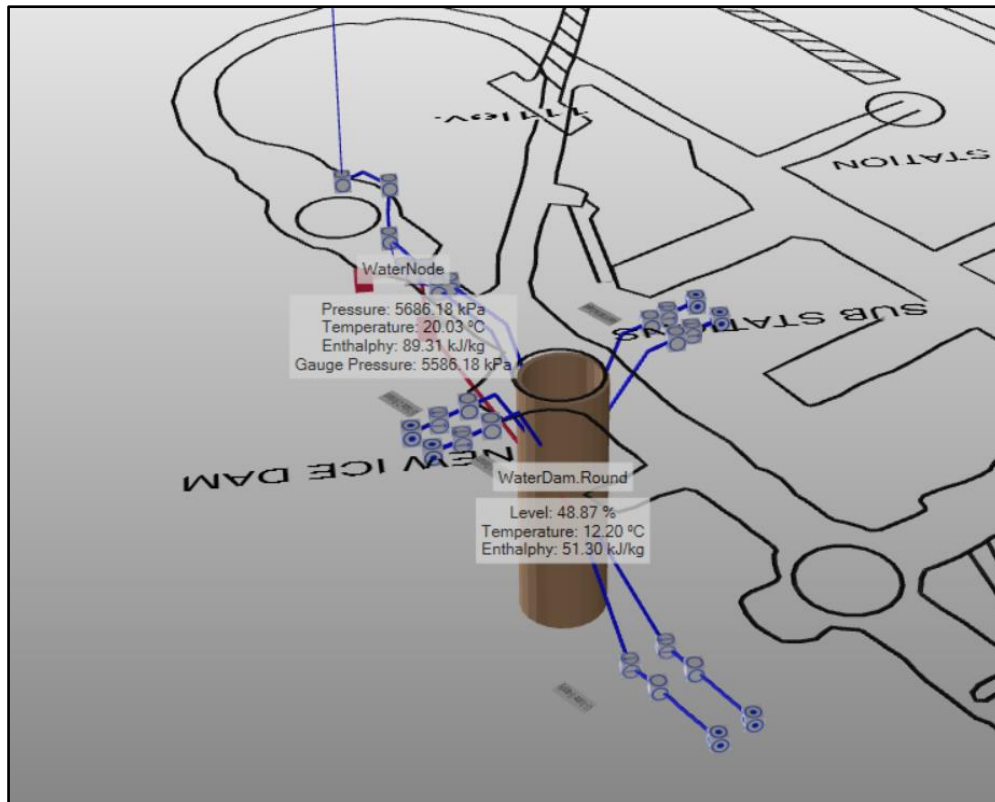


Figure 39: Verification model for PAT simulation models

This model depicted above is a digital twin of the current infrastructure on 84L and 110L and made use of the supplied underground layouts as depicted in Figure 29. All the major components and piping networks were included in the model as the well as the current chilled water dynamics. The model was calibrated accordingly and was verified in the next step of the process.

Model verification

The model verification occurred with the actual data obtained from the comprehensive investigation. The simulation outputs were compared to the actual data to ensure that there was an extensive relationship between the data sets.

Prior to the different scenarios being modelled, a control model was developed to ensure that the performance of the developed model corresponded with the actual data and performance of the system prior to the PAT implementation.

Table 12 illustrates the model verification analysis performed with the actual results (based on KPIs).

Table 12: Model verification with actual results

	Average value obtained		
	110L Ice dam level (%)	110L Ice dam temperature (°C)	Flow to 110L ice dam (l/s)
Simulation	65.1	10.4	182
Actual	67.5	9.92	171
Difference (%)	3.7%	4.6%	4.9%

From the data above, it was safe to assume and be assured that the model built for the PAT simulation depicted an accurate representation of the current WDN and WSS. All the parameters verified were within a 5% error of the actual data, thus portraying an accurate display of the realistic system in place.

Model validation

A series of models were simulated with the aid of a thermal-hydraulic simulation to obtain an array of data and results predicting the performance of a PAT under certain conditions and variables. The results yielded positive results as KPIs were met and proved the viability of the PAT at the chosen location.

From the simulation results, it was estimated that an approximate of 1 MW could be generated, which equates to R10.5 million p.a. based on the Eskom Non-local Authority MegaFlex 2022/2023 tariffs⁴⁰.

The significant difference between the theoretical and simulation results was because of the pipe losses, pressure drop and differential over the turbine which is not considered in the theoretical calculations.

Four scenarios were calibrated and tested in the model to gather results about the PAT and optimum control. Various flows were modelled, and results of the integrated system obtained were gathered and plotted below. The KPIs were used to determine the overall performance of the model. The water flow (l/s), power generated (kW), 110L dam temperature (°C) and level (%) were compared and focused on as certain criteria needs to be met for unaffected mining production as well as power generation. Although the generative capacity is an important KPI, the 110L ice dam has significant importance and its performance needed to be modelled in conjunction with the turbine.

Table 13 compares the results from the simulation scenarios. The daily generated energy, average power, average dam temperature (°C) and dam level (%) are compared in the table.

Table 13: Simulation results overview

Flow (l/s)	Daily energy generated (kWh)	Average power generated (kW)	Average Dam Temperature (°C)	Average dam level (%)
171	23 307.6	971.1	10.3	39.5
200	23 817.6	992.4	10.2	58.1
219	24 234.3	1 009.8	10.2	60.8
245	23 354.3	973.1	10.2	63.8

Examining the results in the table above, we can see a direct relationship between the flow and the power generated. According to Equation 3), considering all variables fixed except for volumetric flow, as flow increases, so does the instantaneous power generated from the turbine. However, the average power generated over the period decreased as the 110L ice dam limits the high flow as it fills at a higher rate, thus decreasing the PAT runtime within a day. Figure 40 illustrates the simulated energy generated results with the corresponding flow.

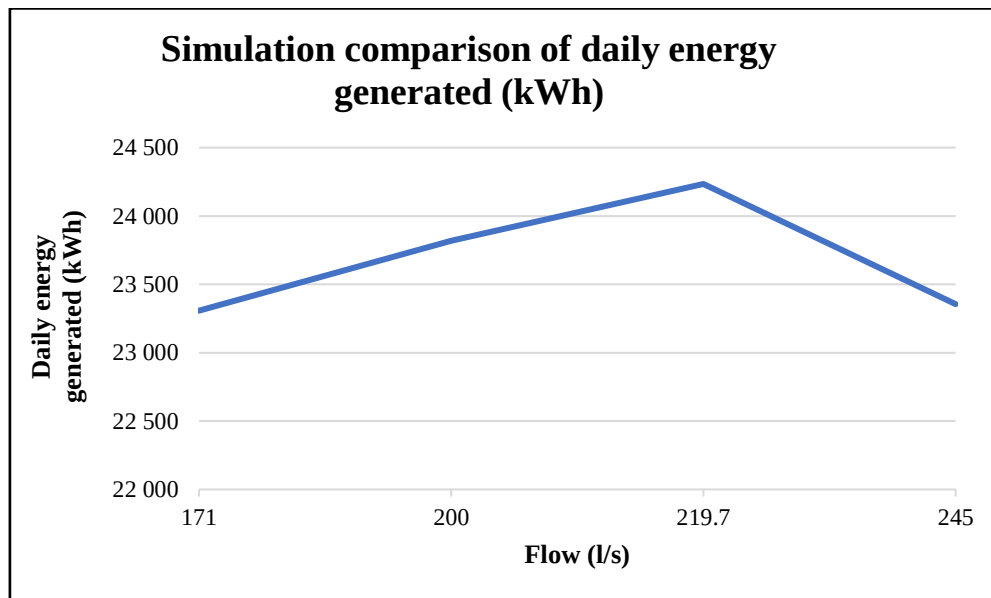


Figure 40: Simulation results – Energy generated daily (kWh)

The energy generated increased as the flow increased but reached maximum generation at a flow of 219. l/s. When the flow was increased, the energy generated decreased due to control limitations on the 110L ice dam.

The generated results were validated in several ways. The simulated models substantiated the theory of a proposed hydropower system installation at Mine X and validated the sustained underground conditions (KPIs), especially the performance of the 110L ice dam. The generated results were validated with the PAT supplier as well as with numerical calculations. The model also corresponded with current conditions on 110L prior to making any adjustments and initiating the turbine.

Model scenarios

With the aid of thermo-hydraulic simulation software (PTB) and the turbine performance curve, a model was developed with the specifications from scenario two, which were obtained from suppliers. The developed model was based on the concept design and allowed for the embodiment design to be generated, as different concepts and ideas could be trialled and tested.

A few scenarios were modelled according to the theoretical calculations performed in the pre-feasibility section. Four scenarios were modelled accordingly, and the results analysed and discussed. The power generated is depicted as a negative value to show the power generation in contrast to the conventional power consumption (positive value).

Figure 41 illustrates the control model developed and the extension or proposed PAT system according to the underground specifications and parameters.

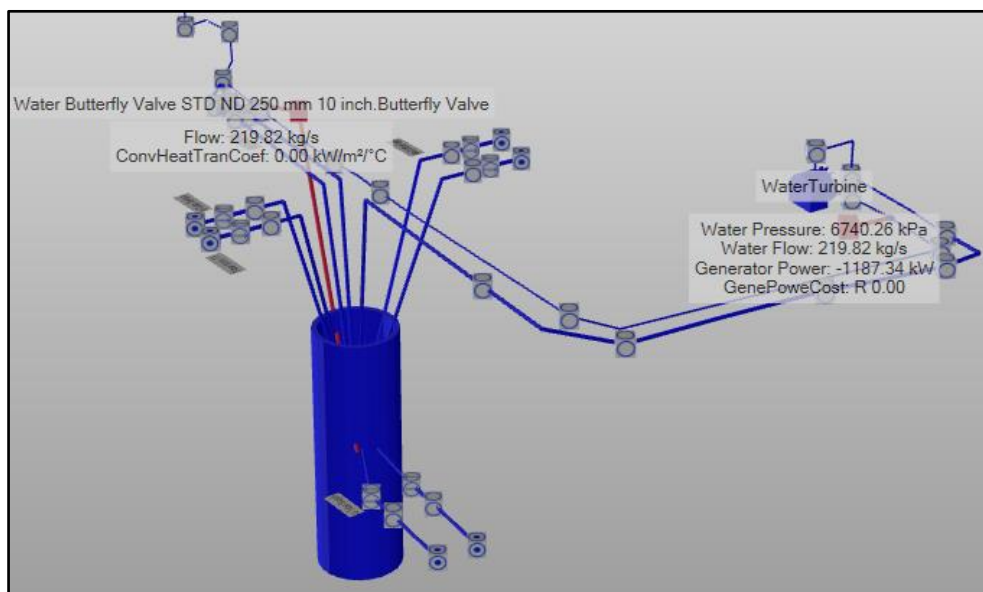


Figure 41: Detailed model in simulation software

171 l/s:

Figure 42 compares the water flow to the turbine and the power generation as a result. It was noted that a steady flow of 170 l/s was achieved, thus also achieving a constant power generation.

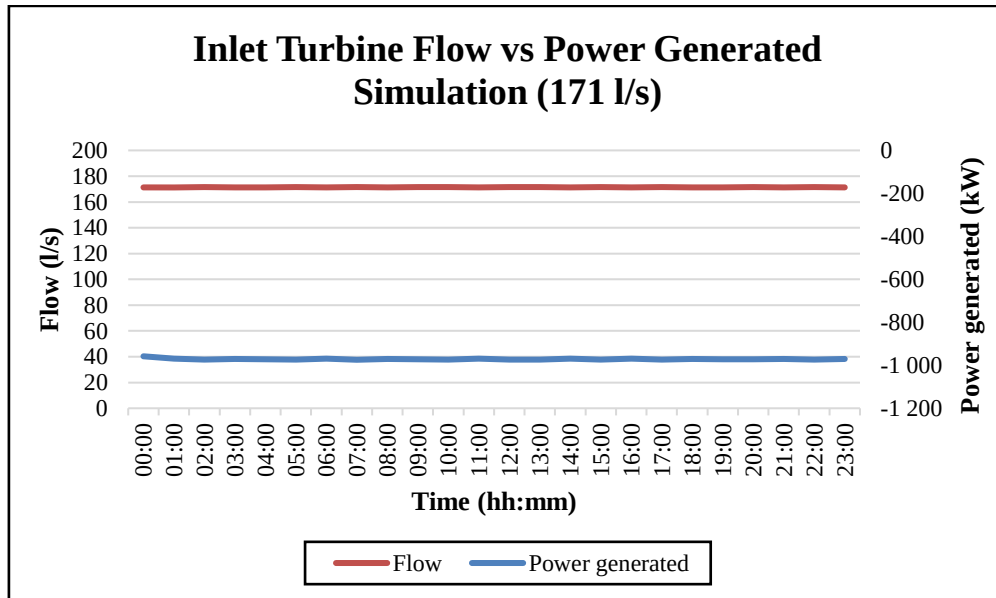


Figure 42: Turbine simulation performance (170 l/s)

With a constant flow of 171 l/s, an average power of 971 kW was generated. Figure 43 illustrates the 110L ice dam level and temperature changes for a twenty-four-hour period while operating the PAT at 170 l/s.

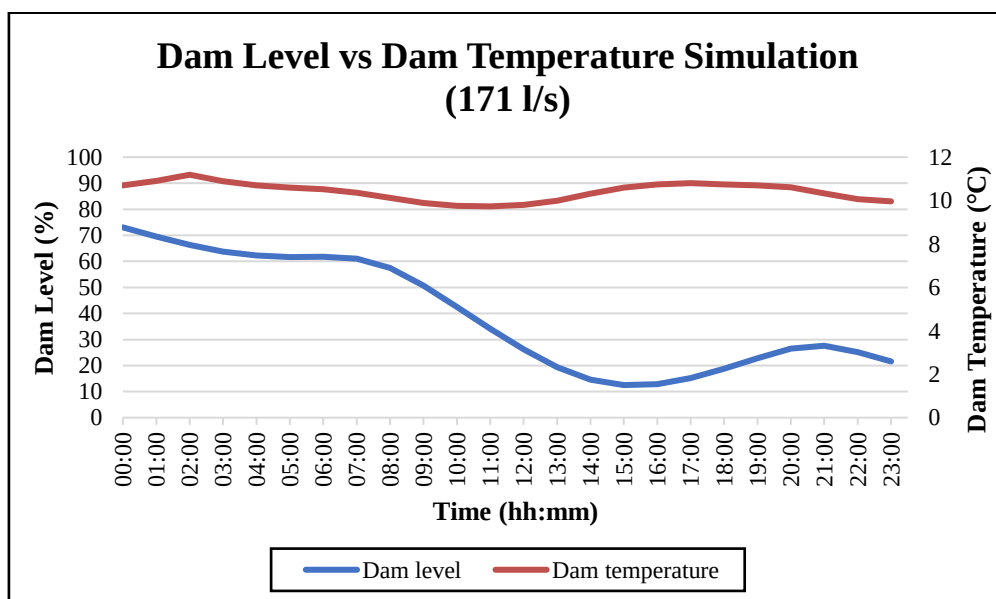


Figure 43: 110L Level and temperature comparison (Simulation: 170 l/s)

It was noted that an average dam temperature of 10.3 °C was obtained. However, due to the low flow, the average dam level obtained for this model was 39.5%. This is not adequate or suitable for the operation of the PAT and normal production. According to the model, 170 l/s is an inadequate flow to maintain an acceptable dam level, therefore rendering this case void.

200 l/s:

The flow within the model was increased to 200 l/s to monitor the effect of a higher flow in terms of the KPIs. Figure 44 displays the generative outcome against the flow.

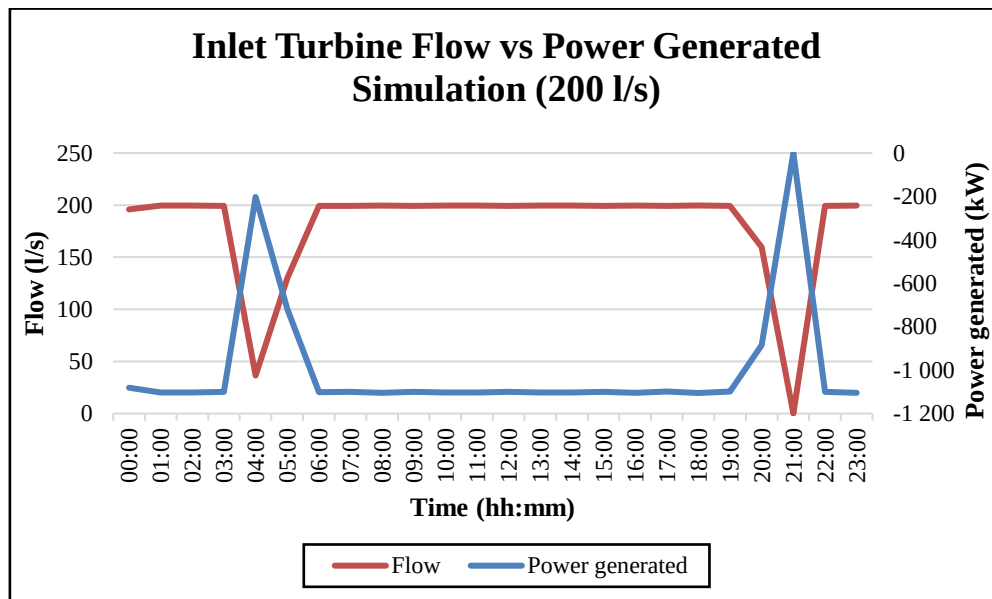


Figure 44: Turbine simulation performance (200 l/s)

From this model and graph, supply to the turbine was terminated twice within the day and was able to achieve an average generative power of 992 kW.

Figure 45 displays the dam performance results from the model.

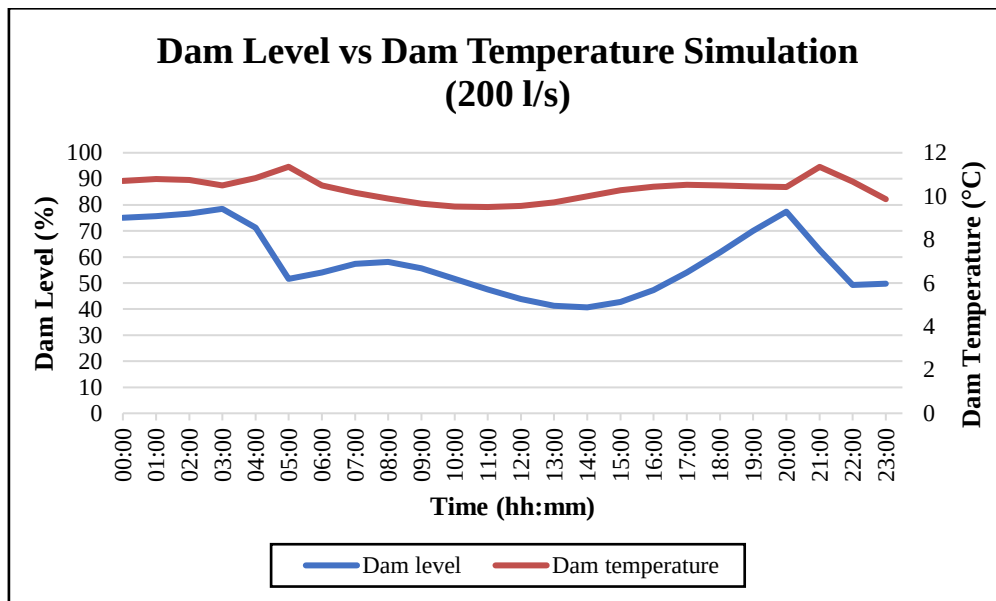


Figure 45: 110L Level and temperature comparison (Simulation: 200 l/s)

In this plot, an average dam temperature of 10.2 °C and dam level of 58.1% was achieved. When comparing this to the KPIs, an acceptable dam temperature was achieved, but the dam level was sub-par. With this type of dam level, mining production demands and strict level limits are not adhered to, thus rendering this option void.

219 l/s:

Figure 46 displays the power generated at a flow of 219 l/s.

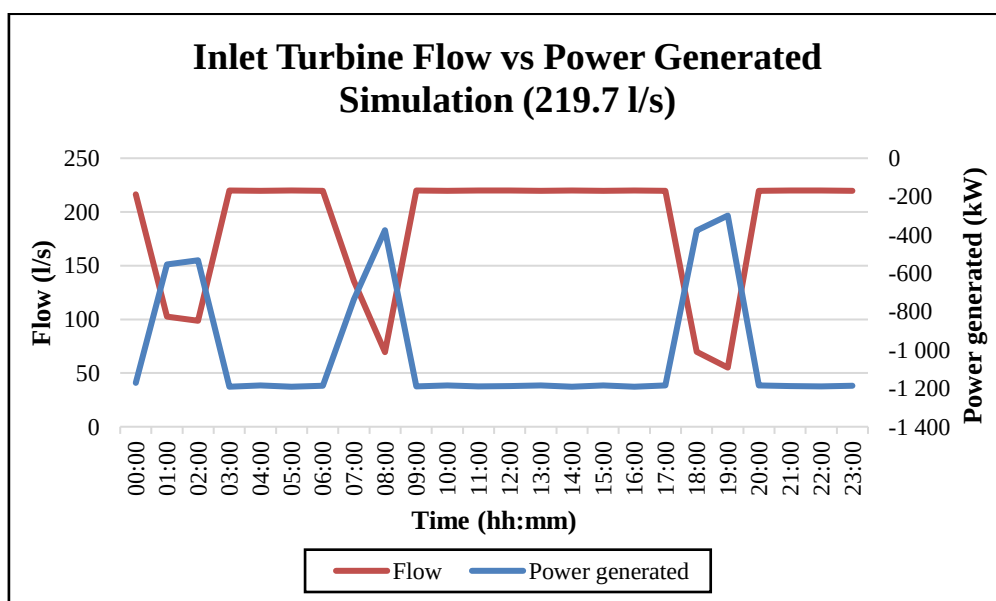


Figure 46: Turbine simulation performance (219 l/s)

The 219 l/s model yielded an average generation of 1 MW whilst supply to the turbine was halted due to the 110L dam level limits being reached.

Figure 47 displays the dam level against the temperature over a twenty-four-hour period at a supply of 219 l/s.

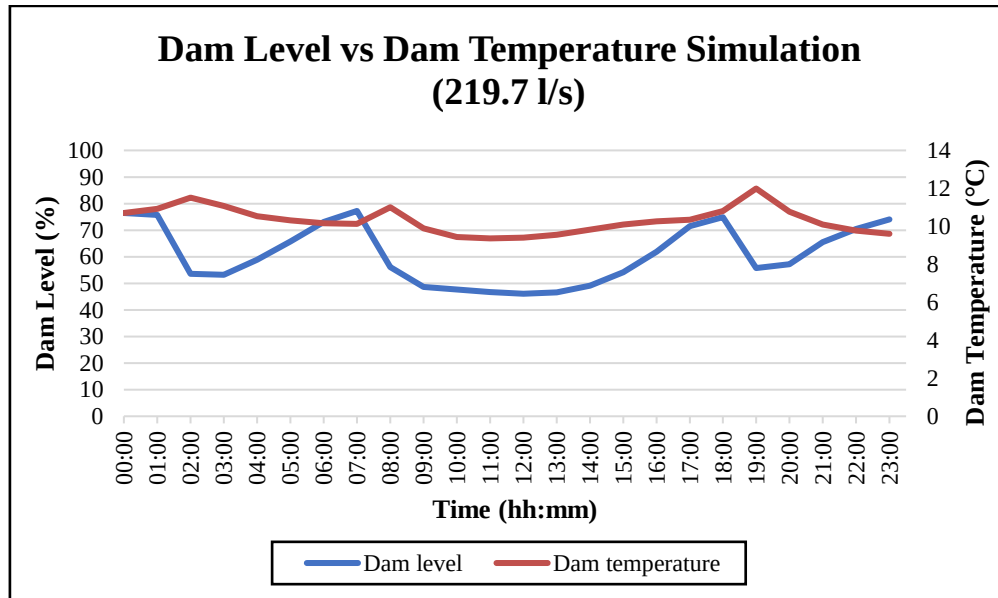


Figure 47: 110L Level and temperature comparison (Simulation: 219 l/s)

The dam performance yielded an average dam temperature of 10.2 °C and average dam level of 60.8 %, which both adhered to the set standard required.

245 l/s:

A final model was built and simulated with the highest possible flow. Figure 48 displays the turbine performance at a flow of 245 l/s.

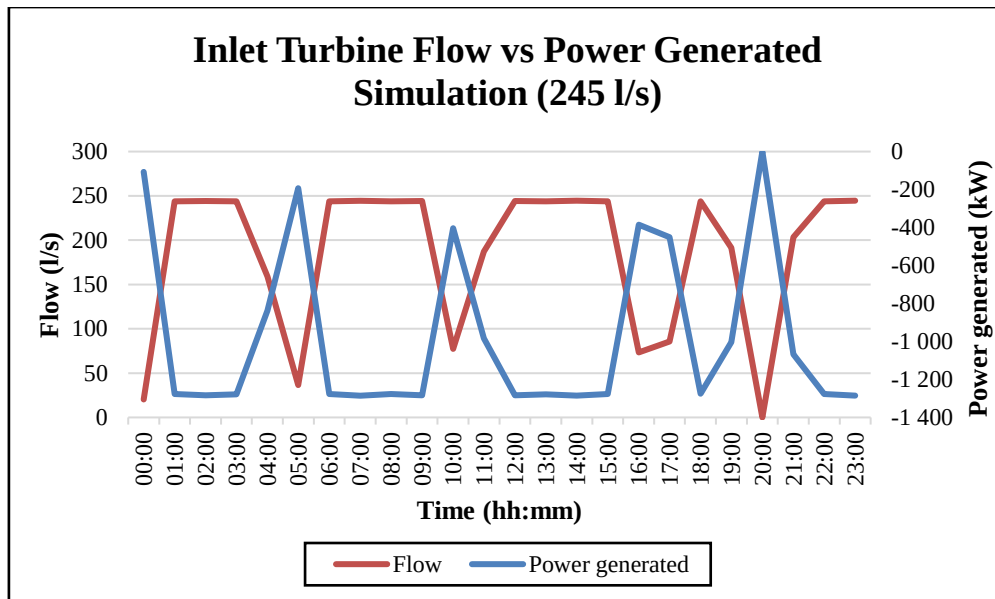


Figure 48: Turbine simulation performance (245 l/s)

In this plot, we can see the flow was ultimately too high as the turbine shut off frequently in the day, thus hindering the generative capacity. This means that the 110L ice dam increased at a rate which exceeded the demand rate. Figure 49 displays the performance of the 110L ice dam for this model. This model was also able to generate approximately 23 354 kWh.

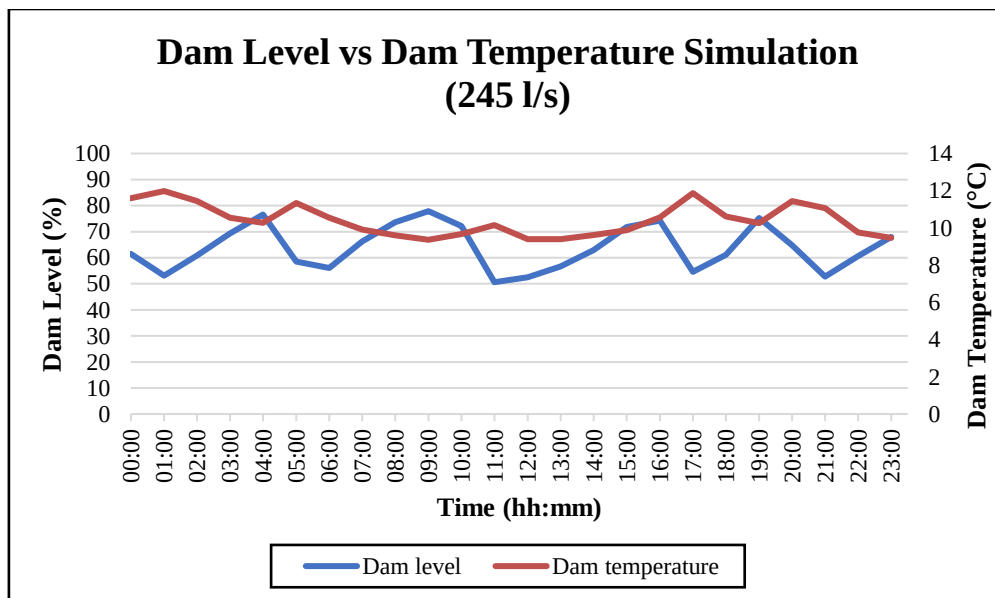


Figure 49: 110L Level and temperature comparison (Simulation: 245 l/s)

A requirement of Mine X is to maintain 60% dam level to ensure supply at an average temperature of 11 °C to ensure that mining production (ore tonnes) is not affected. The simulation was able to model an average dam level of 60.9% at an average dam temperature of 10.2 °C.

Documentation

2. Source machinery and equipment with specifications:

Equipment was sourced from various companies to complete the CAPEX requirements. This required to apply for capital within the next budget cycle once approved from all the committee members.

3. Compile CAPEX lists and requirements:

A CAPEX list was compiled for the initiative which then formed the basis of the business case. The business case was then compiled with both the theoretical, simulation results and CAPEX requirements. In the business case, the project was then presented on a high level, mainly for management purposes, where the project could then be analysed and the final approval decision could be made, provided all the criteria were met.

4. CAPEX approval

The business case (as discussed in the above section) was compiled and then submitted to management and the various committees for final capital approval. Once the project was approved and capital available, the project could be implemented based on the detailed design.

Bases upon the capital comparison completed within Table 9 and Table 10, there was a large capital difference between the two scenarios, which both achieved the same regenerative power. Scenario two was approximately R5.4 million (50%) less expensive and guaranteed the same output. Not only was this option more feasible, but the manufacturing waiting period for the equipment was also drastically shortened as the equipment only needed to be refurbished and not manufactured.

5. Evaluation and discussion of results

Optimal control was established, and the flow maximised to ensure maximal benefit from the turbine while not overloading the system and still adhering to production requirements. The optimal control is displayed in Figure 46 and Figure 47.

A suitable location was identified to recover gravitational potential energy by means of implementing a turbine and generator between two levels with an ideal water flow. A series of numerical and thermo-hydraulic computational simulations were calculated at various water flows. Table 14 illustrates the results comparison. The first column, theoretical results, depicted in the table below was based on the simulation water pressure and flow.

Table 14: Results comparison

Flow (l/s)	Energy generated theoretical (kWh) – Single flow	Energy generated simulated (kWh)	Percentage difference (%)
171	25 711	23 307.6	9.3
200	30 072	23 817.6	20.8
219.7	33 034	24 234.3	26.6
245	36 838	23 354.3	36.6

Based on the theoretical calculations, if scenario two were to be implemented, a payback period of 5.6 months could be expected based on the simulation results using MegaFlex 2022/2023 tariffs. From the above-mentioned CAPEX details, it was recommended to recover the equipment from Mine Y as there was a significant reduction in the amount of CAPEX required for the project and the machinery required minimal re-configuring to achieve the same output as scenario one would. By doing so, the feasibility of the project improved significantly, and a larger return is promised.

Ideally, a constant flow is typically used to calculate potential generation. However, it is insufficient and inaccurate as displayed in Table 14. As the flow increased, the difference between the theoretical and simulated generated power increased. The thermo-hydraulic simulation presented a low generated value as optimal control was established to encompass the entire chilled water supply system. The thermohydraulic simulation is required for such cases due to the complex nature of the mine and water requirements.

The solution proposed has a generative capacity of approximately 24 MWh with considerably less CAPEX by reclaiming and re-purposing abandoned machinery. It equated to R10.5 million p.a. using the MegaFlex 2022/2023 tariffs. The required CAPEX for the project was approximately R5.4 million, which will incur a payback period of 6.2 months.

3.4.4. Implement – Implement the strategy

In section 3.4 (Blueprint), the entire initiative's business and feasibility case was examined to determine the viability of the project. A business case was compiled and submitted for approval to the main top management members of mine X. This initiative was approved and added to the budget for the 2021/2022 financial year for implementation. This procurement process was

timeous and physical site work could only take place once the appropriate approvals from the management of the company had been obtained.

Based on the procedure discussed in section 2.4.4, the implementation process was actioned accordingly as discussed below.

1. Detailed design

The final detailed designs were completed by the onsite draughtsmen of Mine X and approved by the various engineers for implementation due to certain legal limitations and appointments. The detailed design was based on the concept and embodiment design performed in earlier steps within the procedure.

The detailed design of this project did not fall within the scope of this thesis and is not discussed in further detail as the focus is the PAT performance. However, the detailed designs can be found in Appendix C for further reference and detail.

2. Implementation and commissioning

Several groups of contractors were contracted in to perform work on the hydropower system. Contractors were used to install the high-pressure pipeline and pipeline support structures; another was used to install the low-pressure pipeline. The rest of the equipment and machinery was installed underground by Mine X's respective departments.

The electrical department installed and commissioned the generator, as well as the cabling, meter panels and the electrical components. The mechanical department installed the pump, pump bed and the valves. The instrumentation team installed all the relevant pressure sensors, probes, flow meters etc. The integration of the newly implemented PAT system was also commissioned onto the SCADA where all the relevant data was then logged.

Figure 50 demonstrates a screenshot of the 110L PAT on Mine X's SCADA system. Depicted in the figure below is all the performance parameters of the PAT (the inlet and outlet flow, control valve setpoint and operating value as well as the power generated). Several other parameters were monitored on the condition monitoring (vibrations and temperatures) aspect.

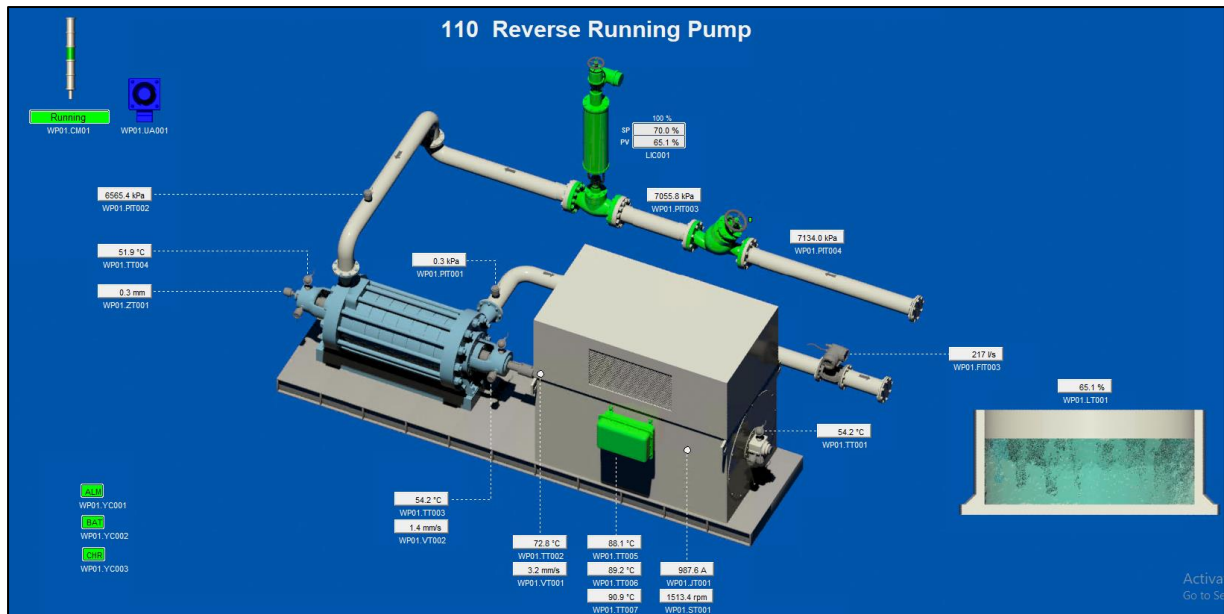


Figure 50: Mine X's SCADA system – 110L PAT

Once all the different components were installed by the various departments, a series of checks forming part of the quality checks and control were completed. This was to ensure that the system was up to standard and to avoid any mechanical and electrical faults or possible failure of the installed PAT. Due to several factors delaying the implementation of the project, the project was only completed and commissioned in 2023.

Appendix D contains photos of the completed and installed system. Within this appendix, photos of the piping (high- and low-pressure), the piping supports as well as the valves, generator and turbine are included.

This commissioning section does not focus on the exact method and procedure followed to install the various components as it did not fall within the scope and outcomes of this study. The outcome of the study was based on the PAT performance as well as the procedure followed to obtain said outcomes.

3. Evaluation

This evaluation focuses mainly on the detailed design of the project as well as the actual physical implementation proposed within the detailed design. For this case, the work completed by the contractors was analysed by the responsible persons on site and deemed of good standard and high-quality. A series of inspections and testing was conducted on the hydropower system which all proved satisfactory. Appendix D shows the work completed by both the contractors and site representatives.

The entire blueprint, described above, satisfied numerous objectives, namely numbers 1, 2, 3, 4, 5, 7 & 8. The blueprint stage incorporated the main steps of the developed generic process aimed at energy recovery with the aid of thermal hydraulic simulation software and the evaluation of a PAT with a preset of KPIs.

3.5. Verification – Verify strategy’s operational efficiency

Now that the implementation of the PAT was completed, an analysis of the actual performance could be performed. Within this step, the actual data of the PAT implementation obtained from Mine X’s SCADA were analysed to determine the effectiveness of the PAT implementation as well as the overall hydropower system performance. The different performance parameters were examined based on the KPIs identified earlier in this section of the thesis.

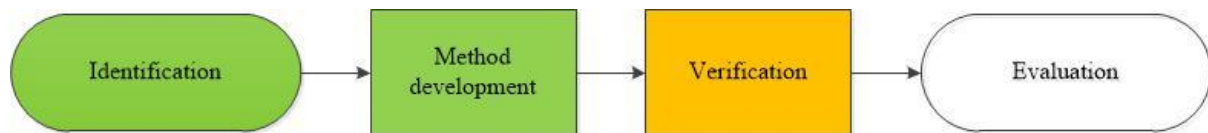


Figure 51: Methodology – Verification step

The data analysed was examined over a two-week period. Weekends were excluded from the data comparison due to operational shutdowns over the weekends. They therefore do not represent consistent operation and BAU. For example, hard and soft ice production is reduced over the weekend, as well as the quantity of chilled water sent underground. The ‘U-Tube’ systems are reduced and stopped at times over the weekend, as production does not occur on the weekend. Therefore, the weekdays and the effect of a production reduction on the PAT performance were analysed.

3.5.1. Weekday performance

The average weekday daily profiles were extracted from the SCADA and plotted to compare the effect of the PAT system on the integrated network. The power values available on the SCADA is based on a computational approach due to a metering issue. The computational approach has proven to be effective within 5% of the actual power generation. For this case, these values will be used to display the PAT system’s performance. It should also be noted that, during this time, Eskom has initiated ‘Load-curtailment’ which also negatively affected the performance of the PAT. ‘Load-curtailment’ is the reduction of energy consumption based on a certain, pre-determined baseload. The reason for the WSS reduction on Mine X was that the quantity of chilled water sent underground was limited, thereby reducing the energy

consumption and power generation. A two-week period was used for this analysis to generate a twenty-four-hour averaged weekday profile.

110L Dam level and temperature

Figure 52 illustrates the performance of the 110L under the operational conditions of the PAT system on a BAU weekday.

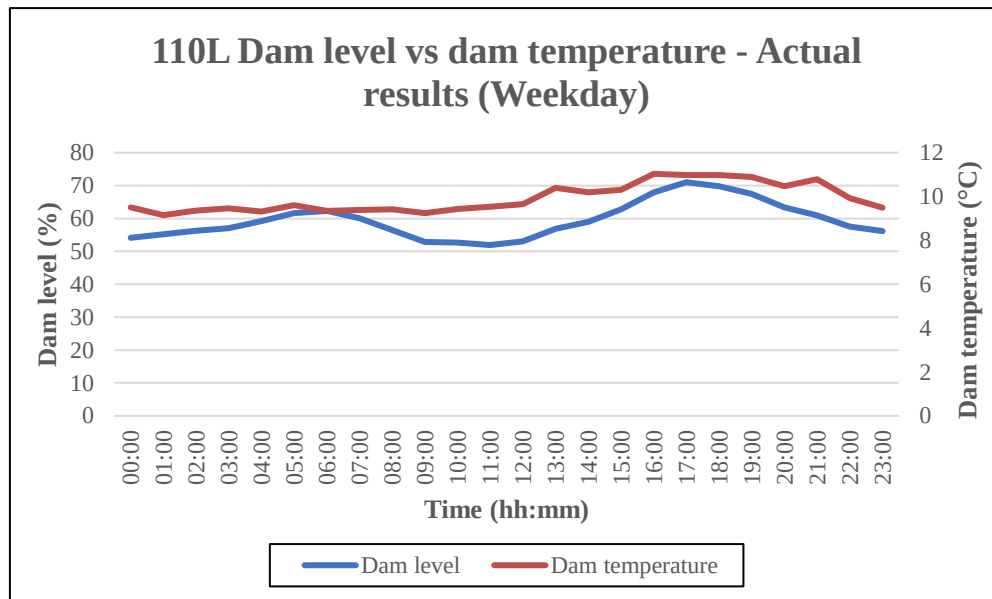


Figure 52: Actual dam temperature and level performance (Incl. Load-curtailment)

As can be seen in the graph above, the dam temperature fluctuates significantly. This is due to a reduction in the amount of chilled water and ice sent underground (Load-curtailment). The dam level also increased in the latter part of the day as production during this evening period was decreased. However, both the dam level and temperature remained balanced over the period, meaning both KPIs did not increase over a daily period, demonstrating that the system remained balanced, and the control of the PAT was effective, adhering to and sustaining the required KPI conditions.

The average dam temperature and level over this period are tabulated in Table 15.

Table 15: Average dam temperature and level (Incl. Load-curtailment)

	Average
Average dam level (%)	59.4
Average dam temperature (°C)	9.9

As mentioned in the table above, the average dam level for this period was at 59.4% and the dam temperature at 9.9 °C which was consistent with the identified KPI conditions established in the feasibility process.

‘Load-curtailement’ negatively affected the performance of the PAT and WSS, although the performance, including ‘load-curtailement’, satisfied the necessary parameters. The performance of the PAT and WSS should be examined excluding ‘load-curtailement’ to ensure consistency.

Figure 53 depicts the dam level and temperature performance of the 110L ice dam where “load-curtailement’ was not implemented over the period analysed.

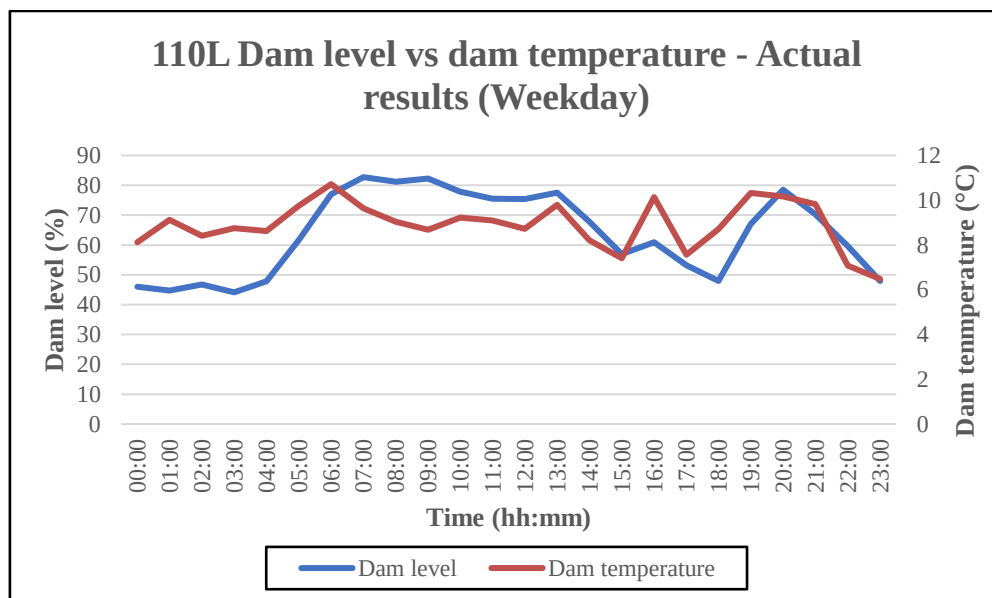


Figure 53: Actual dam temperature and level performance (Excl. Load-curtailement)

In the above-mentioned figure, the performance of the 110L ice dam varied significantly more as the data set was smaller but is a more accurate representation of the performance of the ice dam without the effect of ‘load-curtailement’.

Table 16 tabulates the average performance of the 110L ice dam where ‘load-curtailement’ was not implemented over the period.

Table 16: Average dam temperature and level (Excl. Load-curtailement)

	Average
Average dam level (%)	63.8
Average dam temperature (°C)	8.9

Without the effect of ‘load-curtailment’, it can be noted that the average dam level increased, and dam temperature decreased significantly. Here, it is noted that the effect of ‘load-curtailment’ does in fact have a negative effect on the underground operations and WSS. Table 17 compares the performance of the two different performances.

Table 17: The effect of ‘load-curtailment’ on 110l ice dam performance

	‘Load-curtailment’ implemented	‘Load-curtailment’ not implemented	Difference
Average dam level (%)	59.4	63.8	4.4
Average dam temperature (°C)	9.9	8.9	1.0

The average dam level increased with approximately 4.4% and the average dam temperature improved with 1 °C. Although the standards were met within ‘load-curtailment’ this was not considered as BAU and thus the performance where it was not implemented was considered as BAU and was used to analyse and compare the performance with the simulated and theoretical calculations.

Power generation by PAT

The actual power generated from the turbine was compared to that of the chilled water flow as the two variables are directly proportional to one another. As the chilled water supply increased, the generation capacity increased proportionally according to the performance curve. Figure 54 illustrates the actual weekday PAT performance during a period where ‘load-curtailment’ was implemented. The power generated and chilled water flow were also analysed over a two-week period.

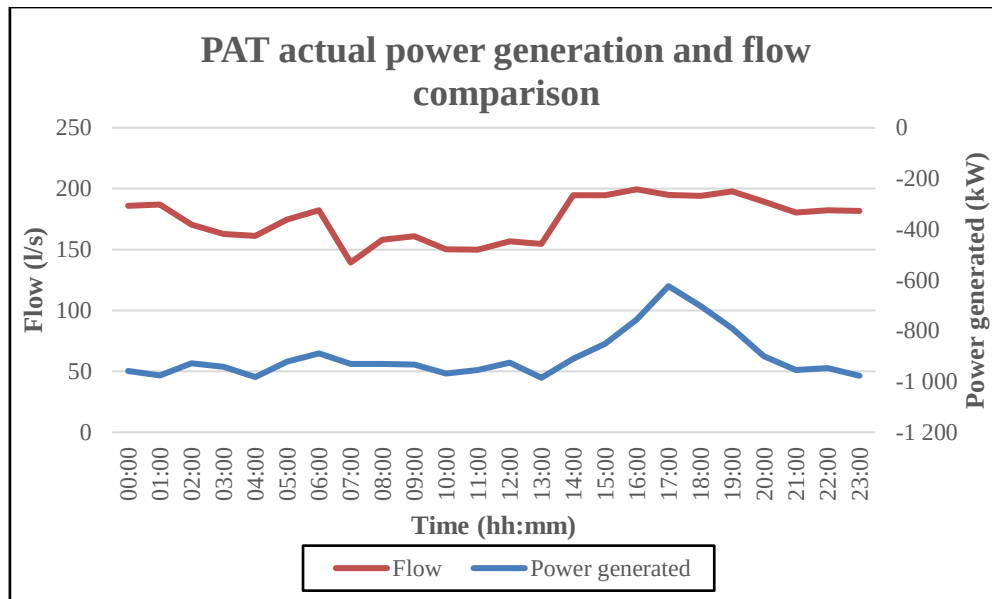


Figure 54: Actual power generation and flow comparison results (Incl. Load-curtailment)

The graph illustrates the performance of the PAT and the relationship with flow as well as the period where the WSS was reduced to comply with the energy reduction. It is easily noticed when compared to Figure 55, which demonstrates the power generation profile without the effect of ‘load-curtailment’.

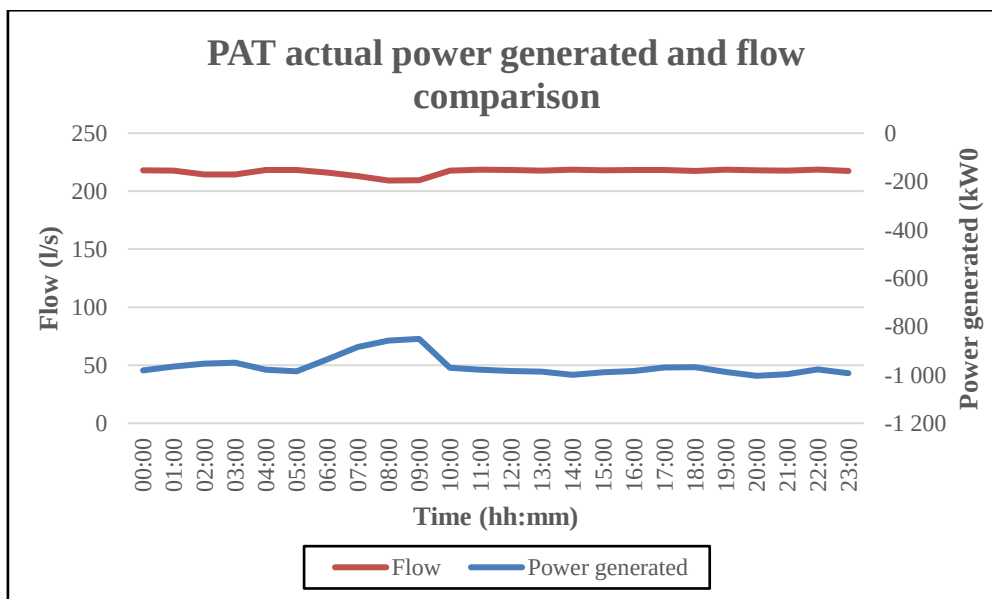


Figure 55: Actual power generation and flow comparison results (Excl. Load-curtailment)

The power generated and flow to the turbine were more stable, and constant compared to the previous analysis. Ideally, this would be the typical operational circumstances. As a result, more power was generated with a more constant flow. Table 18 summarises the power generated and average chilled water supply in the two cases that were compared.

Table 18: Power generated and flow comparison - Weekday

	‘Load-curtailment’ implemented	‘Load-curtailment’ not implemented	Difference
Average energy generated (kWh)	21 638	23 132	1 494
Average power generated (kW)	901.6	963.83	62.3
Average water flow (l/s)	207	216.7	9.3
Efficiency (%)	81.5	82	0.5

Overall, with the reduction of chilled water to the turbine, there was a small decrease in the amount of power and energy generated as shown in Table 18. Although there was a difference in generation capacity, the evaluated values were relatively similar. The efficiency of the PAT also increased with higher flow (BAU – no ‘load-curtailment’). Further analysis resulted in a decrease in the quantity of hard and soft ice being sent underground for cooling capacity, thus the reason for the higher change in dam level and temperature for the 110L ice dam.

3.5.2. Weekend performance

110L Dam level and temperature

Figure 56 depicts the average profiles of the 110L dam performance for a typical weekend scenario. Soft and hard ice production is also reduced over the weekend due to the cooling and refrigeration demand. As the demand of refrigeration decreases, the production of ice is decreased to achieve energy cost savings and match refrigeration supply with refrigeration demand.

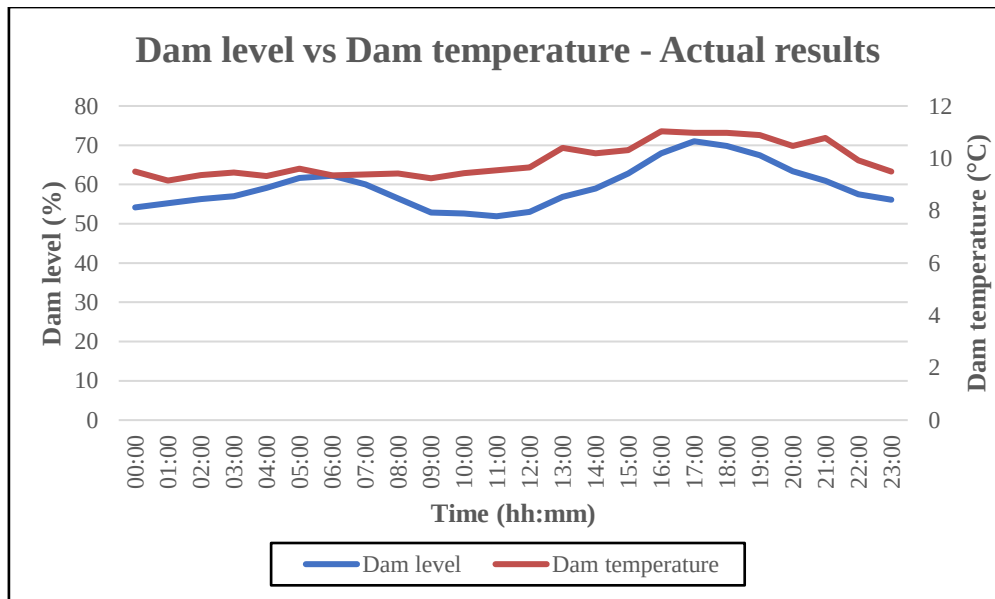


Figure 56: Actual 110L dam temperature and level performance

Over the weekend period, an average dam level of 69.9% was maintained and an average dam temperature of 14.31 °C was obtained.

Power generation by PAT

Figure 57 depicts the PAT performance on a typical weekend. The PAT was not stopped over the weekend and chilled water was still supplied for underground refrigeration purposes. Therefore, the turbine was still able to generate power.

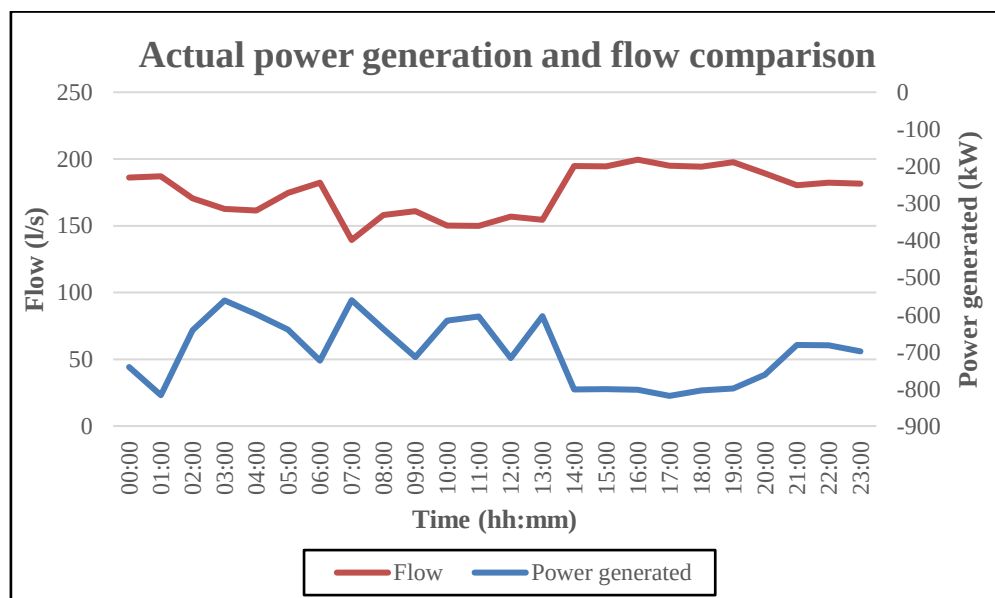


Figure 57: Actual power generation and flow comparison results

The quantity of energy generated over the weekend differed significantly from that of a normal weekday as less chilled water was supplied underground due to a stop of production over the weekend. Production was then ramped up when nearing the start of the week (early Sunday evening), as can be seen in the latter part of Figure 57.

3.6. Evaluation – Evaluate the strategies and overall operational performance

The evaluation of this strategy's overall performance was mainly focused on the energy generation capacity, as the 110L dam temperature and level were not calculated, only verified with the simulation models. The simulation results and original theoretical calculations were compared. By evaluating the overall performance of the hydropower system, we satisfied the objectives number 6 and 8.

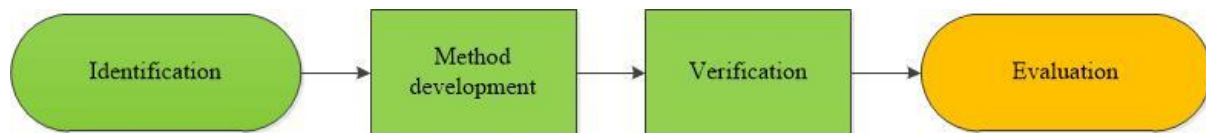


Figure 58: Methodology – Evaluation step

Table 19 highlights the efficiencies of the model simulations based on the performance curve depicted in Figure 38.

Table 19: Simulation model PAT operational efficiency

Flow (l/s)	Volumetric flow ($\frac{m^3}{hr}$)	Efficiency (%)
171	615.6	76.0
200	720.0	80.5
219	788.4	82.3
245	882.0	82.0

Identified from the various simulation models, the best operational flow for the turbine was the third flow option in the above-mentioned table (219.7 l/s), at 82.3%. The simulation model also generated the most energy (24 234 kWh). This emphasises the need for simulation models, especially for the prediction of PAT performance in integrated and complex networks.

Table 20 tabulates and illustrates the relationship between the simulated results and the original theoretical calculations performed within the pre-feasibility stage.

Table 20: Generation capacities comparison

Flow (l/s)	Energy generated (kWh)		
	Theoretical (kWh)	Simulated (kWh)	Difference (%)
171.0	21 536	23 307.6	8.2
200.0	26 867	23 817.6	8.1
219.7	30 252	24 234.3	19.9
245.0	33 736	23 354.3	30.8

From the results in the table above, it is noted that as the flow increased, so did the theoretical generated energy. However, the simulated values peaked at the third flow value and decreased from thereon, thus increasing the percentage difference between theoretical and simulation results. It is also important to note that the theoretical calculations were based on a linear equation, which did not correspond PAT performance with the relevant performance curve. However, the simulation used the performance curve as reference.

The actual PAT performance after implementation was determined to range from 21 638 kWh to 23 132 kWh, depending on the operational circumstances, as previously explained. The operational point of flow ranged from 207 l/s to 216.7 l/s as well at an efficiency of 81.5% to 82%. To adequately compare this, the concept of ‘load-curtailment’ needed to be removed and the normal BAU compared with the correlating flow. Table 21 compares the corresponding simulation model with the actual results obtained after the implementation of the PAT.

Table 21: Actual and simulation comparison of results

	Simulation model	Actual results (Weekday)	Difference
Average energy generated (kWh)	24 234.3	23 132	4.54 %
Average water flow (l/s)	219.7	216.7	3 l/s
110L Dam temperature (°C)	10.2	8.9	1.3 °C
110L Dam level (%)	60.8	63.8	3 %
Efficiency (%)	82.3	82	0.3 %

The results from the comparison showed minor and acceptable differences for the two types of results obtained. As part of the novel contributions of this thesis, the prediction of the performance of the PAT and the effect thereof within an integrated network, was successfully demonstrated with the aid of a thermal-hydraulic simulation suite.

Table 21 also validates the KPI results obtained in the simulation models. The comparison showed minimal differences between the 110L ice dam temperatures (1.3 °C) and dam levels (3 %). This emphasises the use of an integrated thermal-hydraulic simulation suite when predicting the performance of a PAT in a complex network. The theoretical calculations are not sufficient for PAT performance prediction and should be used as an initial indication of the PAT performance. A difference of 4.54% existed between the energy generated from the simulation model and actual results. Based on the 5% simulation difference, this study's simulation results were favourable and corresponded with the actual results. Simulations and modelling possess powerful capabilities that should be leveraged in the engineering sector as proven in this study.

Upon completion of the pre-feasibility and feasibility studies in 2021/2022 (2022/2023 financial year), there were significant changes in the Eskom tariff structure. It should therefore also be compared within the study with the new tariffs for consistency and continuation as the PAT was commissioned in early 2023. This comparison, based on the actual values, was to determine the correct payback period within the period of implementation and corresponding energy tariff as well as the projected cost generated after tariff adjustments.

The National Energy Regulator of South Africa (Nersa) approved a tariff increase of 18.65% to direct-fed customers⁴¹ and the tariffs identified for the Eskom Non-local Authority MegaFlex 2022/2023 tariffs⁴⁰. To adequately compare and predict the PAT performance in currency terms, the 18.65% tariff adjustment needed to be considered. This adjustment resulted in a total generation capacity of R12.45 mil. p.a. This tariff adjustment also resulted in a change in the payback period, which shortened to 5.2 months.

⁴¹ Stoddard, E. (2023). "Nersa approves 18.65% Eskom tariff hike for 2023/24 and 12.74% for the following financial year." Retrieved 1 March 2023, from <https://www.dailymaverick.co.za/article/2023-01-12-nersa-approves-18-65-eskom-tariff-hike-for-2023-24-and-12-74-for-the-following-financial-year/>.

3.7. Conclusion

To adequately summarise the work described in Chapter 3, it is important to mention that a large, energy-intensive system was identified – Mine X, which had monthly electricity bill of approximately R61.4 million per month. This served as the initial identification for the case study. Furthermore, with the already embattled energy power utility (Eskom), there existed a need to identify and investigate the possibility of gravitational potential energy recovery at Mine X.

Upon further investigation of the underground WDN and WSS, a series of Pelton wheel turbines were identified, as well as the sister mine, Mine Y, which possessed a complete, yet mechanically failed hydropower system (PAT). However, as depicted in Figure 35, additional scope was indeed identified to implement a possible hydropower system between 84L and 110L. According to the developed procedure, the next step completed was the pre-feasibility of a possible PAT system at this level. Upon completion of the theoretical calculations, it was determined that approximately 21 500 kWh ranging to 33 800 kWh can be obtained from the possible hydropower system. The financial impact of this being R9.7 mil. p.a. to R15.3 mil. p.a. based on the energy generation capacities.

Based on the results of the pre-feasibility study, the CAPEX estimate of a PAT system was investigated, and two scenarios were established where the mechanically failed system could be recovered, reconfigured, and implemented at R5.4 mil., while a new system would cost approximately R10.8 mil. The difference in CAPEX was significant and would drastically alter the payback period.

Positive pre-feasibility results warranted a complete feasible study which was based on the premise of the use of a thermal-hydraulic simulation model to accurately predict the performance of the PAT in the identified application, with optimal control being applied to sustain the KPIs (110L dam level, temperature and power generated).

The simulation models yielded an energy generation ranging from 23 300 kWh to 24 200 kWh based on the different configurational controls. This also highlighted the need for the simulation model as it provided a more realistic and accurate outcome prediction. The difference between the theoretical and simulation results were significant. Table 22 illustrates the comparison between the theoretical and simulation results.

Table 22: Generation capacities comparison

Flow (l/s)	Energy generated (kWh)		
	Theoretical (kWh)	Simulated (kWh)	Difference (%)
171.0	21 536	23 307.6	8.2
200.0	26 867	23 817.6	8.1
219.7	30 252	24 234.3	19.9
245.0	33 736	23 354.3	30.8

From the comparison, it is can also be noted that the discrepancy between the simulated models and theoretical results grew with increasing flow, as the theoretical aspect made use of the linear equation (Equation 3) to predict the performance.

Based on the outcomes of the feasibility study and submitted business case report (submitted to Mine X management), CAPEX approval was granted, and the PAT installation and implementation was completed with the aid of contractors on the mine.

Once the installation was completed and the PAT controlled at the optimal BEP, the actual and simulated model results were compared. Table 23 tabulates the comparison between the actual (Weekday results) with the simulation model results.

Table 23: Actual and simulation comparison

	Simulation model	Actual results (Weekday)	Difference
Average energy generated (kWh)	24 234.3	23 132	4.54%
Average water flow (l/s)	219.7	216.7	3
110L Dam temperature (°C)	10.2	8.9	1.3
110L Dam level (%)	60.8	63.8	3
Efficiency (%)	82.3	82	0.3

The installed PAT, operating at a flow of 207 l/s to 216.7 l/s, was able to obtain an efficiency of 82.3% according to the supplied performance curve, as well as to maintain the KPI requirements as set out in the beginning of Chapter 3 (Section 3.4.3). The actual results obtained also served as a form of model validation for both the developed strategy as well as the simulation models modelled for this application. Based on the actual results obtained, the PAT system was able to generate approximately R12.45 mil. p.a. (18.65% tariff increase

included as from the 1st of April 2023). As a result of the increased generation capacity, the payback period for this case study therefore decreased to 5.2 months.

The successful implementation of the PAT can be partly attributed to accurate performance and optimal control prediction in the initial phases of the project, which was a major concern as highlighted in the literature study of PATs.

Furthermore, successful maintenance thereof is critical for long-term success. Mine X has systems in place that monitor the condition monitoring of the PAT system (this is not discussed in detail, although mentioned as part of the instrumentation section, and does not fall within the scope) as part of the maintenance plan and not based on preventative maintenance. This forms part of Mine X's operational process. Within the condition monitoring, several parameters are monitored, namely:

- Bearing temperatures
- Bearing vibrations
- Inlet and outlet water pressures
- Motor current
- Motor revolutions per minute (RPMs)
- Inlet water flow
- Control valve position and setpoint position
- Turbine efficiency

Based on the performance of the above-mentioned parameters, a series of alarms are setup accordingly with the instrumentation technicians where upper and lower limits are determined. Work orders are generated once a series of alarms are triggered showing a decrease in performance or possible mechanical failure.

CHAPTER 4

CONCLUSIONS & RECOMMENDATIONS

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Novel contributions

4.1.1. Predict the performance of PAT in an integrated WSS and WDN with the aid of a thermal-hydraulic simulation and determine the effect of the PAT on the system configuration.

The results obtained from the case study and demonstrated in Chapter 3 have shown that the performance of a reclaimed, refurbished, and repurposed PAT was accurately predicted within a WSS and WDN with the aid of a thermal-hydraulic simulation software. These simulated results were validated by means of an actual implementation.

Certain KPIs identified with set parameters and performance requirements were adhered to in both the simulation model developed and physically once the PAT was implemented and controlled optimally for optimal benefit.

4.1.2. Reclaim a PAT, test feasibility and repurpose the PAT for a different application to recover potential gravitational energy.

This study also showed that old and abandoned machinery and equipment (hydropower systems) can be recycled and repurposed to implement an operational and sustainable hydropower system for energy benefits. The study also followed a procedure to ensure a successful hydropower system by first testing the feasibility of the PAT in a new application and ensuring its viability.

4.1.3. Develop a generic and simplified procedure for PAT implementation for a corporate environment.

Many simulation procedures exist that explain the process of how a simulation should be built. However, this study did not only include a generic, yet simplified process to build a simulation model, but also a generic and simple procedure to install a hydropower system as well as test the feasibility in several ways. This procedure was also developed in a manner which includes the corporate environment where project and CAPEX approval is required from top management.

4.1.4. Optimally control the PAT in industry based on the thermal-hydraulic model taking integrated network KPIs into account.

A main objective the study was firstly, to test the feasibility of a recovered PAT in a new application and secondly, to obtain optimal control of the PAT to ensure maximum benefit. Obtained from the results presented in Chapter 3, it was shown that the thermal-hydraulic simulation model not only accurately predicted the performance but was also able to determine the BEP and test this point within the WDN and WSS successfully, warranting its implementation at the recommended flow rate. All the identified KPI requirements were also satisfied during the simulation phase, ensuring an effective hydropower system.

4.2. Conclusion

This thesis focused on developing a generic solution strategy to implement a hydropower system (namely PAT) by means of feasibility testing in the CFD domain. A detailed and comprehensive solution blueprint was developed (Figure 26) that was followed and implemented on a case study as a result of the current energy circumstances within South Africa. Energy supply from Eskom has been a major concern and problem for large industries (energy tariff increases and consistent, uninterrupted supply). Therefore, energy production (renewable energy) is encouraged and should be explored to reduce the dependency on the embattled power utility, Eskom.

The primary objectives identified and established within this thesis (Chapter 1) were concluded to recover potential gravitational energy (using hydropower principles) by means of a PAT or turbine system with the aid of a thermal-hydraulic simulation suite using a preset of KPIs in an integrated network. The main purpose of the simulation model was to accurately predict the performance of the PAT or turbine at the BEP within an integrated network, following a preset of KPIs, which would determine the feasibility of a hydropower system in the identified location.

Literature has shown that studies have concentrated on numerical and experimental analysis and, to some extent, CFD analysis. However, not enough attention has been placed on a collective of objectives, as defined previously. This emphasises the need for additional research within the PAT performance prediction, thermal-hydraulic simulation and integrated network with KPIs domain.

Chapter 2 describes the development of a comprehensive solution method (Blueprint) which was based on previous studies for the implementation of hydropower system in a corporate environment. This developed solution method was also applied to a case study, Mine X, as explained in Chapter 3.

Comprehensive investigations on both Mine X and Mine Y revealed compelling and favourable results. A potential hydropower system was identified on 110L, supplied from 84L at an average flow rate of 220 l/s with a head of 792.48 m. Further investigation led to the retrieval of an abandoned hydropower system and most of the relevant and required components for a repurposed system. Based on the pre-feasibility analysis, the hydropower system proved profitable as approximately 1.4 MW of power could be recovered, equating to R15.27 mil. p.a. Further analysis yielded two possible CAPEX scenarios, where a new hydropower system would be procured in the first scenario, compared to where one would be reclaimed and refurbished in the second scenario. The respective CAPEX analyses showed a 4- or 8-month payback period, with the reclaimed scenario having the lower payback period.

A feasibility study was then completed to test the viability of the PAT with a preset of KPIs that ultimately governed the operation of the PAT. A control model was constructed (digital twin), calibrated and verified against actual data, with satisfactory results. Four scenarios were modelled, predicting the performance of the PAT at various flows and the performance of the 110L ice dam. The results proved that an operational PAT was feasible.

The simulation model tested the viability of the PAT sustaining the WDN conditions and not negatively affecting the production and operational ability of the organisation (underground mine). The developed simulation model was ultimately used as the embodiment design, the foundation for the detailed design. The results were presented to the mine's top management and project approval was obtained with the required CAPEX.

Upon completion of the installation of the PAT, the PAT was commissioned, and results were compared with the simulation model. This comparison showed a minimal difference between the developed models and the actual implemented results.

R5.4 million capital was required to implement a hydropower system capable of producing 23 132 kWh on a weekday and 16 827 kWh on the weekend per day. This equated to approximately R12.45 mil. p.a. with a payback period of 5.2 months. The proposed solution

promised to resolve a minor problem for Mine X, although applied across a variety of mines may ease the electricity cost burden and dependency on Eskom.

Table 24 tabulates and summarises the correlation of the objectives of the study and the alignment with them within the document.

Table 24: Objective comparison and summary

Objective number	Section	Description
1	3.3, 3.4 & 3.5	These sections describe the process to determine the potential recovery of gravitational potential energy using engineering and hydropower principles.
2	3.3, 3.4.3 & 3.4.4	Recovery process applied on a case study and implemented.
3	3.4.3 & 3.4.4	A thermo-hydraulic simulation was generated, and different scenarios modelled to test the feasibility (performance prediction) and optimal control (BEP).
4	3.4.1, 3.4.2 & 3.4.3	The developed method was applied to a case study, where a PAT was recovered and reconfigured for Mine X.
5	3.4.2 & 3.4.3	Theoretical and CFD analysis was performed on a case study. See Sections 3.5 and 3.6 for prediction performance and accuracy.
6	3.4.2 & 3.4.3	The PAT performance was predicted (numerical and CFD analysis) and evaluated to determine the viability thereof.
7	3.4.3	Different flow parameters were modelled numerically and by means of CFD analysis to test the feasibility and determine the most optimum benefit.
8	3 & 3.3 - 3.6	Section 2.4 shows the development of the solution method and in Section 3.4, the developed method was applied on a case study (Mine X and Mine Y).

4.3. Recommendations

This study allows for more work and research to be completed in the following fields:

4.3.1. Comparison between turbine and PAT performance and cost (efficiency and effectiveness)

More focus can and should be placed on the performance comparison between the normal turbine (Pelton) and the PAT. Although the turbine can generate more power, the initial capital required is higher and therefore reduces the payback period. The turbine also has higher maintenance costs due to possible mechanical breakdowns which should also be considered.

4.3.2. Theoretical and numerical PAT prediction method

Throughout the study, it was determined that the numerical PAT performance prediction becomes more inaccurate when the inlet flow surpasses a certain value. More focus and research should be exercised to improve on the current numerical method presented within the study.

4.3.3. Replacement of turbine with PAT in parallel due to breakdown and high costs

Many turbines (Pelton) exist within large hydropower systems and moreover in deep-level gold mines. However, they suffer from the same mechanical breakdown issues. A study investigating the feasibility of replacing the turbines with PATs as well as the cost implications and performance prediction based on the current applications of the turbine can result in a more sustainable and reliable energy source being implemented.

4.3.4. Turbine breakdown and mitigation mechanisms

There is currently a lack in literature pertaining to the turbine failure mechanisms as well as causes. More focus should be placed on these mechanisms as well as possible mitigation solutions to reduce downtime and improve the overall effectiveness of turbines and PATs in existing and future hydropower systems as renewable energy, especially within South Africa, is a growing commodity.

4.3.5. PAT maintenance intervals

The maintenance intervals of the PAT and hydropower system should be investigated and researched as this is not the traditional pumping system. The traditional maintenance period of a centrifugal pump should not be applied to the PAT as the internal hydraulics and operations

differ. Therefore, more research is required to perform maintenance at the optimum point on these types of systems. Predictive maintenance on PATs may improve the overall generation capacity and reduce downtime. The PAT maintenance intervals need further investigation due to current outdated and reactive maintenance processes and procedures. This will further improve the longevity of the installed PAT system and avoid serious mechanical failures.



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APPENDIX A

THEORETICAL COST SAVINGS AND CALCULATIONS

Appendix A depicts the theoretical cost saving calculations and calculators used to determine the financial impact of the simulation models developed in Chapter 3 as part of the feasibility study.

Table 25 depicts the additional Eskom charges not related to the amount of power generated but the administrative charges. The various flow models are then discussed and depicted in the various graph plots and tables.

APPENDIX A

Theoretical cost saving calculations:

Table 25: MegaFlex - Non-local Authority Charges

MegaFlex – Non-local Authority	
Customer categories	> 1 MVA
Transmission zone	$\leq 300\text{km}$
Voltage	$\geq 500\text{V}$ & $< 66\text{kV}$
Ancillary service charge [c/kWh]	R 0.59
Affordability subsidy charge [c/kWh]	R 5.69
Electrification and rural network subsidy charge [c/kWh]	R 11.63
Transmission network charges [R/kVA/m]	R 11.96
Reactive energy charge [c/kVArh] (High season)	R 21.03
Reactive energy charge [c/kVArh] (Low season)	R -
Network capacity charge [R/kVA/m]	R 23.85
Network demand charge [R/kVA/m]	R 45.24
Urban low voltage subsidy charge [R/kVA/m]	R -
Service charge [R/account/day]	R 298.57
Administration charge [R/POD/day]	R 134.56
VAT (Excl./Incl.)	Excl.

Table 26: Hourly Eskom Non-Local Authority MegaFlex 2022/2023 tariffs

Time	Summer			Winter		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
00:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
01:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
02:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
03:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
04:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
05:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
06:00	R 1.01	R 0.64	R 0.64	R 4.50	R 0.74	R 0.74
07:00	R 1.47	R 1.01	R 0.64	R 4.50	R 1.36	R 0.74
08:00	R 1.47	R 1.01	R 0.64	R 4.50	R 1.36	R 0.74
09:00	R 1.47	R 1.01	R 0.64	R 1.36	R 1.36	R 0.74
10:00	R 1.01	R 1.01	R 0.64	R 1.36	R 1.36	R 0.74
11:00	R 1.01	R 1.01	R 0.64	R 1.36	R 1.36	R 0.74
12:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
13:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
14:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
15:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
16:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
17:00	R 1.01	R 0.64	R 0.64	R 4.50	R 0.74	R 0.74
18:00	R 1.47	R 1.01	R 0.64	R 4.50	R 1.36	R 0.74
19:00	R 1.47	R 1.01	R 0.64	R 1.36	R 1.36	R 0.74
20:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
21:00	R 1.01	R 0.64	R 0.64	R 1.36	R 0.74	R 0.74
22:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74
23:00	R 0.64	R 0.64	R 0.64	R 0.74	R 0.74	R 0.74

171l/s:

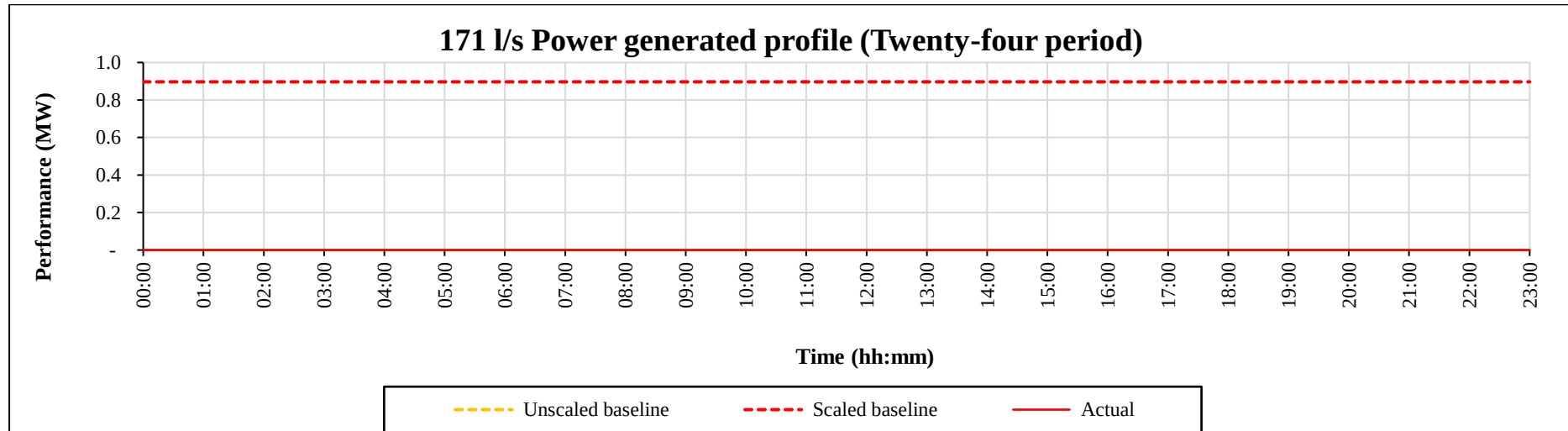
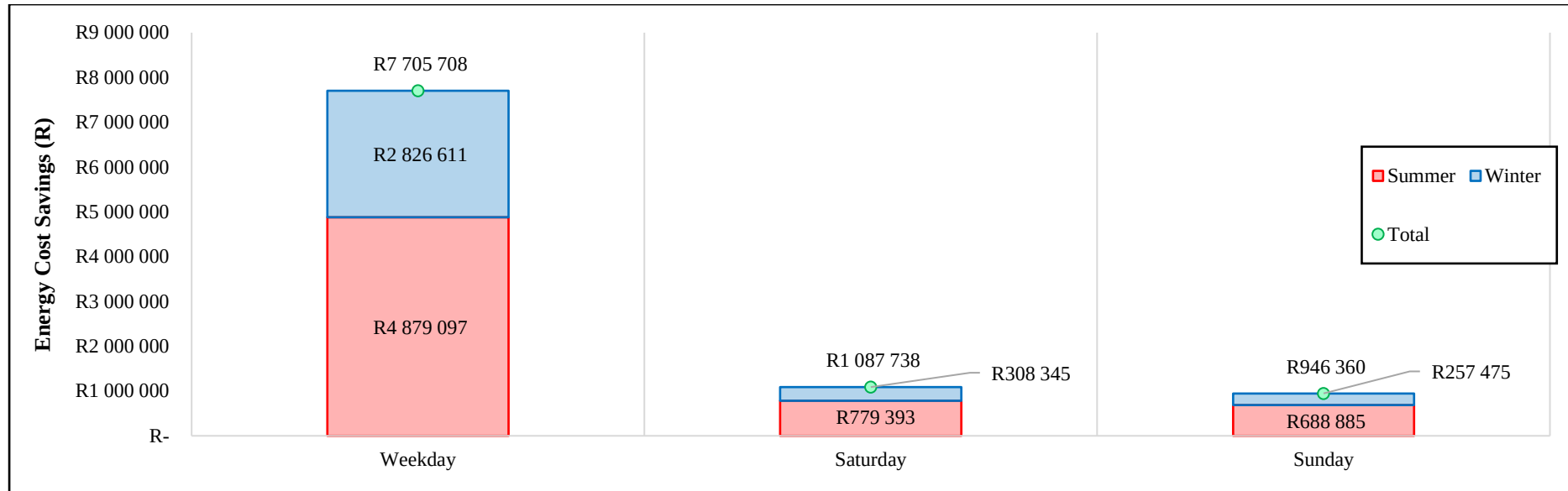


Figure 59: 171 l/s - Power generation in a twenty-four period

Table 27: 171 l/s - Seasonal power generation (R)

Cost savings (R)	Total	Summer + Winter			Summer			Winter		
		From/To	2022/06/01	2023/05/31	From/To	2022/09/01	2023/05/31	From/To	2022/06/01	2022/08/31
		Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Days in period	365	261	52	52	195	39	39	66	13	13
Daily	R 26 684.40	R 29 523.78	R 20 918.04	R 18 199.23	R 25 021.01	R 19 984.44	R 17 663.72	R 42 827.44	R 23 718.83	R 19 805.76
Total in period	R 9 739 806.03	R 7 705 707.83	R 1 087 738.08	R 946 360.12	R 4 879 096.50	R 779 393.25	R 688 885.24	R 2 826 611.33	R 308 344.83	R 257 474.88

**Figure 60: 171 l/s - Total day type generation split**

200l/s:

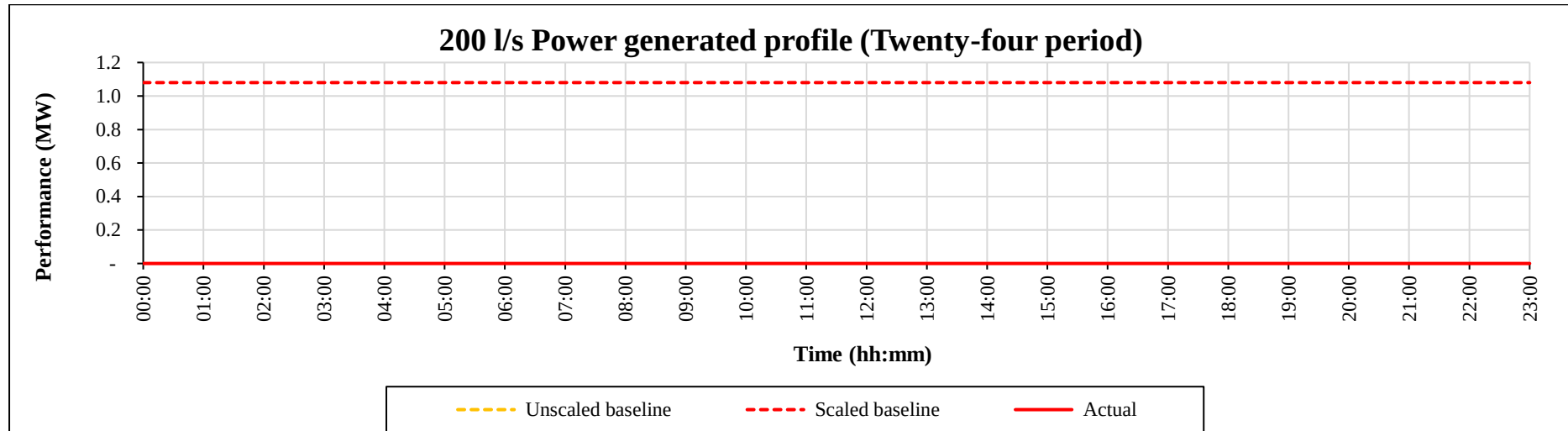


Figure 61: 200 l/s - Power generation in a twenty-four period

Table 28: 200 l/s - Seasonal power generation (R)

Cost savings (R)	Total	Summer + Winter			Summer			Winter		
		From/To	2022/06/01	2023/05/31	From/To	2022/09/01	2023/05/31	From/To	2022/06/01	2022/08/31
		Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Days in period	365	261	52	52	195	39	39	66	13	13
Daily	R 32 128.37	R 35 547.03	R 25 185.60	R 21 912.12	R 30 125.63	R 24 061.54	R 21 267.36	R 51 564.82	R 28 557.79	R 23 846.40
Total in period	R 11 726 856.76	R 9 277 775.32	R 1 309 651.20	R 1 139 430.24	R 5 874 497.46	R 938 399.90	R 829 427.04	R 3 403 277.86	R 371 251.30	R 310 003.20

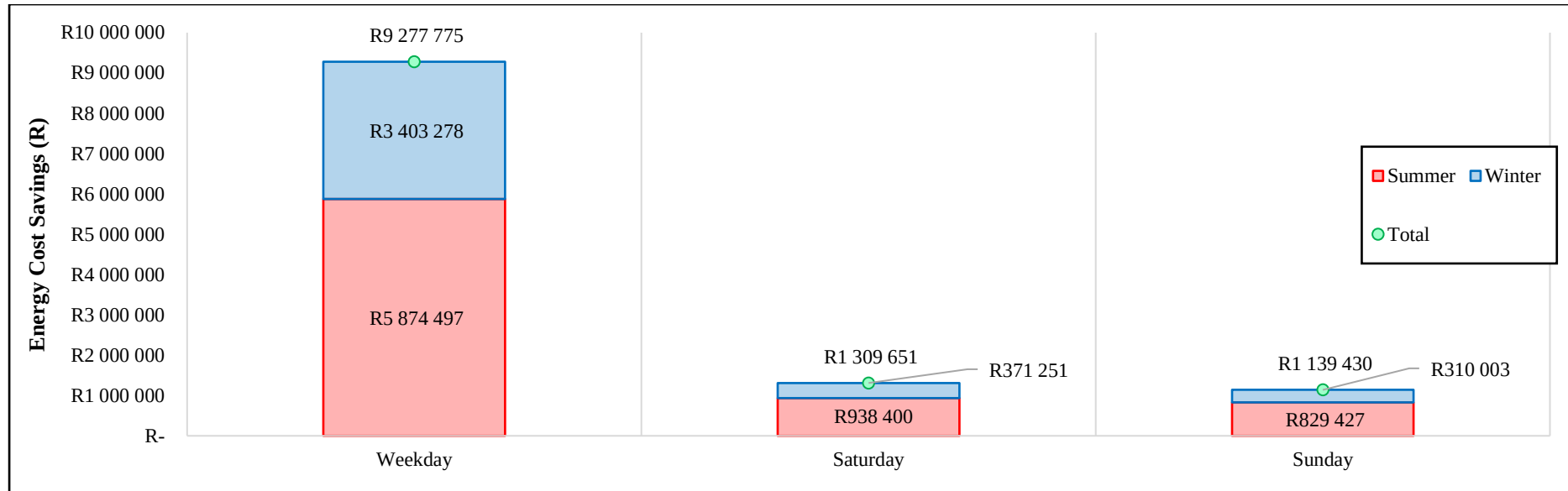


Figure 62: 200 l/s - Total day type generation split.

219 l/s:

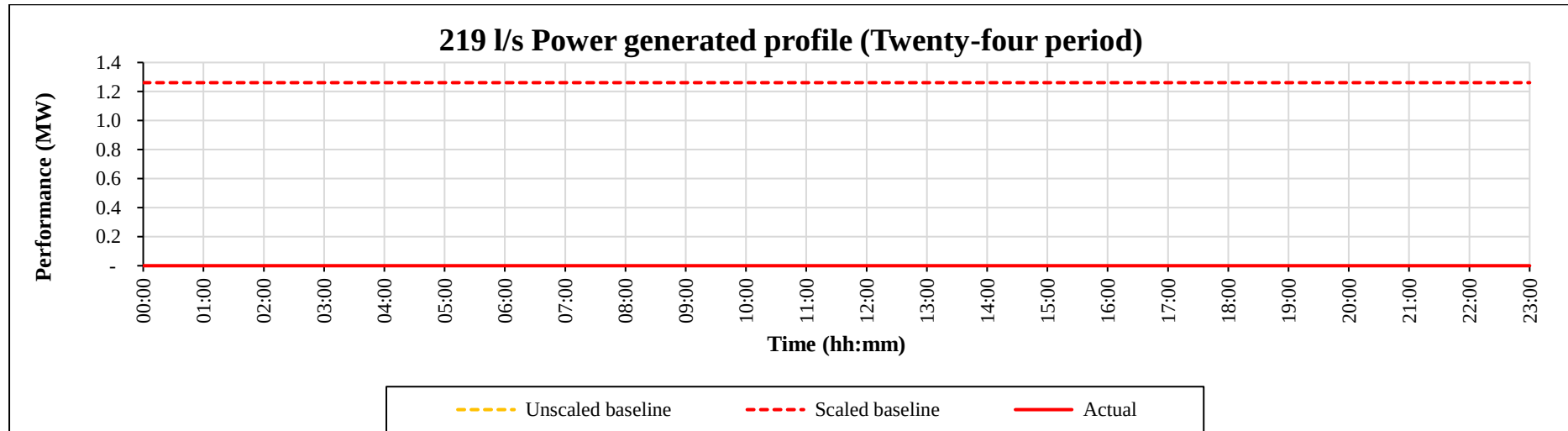


Figure 63: 219 l/s - Power generation in a twenty-four period

Table 29: 219 l/s - Seasonal power generation (R)

Cost savings (R)	Total	Summer + Winter			Summer			Winter		
		From/To	2022/06/01	2023/05/31	From/To	2022/09/01	2023/05/31	From/To	2022/06/01	2022/08/31
		Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Days in period	365	261	52	52	195	39	39	66	13	13
Daily	R 37 512.85	R 41 504.45	R 29 406.52	R 25 584.43	R 35 174.46	R 28 094.07	R 24 831.61	R 60 206.70	R 33 343.87	R 27 842.88
Total in period	R 13 692 191.08	R 10 832 661.73	R 1 529 139.04	R 1 330 390.31	R 6 859 019.72	R 1 095 668.78	R 968 432.87	R 3 973 642.02	R 433 470.26	R 361 957.44

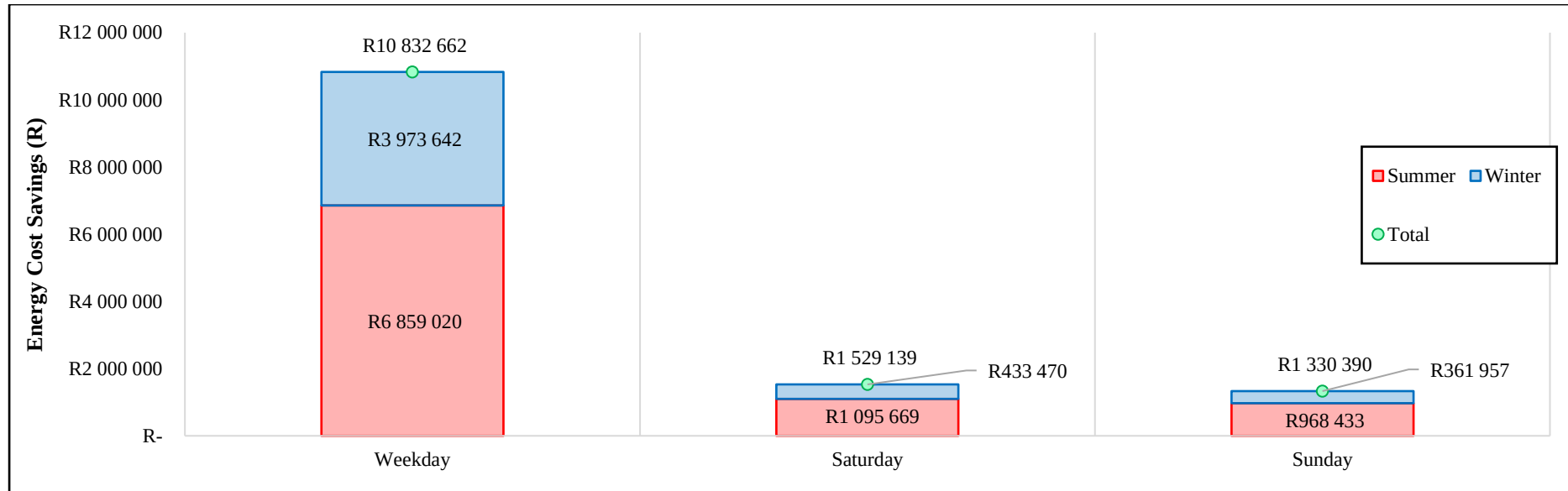


Figure 64: 219 l/s - Total day type generation split.

245 l/s:

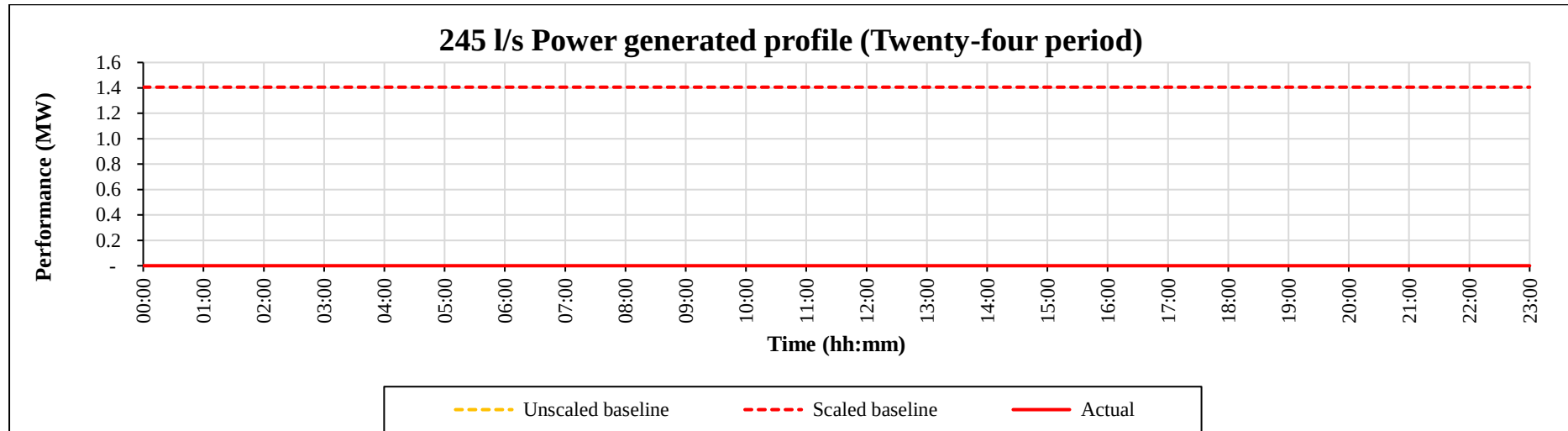


Figure 65: 245 l/s - Power generation in a twenty-four period

Table 30: 245 l/s - Seasonal power generation (R)

Cost savings (R)	Total	Summer + Winter			Summer			Winter		
		From/To	2022/06/01	2023/05/31	From/To	2022/09/01	2023/05/31	From/To	2022/06/01	2022/08/31
		Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
Days in period	365	261	52	52	195	39	39	66	13	13
Daily	R 41 826.38	R 46 276.97	R 32 787.92	R 28 526.33	R 39 219.10	R 31 324.56	R 27 686.95	R 67 129.75	R 37 178.01	R 31 044.48
Total in period	R 15 266 630.18	R 12 078 288.98	R 1 704 971.84	R 1 483 369.37	R 7 647 725.40	R 1 221 657.65	R 1 079 791.13	R 4 430 563.58	R 483 314.19	R 403 578.24

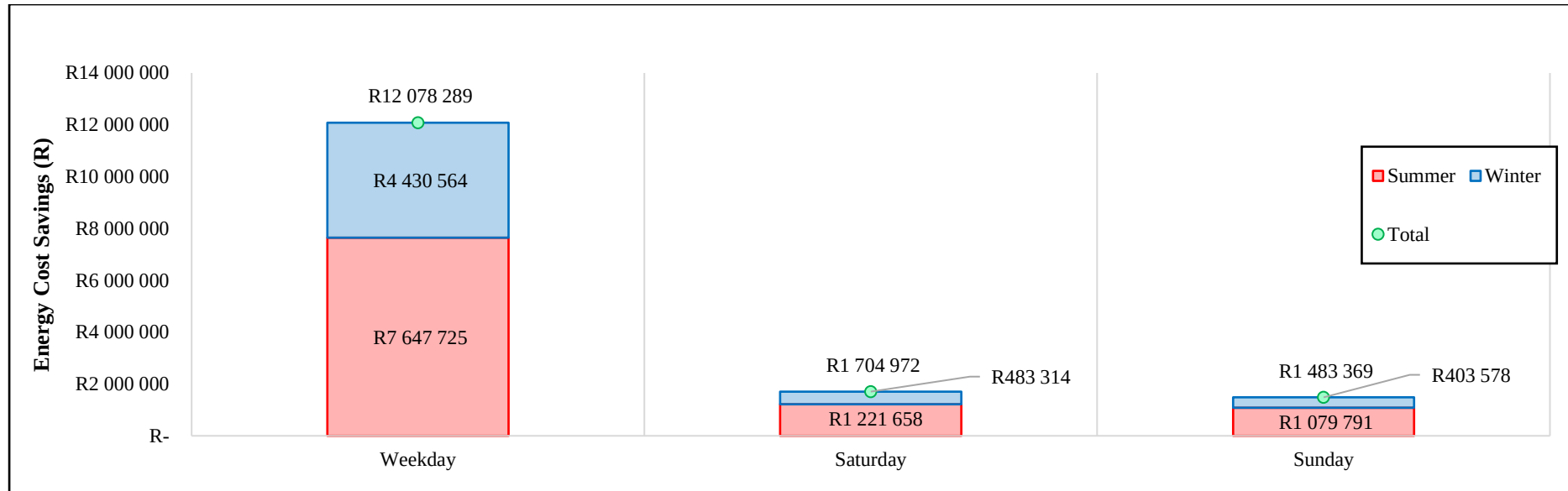


Figure 66: 245 l/s - Total day type generation split

APPENDIX B

PTB SIMULATION INPUTS

Figure 67 illustrates the ‘U-Tube’ system water flow, supply and return to the 110L ice dam which is used within the simulation model to determine the dam level and temperature.

Figure 68 illustrates the hard and soft ice supply to the 110L ice dam. The flow is depicted in mass flow and -2°C temperature is used for simulation model.

APPENDIX B

PTB Simulation inputs, and results:

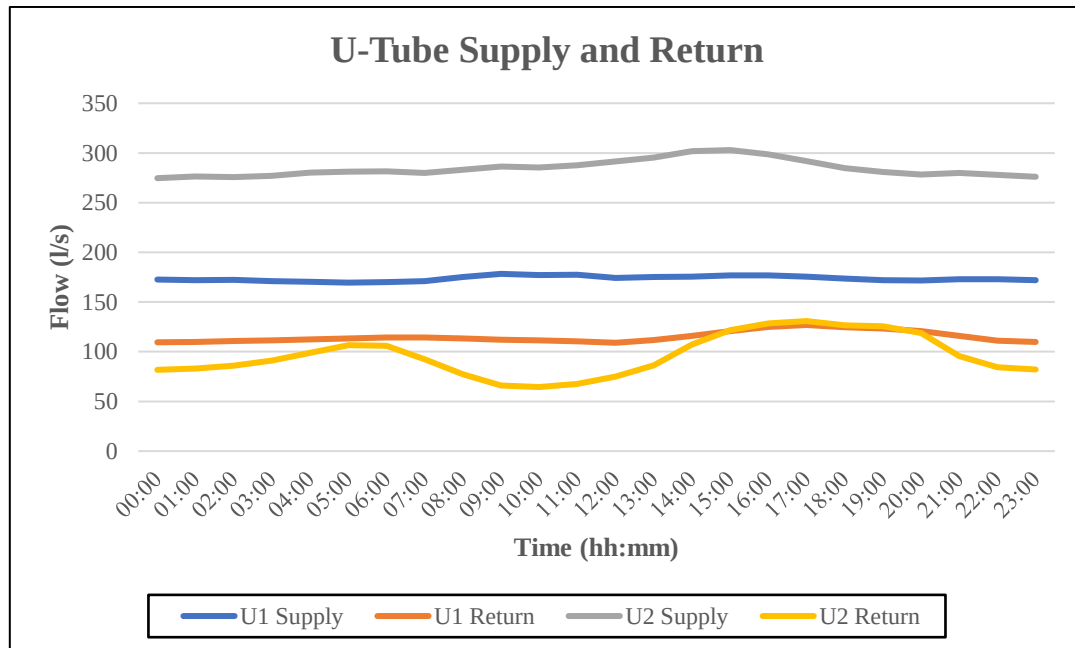


Figure 67: U-Tube system chilled water supply and return flows

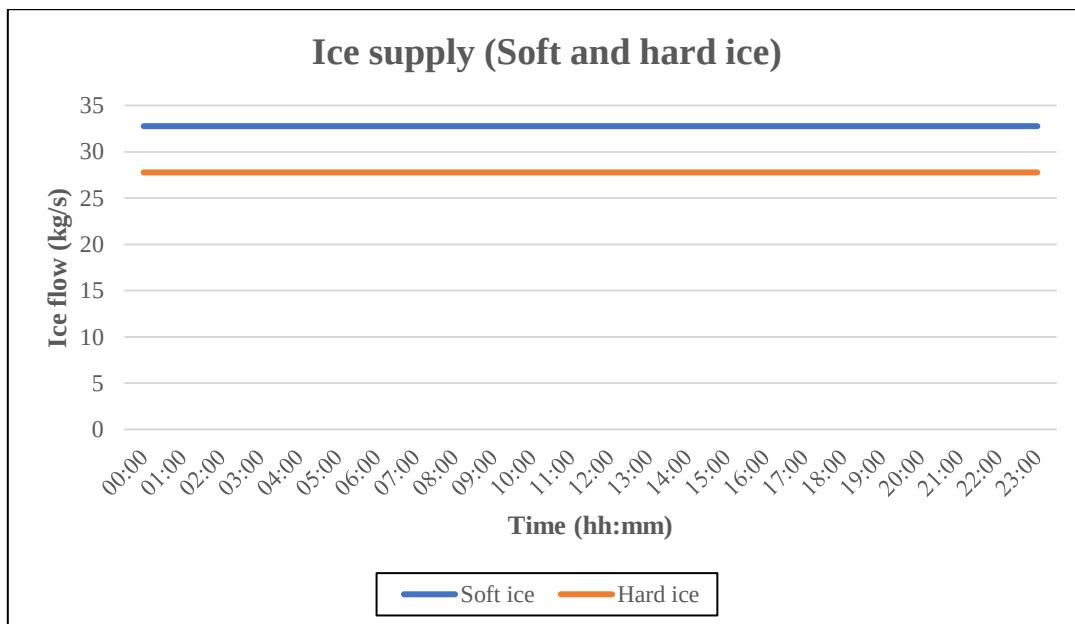


Figure 68: Soft and hard ice supply to 110L ice dam

APPENDIX C

DETAILED DESIGN AND DRAWINGS FOR 110L PAT

Appendix C illustrates the detailed design and drawings drawn by the design team based on the embodiment and concept design. Figure 69 to Figure 75 depicts the designs for the pipeline layout (high and low-pressure), pipe supports, PAT and generator location and setup. The installation of the hydropower system was based upon the detailed designs and implemented accordingly.

APPENDIX C

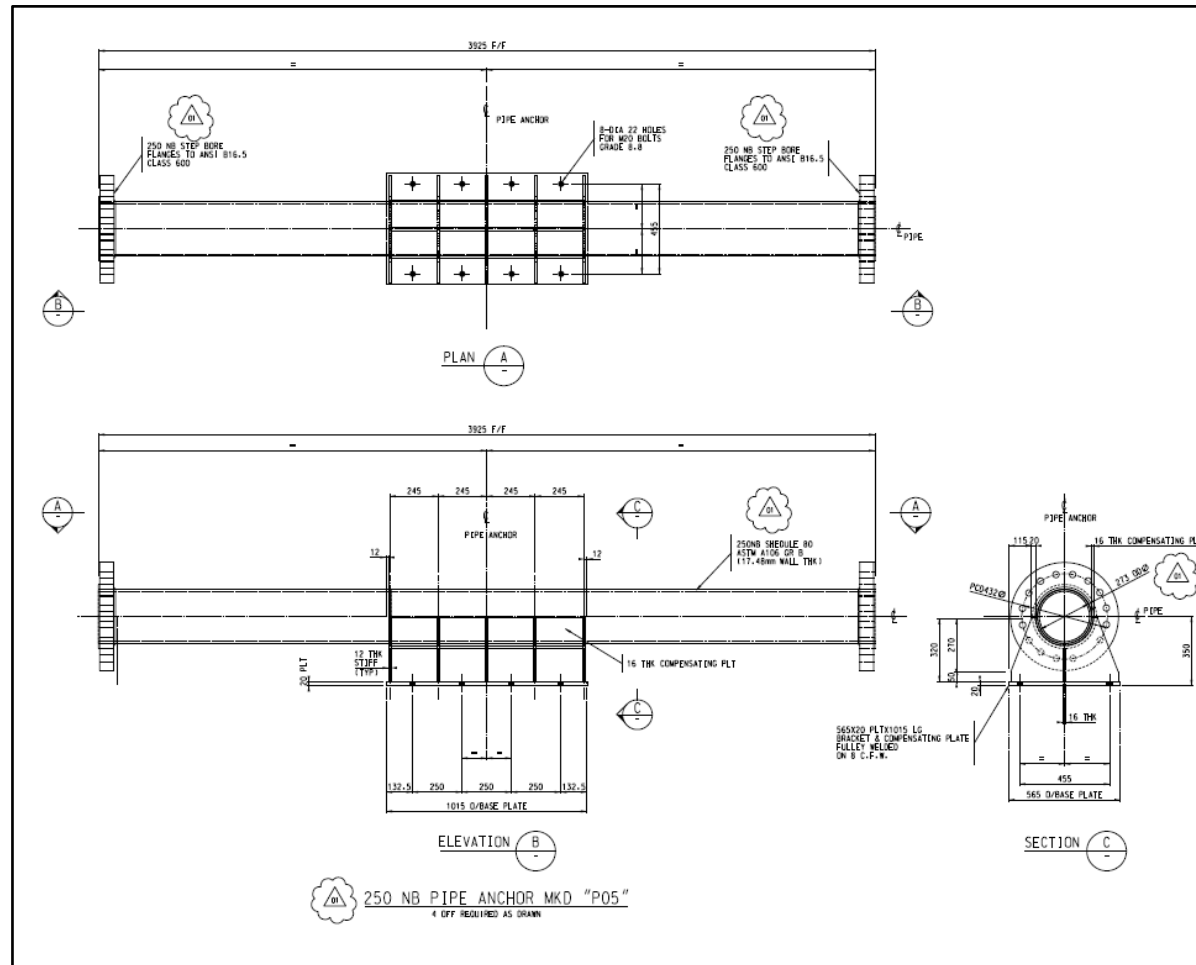


Figure 69: Detailed design A





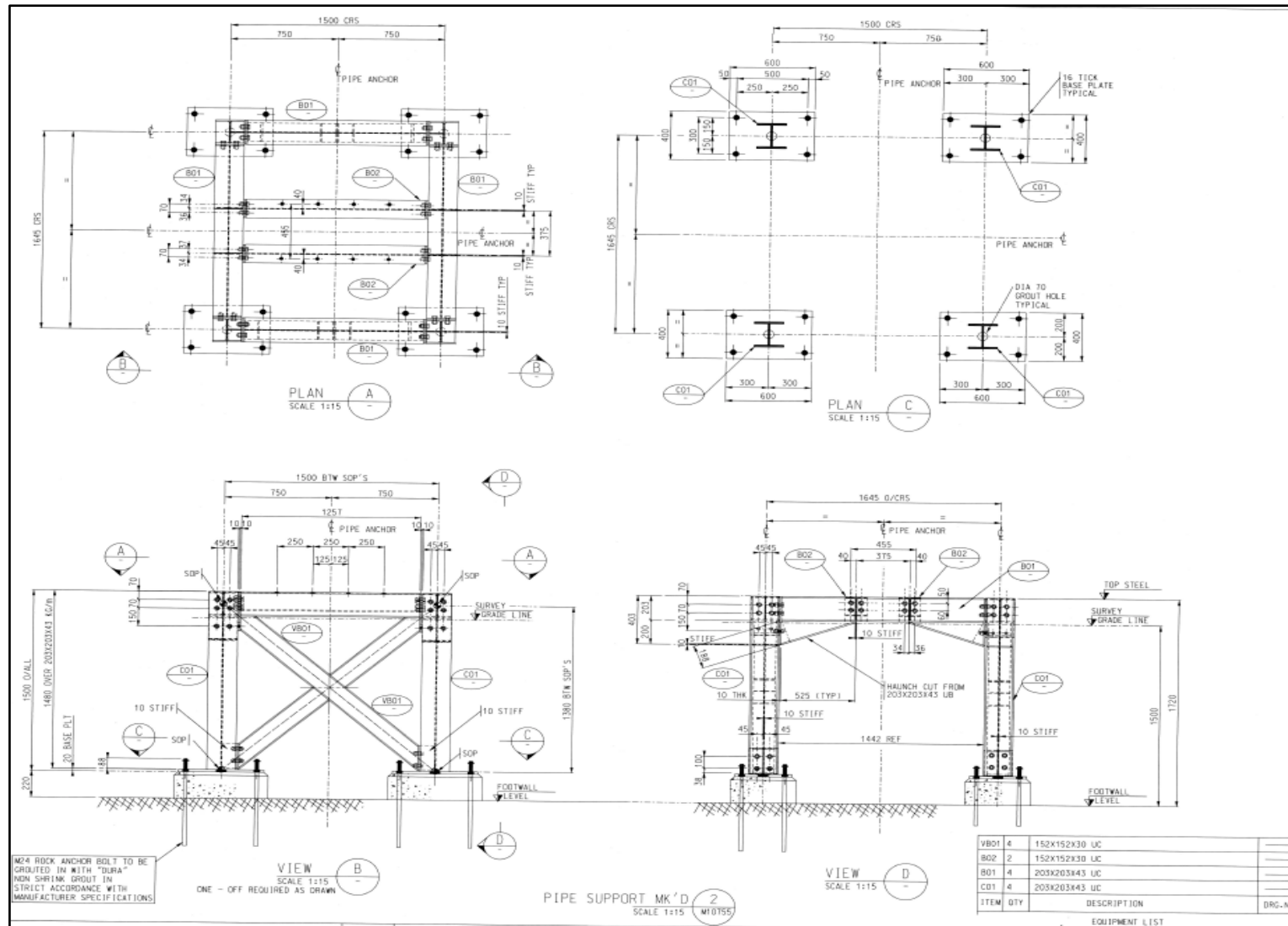


Figure 72: Detailed design D

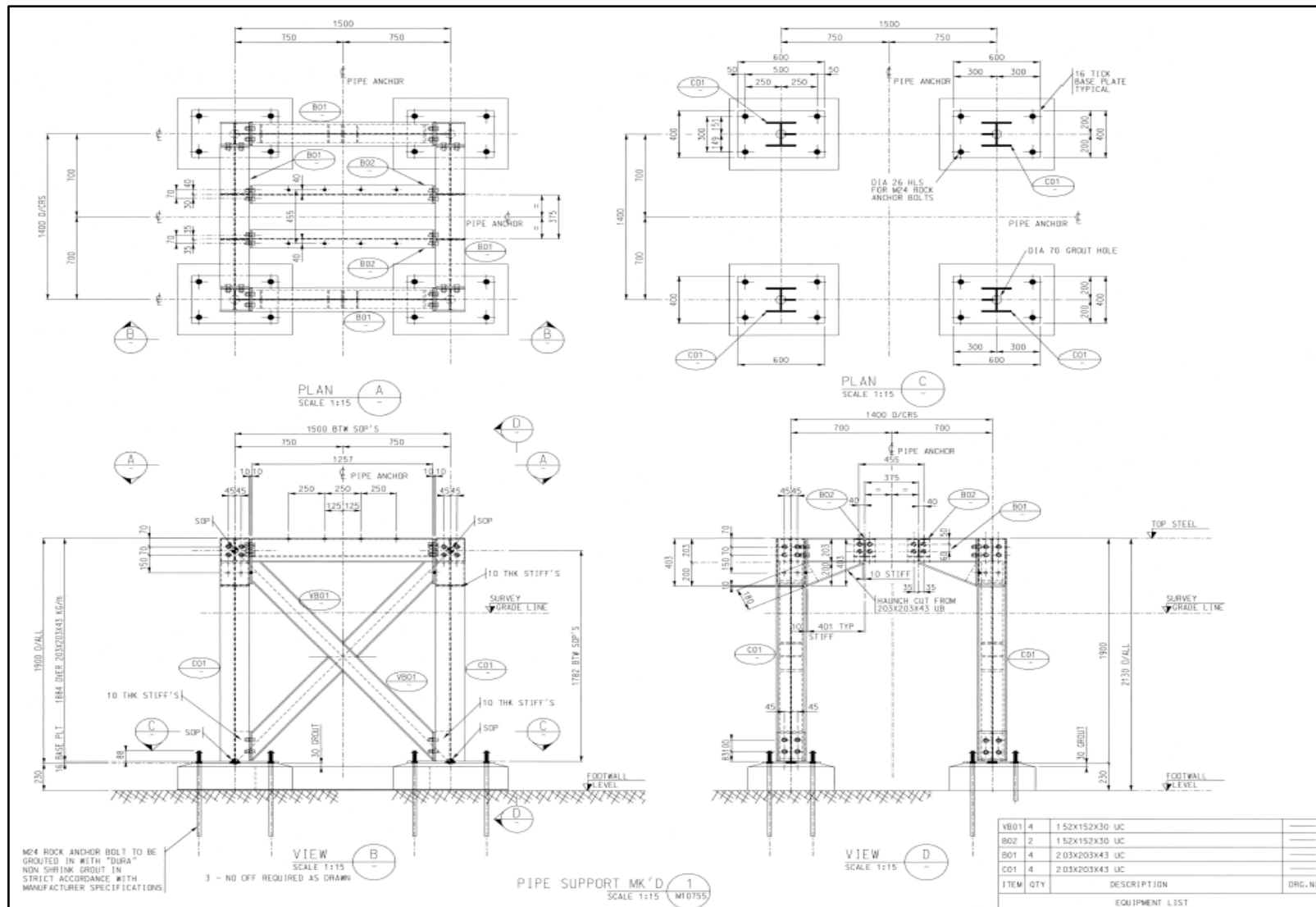


Figure 73: Detailed design E

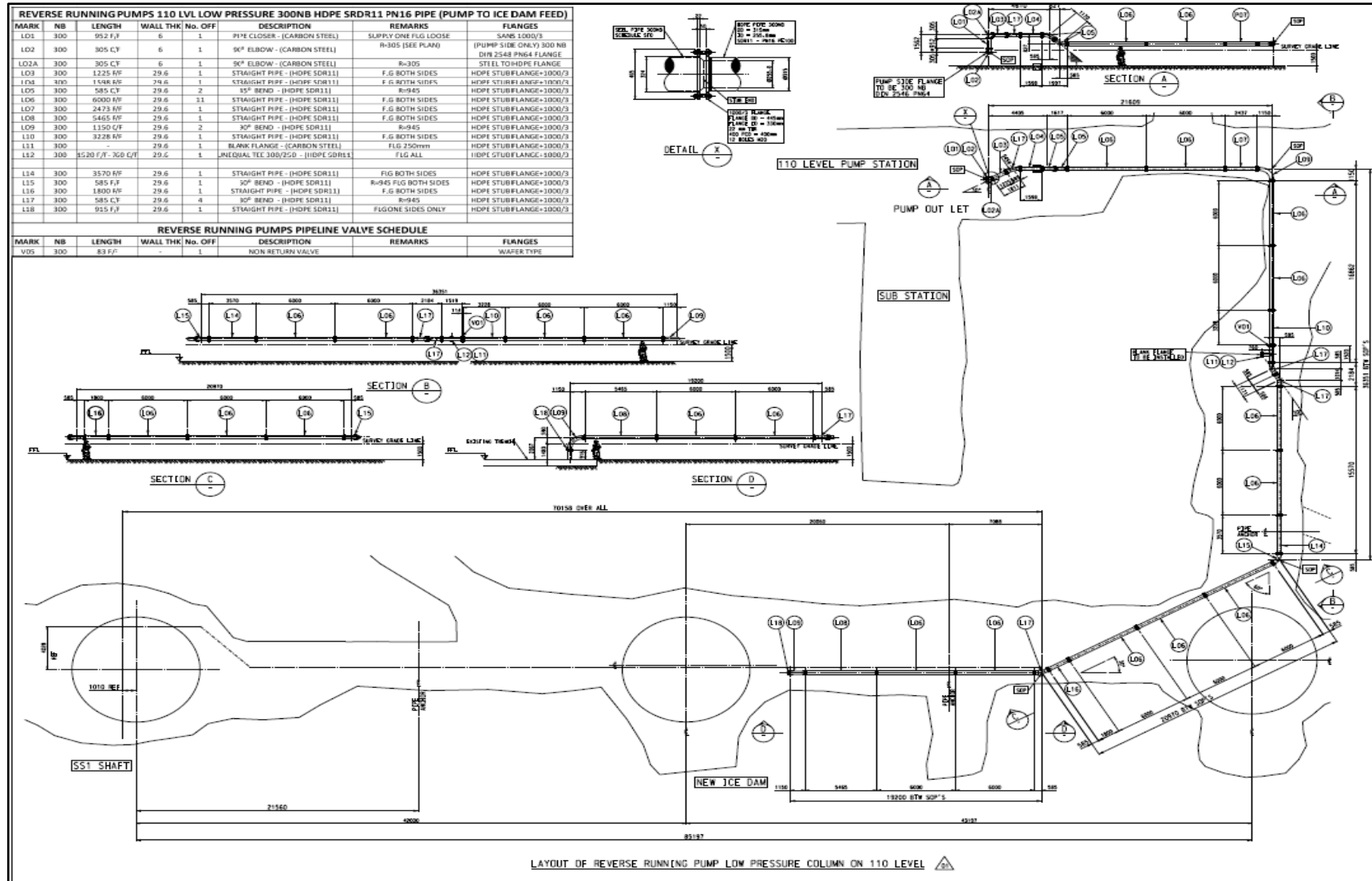


Figure 74: Detailed design F



Figure 75: Detailed design G

APPENDIX D

110L PAT INSTALLATION PHOTOS

Appendix D illustrates Figure 76 to Figure 79, which is the actual installation of the designed PAT hydropower system on 110L. The figures depict the PAT itself, the connected generator, control valve, the inlet and outlet configuration and lastly, the instrumentation installed and connected to the SCADA system for monitoring.

Not all photos have been included, as this is for demonstration purposes mainly to show the outcome and validate the installation of the PAT on 110L.

APPENDIX D



Figure 76: Installed and operational PAT and generator



Figure 77: Installed flow meter for PAT



Figure 78: Installed control valve for PAT



Figure 79: Installed inlet and outlet configuration of PAT

APPENDIX E

CONFERENCE PRECEEDINGS

APPENDIX E

NOVEL USE OF SIMULATIONS TO RECONFIGURE CENTRIFUGAL PUMPING SYSTEMS IN REVERSE OPERATION TO GENERATE ELECTRICITY

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ABSTRACT

Energy is a major expense for industrial consumers such as deep-level mines. Energy costs are increasing and there exists a resistance towards renewable energy sources especially in the mining sector. Gravitational potential energy can be recovered in various ways on mines. Integrated simulation software offers unique solutions for energy-intensive systems. One common energy-intensive component in mines is dewatering pumps. This study will focus on reconfiguring pumps in reverse operation to generate electricity by recovering energy. With the aid of simulations, the overall pump control strategy is optimized for optimal benefit and lower maintenance costs. This case study presents an integrated simulation for a reconfigured mine pump. It is shown that the reconfigured system (hydropower) produced approximately 1.007 MW of power, saving the mine an equivalent of R10.5 million p.a. Capital expenditure of R4.9 million is required to realize the project which will incur a payback of 5.6 months.

Keywords: hydropower, pump in reverse operation, energy generation, renewable energy, energy recovery, pump as turbine

1 INTRODUCTION

1.1 South Africa's current energy status

South Africa's energy system has been exceptionally dependent on mineral resources which has also contributed significantly to the country's economic development [1]. South Africa is a coal abundant country due to the rich and bountiful deposits, which allows for inexpensive electricity generation [1]. Despite this, there is an evident absence in the generation infrastructure to ensure consumers have electricity [1]. As a result of the infrastructure inefficiency, South Africa has been experiencing load shedding. A total of 22.9 days has been lost to power outages during the year 2022 to date (9th May 2022) [2].

The South African energy system is extensively carbon-intensive and has been overwhelmed by unreliable power generation as well as theft and end users non-remittance [3]. To further complicate the situation, Eskom has a hesitancy towards signing power agreements with renewable energy generators therefore maintaining the monopoly in the sector [3]. Figure 1 demonstrates the comparison between the main energy sources of South Africa.

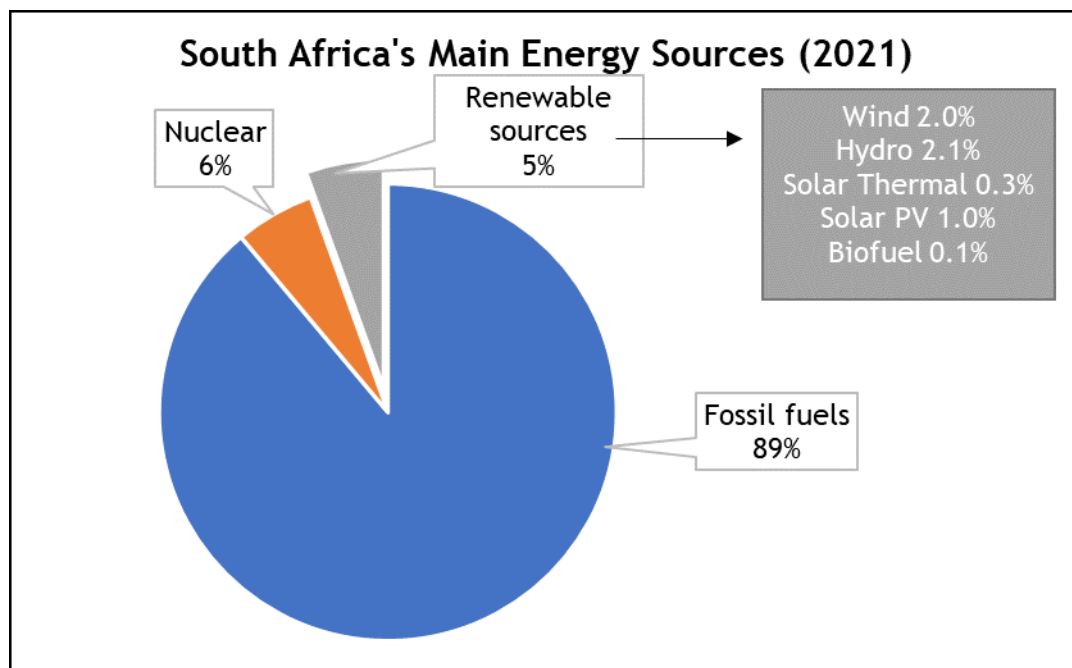


Figure 1: The energy distribution within South Africa in 2021 [4]

Eskom's tariffs have increased drastically from 2004/2005 to 2020/2021. Tariffs have increased from year to year an average of 13% and a total of 957c/kWh over the above-mentioned period. Figure 2 depicts the tariff increases over the entire period.

There is a growing need for alternative energy sources within the energy sector to complement the current energy supplier and possibly in the future, convert completely to a sustainable energy source with minimal greenhouse effects and maximum energy potential [5, 6].

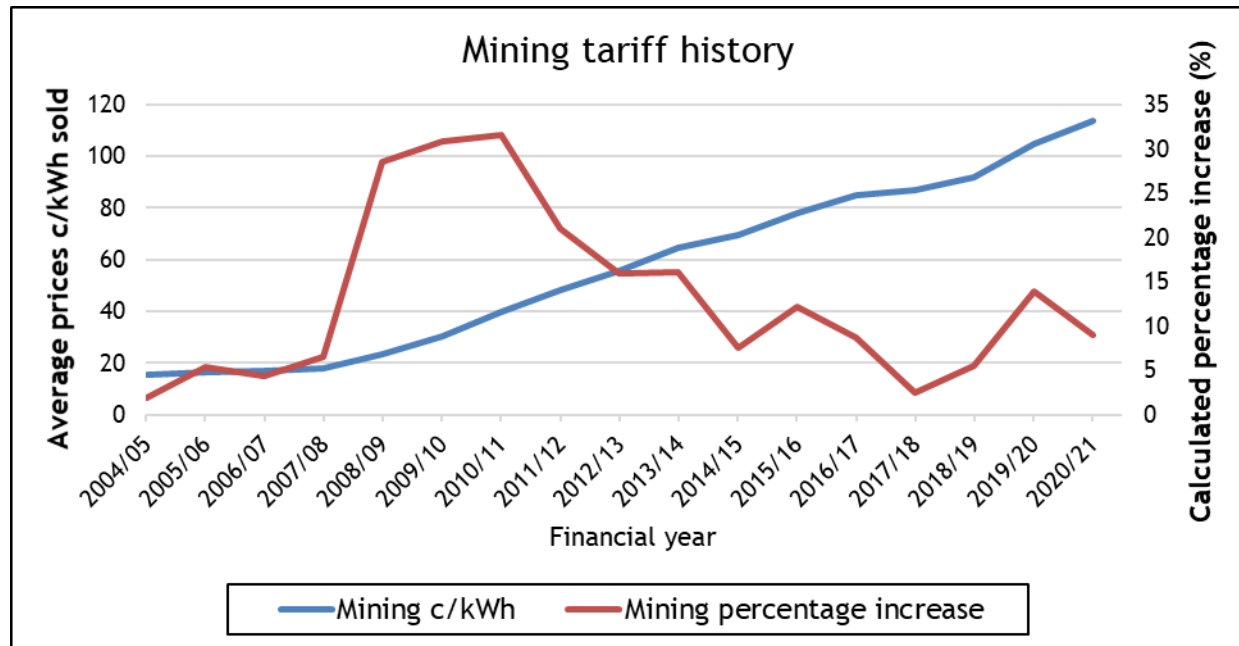


Figure 2: Eskom average tariff vs. inflation (CPI) [7]

Hydropower is considered one of the most popular renewable energy sources as it is convenient and reliable [8] and is growing swiftly across the globe [9]. Hydropower is responsible for 17% of the world's total power generation and is the least expensive source of energy [8].

Rising energy demand has started to engulf the coal generative plants in South Africa [4] and Eskom has resisted the ideology of sustainable energy sources, which has led to the further demise of the current energy situation [3]. South African deep-level mines have been suffering as a result of the load shedding and load curtailment schedules, but possesses generative capacities ranging from 0.5 – 1.5 GW, because of the abundance of water underground [10].

Excluding Eskom's installed hydropower systems, it is projected that 60 hydropower systems, installed by private and communal societies, have been installed in the underground mining sector which is currently being overlooked [11].

1.2 Hydropower

Hydropower is a versatile system and can be implemented in various configurations. Three types of configuration exist that can be implemented [12], namely Impoundment, Diversion and Pumped storage.

Impoundment is the most common form of hydropower and typically is used to store water obtained from a river or water source, at a certain height (Head (m)), which is then discharged to flow through a turbine. The turbine in turn, initiates a generator where electricity is generated [12].

Diversion also known as “run-of-river”, diverts a percentage of flow of the running source down a natural terrain decline to generate electricity [12].

Pumped storage systems primarily functions as an energy storage system, utilising another power source (renewable energy) to pump water to an elevated reservoir during low electricity demand periods [12]. The gravitational potential energy of the pumped storage is then converted to useful work via a turbine to generate electricity during high electricity demand periods [12].

1.3 Generative calculation

A turbine converts water pressure accumulated typically by possessing potential energy (Head) into mechanical energy through the turbine shaft [13]. The turbine shaft rotates as a result and is attached to a generator [13]. The turbine shaft rotates the generator shaft and electricity is then generated [13]. The electricity generated via the hydropower system can be calculated through Equation (1) [13, 14]:

$$P_{Gen} = \rho * g * H_n * Q * \eta_t * \eta_p \quad (1)$$

Here:

P_{Gen} = Power generated (W)

ρ = Water density (1 000 kg/m³)

H_n = Net head (m)

Q = Water flow rate (m³/s)

g = Gravity (9.81 m/s²)

η_t = Turbine efficiency

η_p = Pump efficiency

Water pressure can be calculated with the following equation [15]:

$$P_W = \rho * g * H_n \quad (2)$$

Here:

P_W = Water pressure (Pa)

Thus, the final equation can be deduced to:

$$P_{Gen} = P_W * Q * \eta_t * \eta_p \quad (3)$$

1.4 Turbine applications and cases

Literature has shown many efforts to improve the operational efficiencies of the pump-as-turbine (PAT) as well as numerous testing methods via numerical, experimental, and computational trials. PATs offer many benefits which include [16]:

- Availability for various head and flow
- Various standard sizes
- Inexpensive
- Availability of parts
- Easy installation

Researchers have also focused on PAT selection and various forms of PAT in different applications as shown in Table 1.

1.5 Need and objectives of study

There is extensive literature for PATs and hydropower in complex water networks, however, there exists a lack in the use of a thermo-hydraulic simulation software. This shortage encompasses the entire water complex, its key performance indicators (KPIs) and developed control strategies designed to sustain production and maintain water supply at identified KPIs.

There exists a need for the use of thermo-hydraulic simulation software to develop an optimal control strategy to reconfigure or specify a PAT for an application to generate electricity and leave the current operations unaffected. The high-level simulation will be able to determine the feasibility of the PAT in the identified system.

The objectives of the study are to generate electricity using hydropower principles, optimise control and test the feasibility with a thermal-hydraulic simulation software as well as predict the output

performance of the PAT in large mining and energy intensive systems. The PAT performance will also be evaluated in various applications and configurations exploited for optimum benefit.

Table 1: Applications of turbines in literature

No.	Author(s)	Cit.	Computational simulation	Description	Reconfiguration analysis
1	Van Antwerpen and Greyvenstein	[17]	No	Variable and constant turbine speed systems can be used to recovery energy and pressure regulation in deep mines	No
2	Liu <i>et al.</i>	[18]	Yes	Vertical axis water turbines are analysed under single-phase water and two-phase open channel flow to analyse performance	No
3	Edirisinghe <i>et al.</i>	[19]	Yes	Experimental analysis of gravitational water vortex turbines and performance improvement using Computational Fluid Dynamic analysis for different blade configurations	No
4	Velasquez <i>et al.</i>	[20]	Yes	Analysis of the basin and inlet channel of a gravitational water vortex hydraulic turbine using the surface response methodology	No
5	Kumar and Saini	[21]	Yes	Analysis of the flow field and performance of a small scale Savonius turbine at a low water velocity	No
6	Badrul Salleh <i>et el.</i>	[22]	No	Evaluation of power performance of a conventional Savonius turbine augmented with various configurations using a water channel and wind tunnel with identical flow dynamics	No
7	Khan and Sasikumar	[23]	Yes	Analysis of a water droplet erosion-induced fatigue crack propagation and failure in turbines at low pressure	No
8	Derakhshan and Nourbakhsh	[24]	Yes	Various forms of analysis were utilised to determine the best efficiency point of a centrifugal pump in reverse operation	No
9	Kandi <i>et al.</i>	[25]	Yes	The criteria of pump selection for a pump as turbine are modified and performance improved	No
10	Nejadali	[26]	Yes	The performance of a pump as turbine was analysed in a Pico-hydropower plant and revealed an acceptable prediction (excluding very low flows)	No

No.	Author(s)	Cit.	Computational simulation	Description	Reconfiguration analysis
11	Qin <i>et al.</i>	[27]	Yes	A runner optimisation strategy was used to increase efficiency on the high-pressure side in both pump and turbine mode especially focussing on the blades	No
12	Mao <i>et al.</i>	[28]	Yes	An analysis of internal fluid stability of a pump turbine by reducing the change rate of pressure and improving the flow regime	No
13	Le Marre	[29]	No	The hydraulic regulation and hydraulic electric regulation were studied in economic and energy terms where a decision-based support algorithm was utilised to conduct the study	No

2 Methodology

Implementing a hydropower system can be complex and requires adequate financial, logistical, economical, and practical preparation. A solution development procedure has been developed which focuses on achieving the main objectives and ensuring the optimal and suitable solution has been created and chosen for each case.

The “case study methodology” is comprised of four main stages which are depicted the flow diagram, Figure 3 [30].

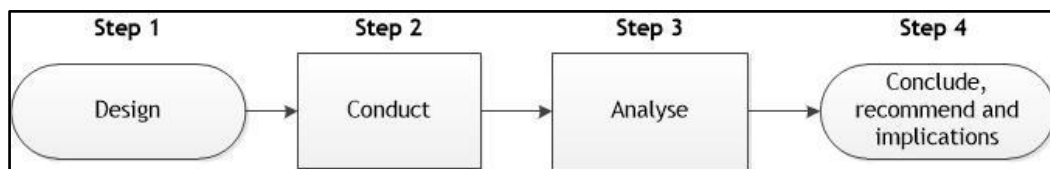


Figure 3: Case study methodology flow diagram [30]

The design step entails determining what is required and developing a procedure which is then reviewed [30]. Thereafter, the case study is conducted and data is collected [30]. The data is then analysed and from the analysis, recommendations and implications are developed [30].

Based upon the original “case study methodology” and adapted for this specific application, the solution methodology includes feasibility studies [31] as well as a simulation section due to numerical and computational benefits for engineering problems [32]. It is also critical to ensure the business aspect is included due to CAPEX (capital expenditure) requirements and approvals for establishments.

The procedure is continuously evaluated throughout with iterative processes, ensuring the optimal solution is selected for the identified problem. Figure 4 exemplifies the adapted method.

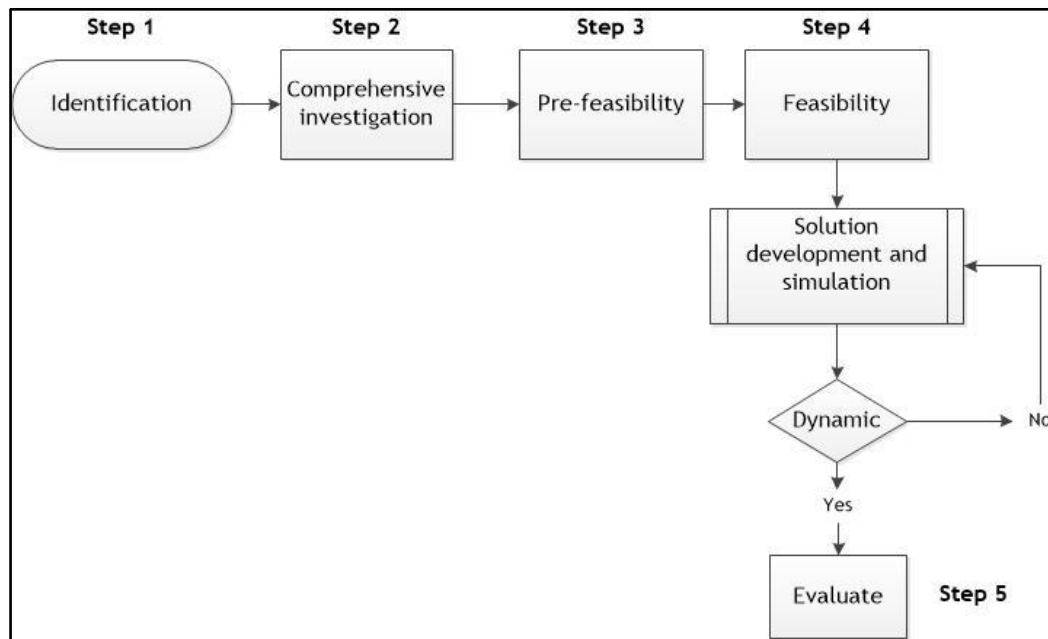


Figure 4: Solution development procedure

Entailing the main components of the engineering design and problem-solving process, the procedure was adapted to a computational approach for a more detailed and comprehensive study [33, 34]. The solution procedure identifies the problem with a comprehensive investigation, a solution is developed with the aid of computational power (based on numerical methods favoured by engineering [32]) and verified for important decision making. This process is explained in further detail below.

2.1 Step 1: Identification

Identifying the initial problem and needs is crucial when developing an efficient and successful solution [34]. Identifying the root cause will allow for the correct solution to be designed and selected. Within “Identification”, the following topics will be investigated:

- Problem statement (e.g., High energy consumption and tariffs)
- Objective of the project (Possibility to recovery energy)

2.2 Step 2: Comprehensive investigation

Once the problem and needs of the study have been defined, a comprehensive investigation should be completed where all the necessary information relating to the study is assembled. This information will typically include.

- Collect existing information available (maps, layouts, experiments, actual data etc.)

- Perform comprehensive audits on the hydro-system (water source, flow rate, system type and energy recovery type)

2.3 Step 3: Pre-feasibility

To develop a comprehensive solution both a pre-feasibility and feasibility analysis is required to be conducted. This allows and ensures that the solution developed is addressing the problem statement and objectives are met.

The pre-feasibility study primarily screens possible solutions and identifies the most auspicious solutions. It entails:

- Theoretical calculations
- Estimated CAPEX
- Preliminary (Concept) design

The pre-feasibility study will be able to highlight the KPIs and form the basis of the solution method. The return on investment (ROI) will play the vital role in determining whether the hydropower project is viable. Ideally, capital intensive projects are subsequently avoided with an ROI of more than a year [35].

2.4 Step 4: Feasibility

The feasibility study analyses the solution more extensively and permits for a suitable solution to be selected for implementation. It entails:

- Source machinery and equipment with specifications
- Compile CAPEX list for scenarios and obtain pre-approval
- Build detailed simulation with design specifications for various scenarios
- Obtain approval from committee members for capital and project implementation

Once the feasibility study is completed, it will contain a list of possible solutions detailing the process and KPIs of models. From this list, the most suitable is chosen for the application. The ideal solution will also be optimised and improved to obtain the maximum benefit.

Solution development and simulations:

When constructing the detailed model, it is beneficial to follow a structured process. A thorough process that should be followed is shown in Figure 5:

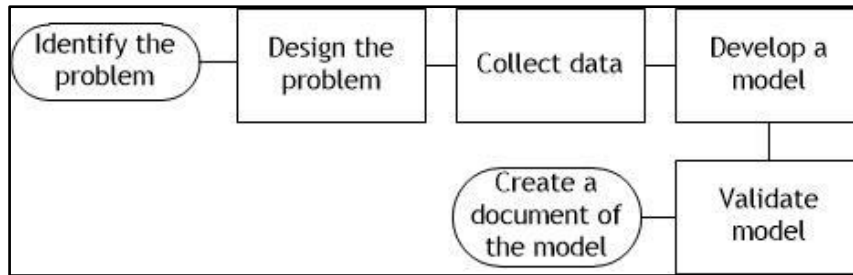


Figure 5: Flow diagram of detailed simulation process [36]

This process allows an initial problem statement to be formed, the problem is then designed with all the factors and data is then collected surrounding the problem [36]. Prior to the model being developed, it is also important consider which simulation software is to be used, as different software's achieve different outcomes [37]. The software must be tailored for the specific purpose.

A model is then developed based on the information collected and validated by modelling various actual scenarios under different conditions and then documented for future use [36]. Minor adjustments can be made to the control strategy to optimise control and obtain the maximum benefit from the energy recovery system. To ensure the optimal solution is modelled, the solution should be dynamic before progressing to the next step of the methodology, thereby ensuring an iterative process.

2.5 Step 5: Evaluate

Evaluating the solution development during the process performed to ensure the quality of stages prior and that the ideal solution has been selected to be implemented. The ideal solution will also be optimised and improved to obtain the maximum benefit.

The updated models are then compared with the theoretical models to distinguish the better option prior to implementation. This step in the process allows for the more suited solution to be selected with a higher quality data set. "Evaluate" performs as a method of quality control. The process of evaluation will determine whether the developed solution is optimal and can further be enhanced. If the process is optimal, further enhancement is void and the solution developed is suitable.

3 Results and discussion

Mine X will be used in this paper as the case study to demonstrate how the above-mentioned solution development has been used to identify inefficiencies and effectively develop an adequate solution proposal as well implementation.

3.1 Step 1: Identification

Mine X operates in South Africa and uses approximately 47.14 GWh monthly which equates to R61.4 million. The objective of the study is to implement a developed solution on Mine X where energy can be recovered by means of renewable measures, assisting with the ever-increasing electricity costs.

3.2 Step 2: Comprehensive investigation

Mine X has a total depth of approximately 3 900 m with 3 sets of turbines operating at various levels recovering potential energy and converting it to electricity. The electricity is then rerouted within the grid to the dewatering system, reducing the overall load.

Comprehensively investigating Mine X led to the retrieval of:

- Underground level layouts
- Current underground infrastructure (Dewatering)
- Dewatering supply, demand, and re-circulation
- Current underground energy recovery system
- Flows to turbines
- Power generated by turbines
- Turbine specifications (Pelton turbine)
- Turbine inefficiencies

Figure 6 illustrates the current underground chilled water supply where it undergoes various stages of energy recovery due to the large depth of Mine X. As discussed in the literature, this type of hydropower system can be concluded to a pumped-storage plant due to the high head and reservoirs that supply further underground.

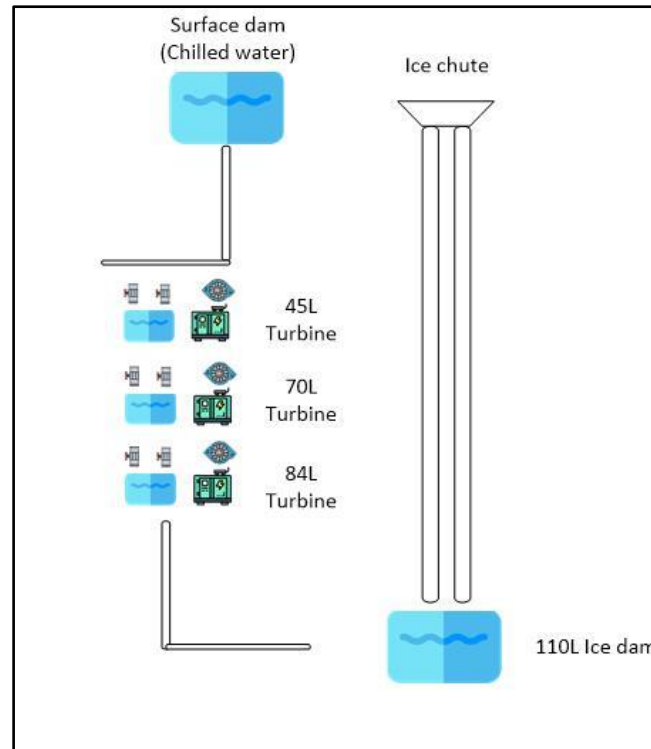


Figure 6: Mine X Chilled water supply

The turbines performance in terms of average flow and power generated are illustrated in Table 2.

Table 2: Turbine performance

Level (L)	Head (m)	Flow (l/s)	Energy generated (kWh)
45L	1 371.6	240.5	77 135.7
70L	762.0	246.4	46 913.7
84L	426.7	242.3	14 882.4

Due to the high head difference and efficiency of the turbines and generators, the power generated varies significantly. Flow between the turbines remains consistent, however the high head difference allows for more power to be generated as more pressure is then sustained as depicted in Equation (2).

Identified from the extensive investigations, Mine X possesses an impoundment system where a turbine may be installed between the 84L and 110L ice dam. Figure 7 depicts the turbine location.

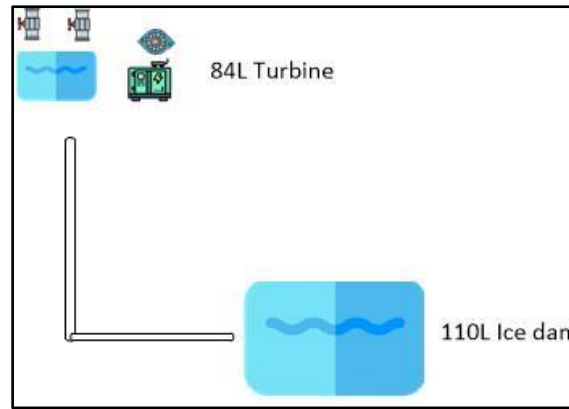


Figure 7: Turbine placement on Mine X

As illustrated above, a head of 792.48 m exists as well as an average flow of 222 l/s. Potential exists to move the equipment to mine X and install as suggested in Figure 7.

Upon the investigation, the following machinery and equipment was located at Mine Y (Within Mine X complex), which was used for an abandoned turbine project:

- Sulzer HPH-54-27/7SIG in reverse operation
- 1.6 MW Generator (11 kV)
- Dissipater valve
- Mechanical isolation valve

3.3 Step 3: Pre-feasibility

Theoretical calculations were completed based on the data collected within the investigation stage and using Equation (1). An approximated value obtained from suppliers was used for the pump and generator efficiencies. Respectively a pump efficiency of 81.4% and generator efficiency of 99% was used to calculate the theoretical generation capacity. The results of the calculations are reported in Table 3.

Table 3: Generative capacity (Theoretical)

Flow (l/s)	Total daily energy generated (kWh)	Average daily power generated (kW)
171.0	25 711	1 071
193.0	29 019	1 209
219.7	33 034	1 376

As a result of reduced average flow rate and lower head, the calculated power generated is considerably lower than the current turbines at Mine X, however, there exists a potential of 1.376MW of energy to

be recovered which equates to R14.9 million p.a. based on the Eskom Non-local Authority MegaFlex 2022/2023 tariffs [38] and theoretical calculations.

A preliminary design with the aid of the design office and team of engineers was modelled according to the identified location. The following equipment will be required for a complete pump in reverse operation setup:

- Pump in reverse operation
- Generator (11 kV)
- Dissipater valve
- Mechanical isolation valve
- Flow control valve
- Piping (High-pressure and low-pressure piping)
- High pressure pipe supports, installation pipe installation
- Instrumentation (Pressure probes, flow meters, PLC etc.)

3.4 Step 4: Feasibility

Adhering to the simulation processes explained in the methodology, the following process was followed to achieve an integrated and accurate model.

Identify

The identified problem is to implement a pump as turbine on 110L without affecting the production or the KPIs. The identified KPIs are:

- 110L dam level
- 110L dam temperature
- Flow to 110L
- Power generated from turbine

Design

Figure 8 defines the problem and possible solution that can be implemented. A concept or initial design is required as a blueprint for the detailed model.

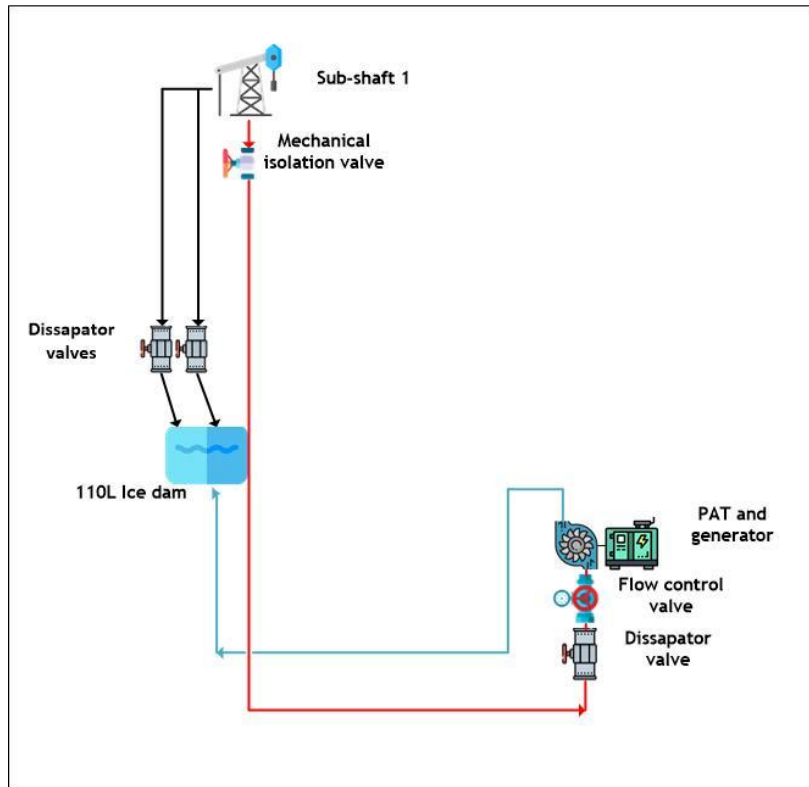


Figure 8: Initial solution design on 110L

Bypassing the 110L ice dam to the pump station, a new high-pressure pipeline (red) has been designed to the existing pump station and newly designed PAT. The low-pressure or discharge (blue) is then fed to the 110L ice dam. Required equipment for the design is a mechanical isolation valve, flow control valve, dissipater valve, PAT, and generator.

Collect data

Majority of required information has been collected in the comprehensive investigation. Figure 9 represents the average flow profile to all the turbines including the flow to 110L ice dam.

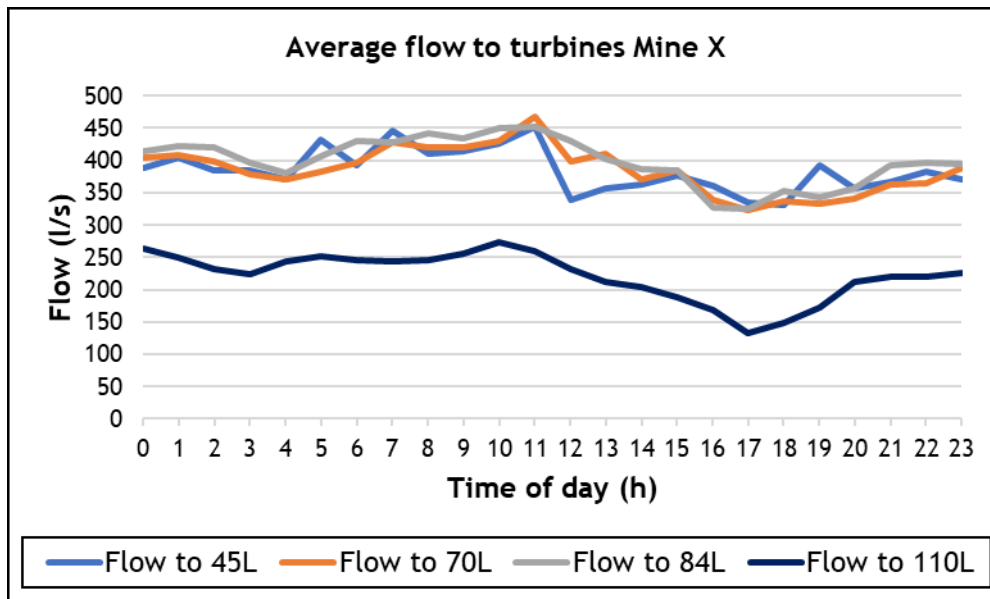


Figure 9: Average flow profiles to underground turbines

With the average flow profile in Figure 7, the pre-feasibility and feasibility studies can be completed. The flow profile can be used to determine an estimate power generation and will be used within the thermo-hydraulic simulation to determine optimal control for the entire turbine system.

Develop model

The model's aim is to confirm the application of the turbine on 110L. A detailed and complex model was developed to simulate the performance of the turbine as well as the 110L dam to ensure there is no negative effect on production (chilled water supply and temperature).

For this specific application as stated by Maré [37], Process Toolbox (PTB) is able to simulate the control of integrated systems and energy management specifically relating to mining refrigeration and dewatering systems. With the aid of thermo-hydraulic simulation software, and the turbine performance curve, a model was developed with the specifications from scenario two, which were obtained from suppliers. The developed model was compared with actual operational data from Mine X and calibrated within a 5% difference.

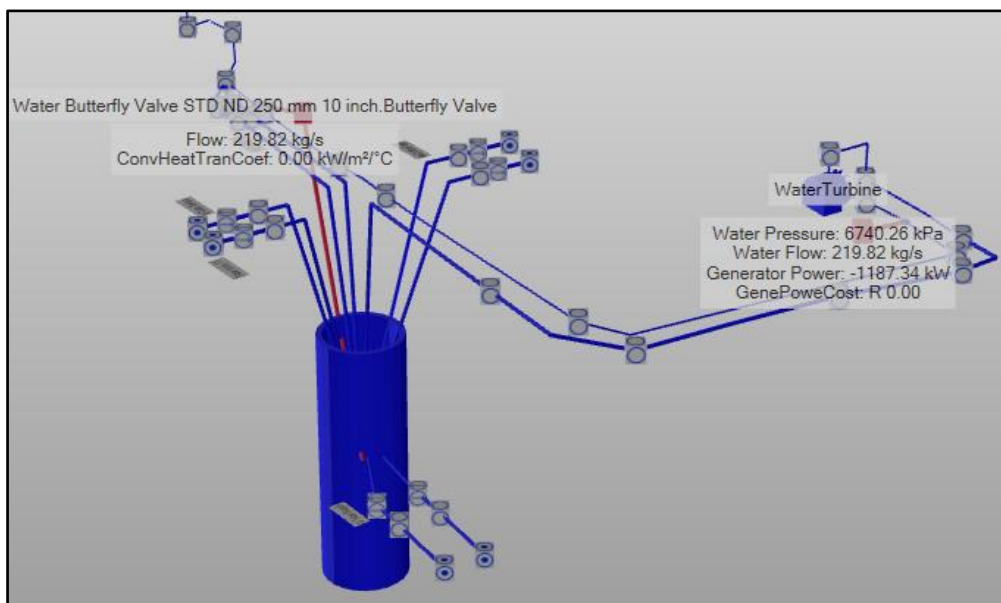
Table 4 compares the thermo-hydraulic simulation results with the theoretical results. A few instances were calculated for the theoretical section, as single and average profile was used to determine generative potential.

Table 4: Results comparison

Flow constant (l/s)	Energy generated (kWh)		
	Single flow	Flow profile & pressure differential (Simulation)	Simulated
171.0	25 711	25 630	13 390
193.0	29 019	27 315	19 578
219.7	33 034	28 048	23 036

There exists a significant different between the three sets of results mainly because of the simulation which makes use of pressure drops over the system, which the theoretical version does not accommodate. Another set of calculations were performed using the flow profile and pressure differential over the turbine to determine the generative capacity.

Figure 10 depicts the detailed model used for the solution. From the simulation results, it is estimated that an approximate of 1.007MW can be generated which equates to R 10.5 million p.a. based on the Eskom Non-local Authority MegaFlex 2022/2023 tariffs [38].

**Figure 10: Detailed model in simulation software**

The significant difference between the theoretical and simulation results is because of the pipe losses, pressure drop and differential over the turbine which is not considered within the theoretical calculations. As mentioned above.

Figure 11 displays the power generated at a flow of 219 l/s with the aid of the thermo-hydraulic simulation.

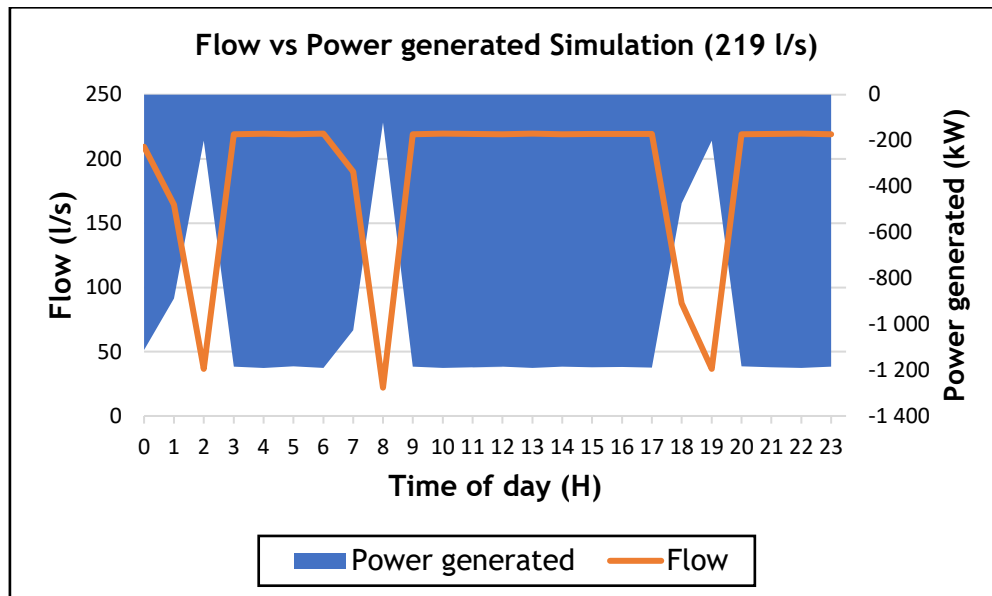


Figure 11: Turbine performance comparison (Simulation)

Although, the generative capacity is an important KPI, the 110L ice dam has significant importance and its performance needs to be modelled in conjunction with the turbine. Figure 12 displays the dam level against the temperature over a 24-hour period at a supply of 219 l/s.

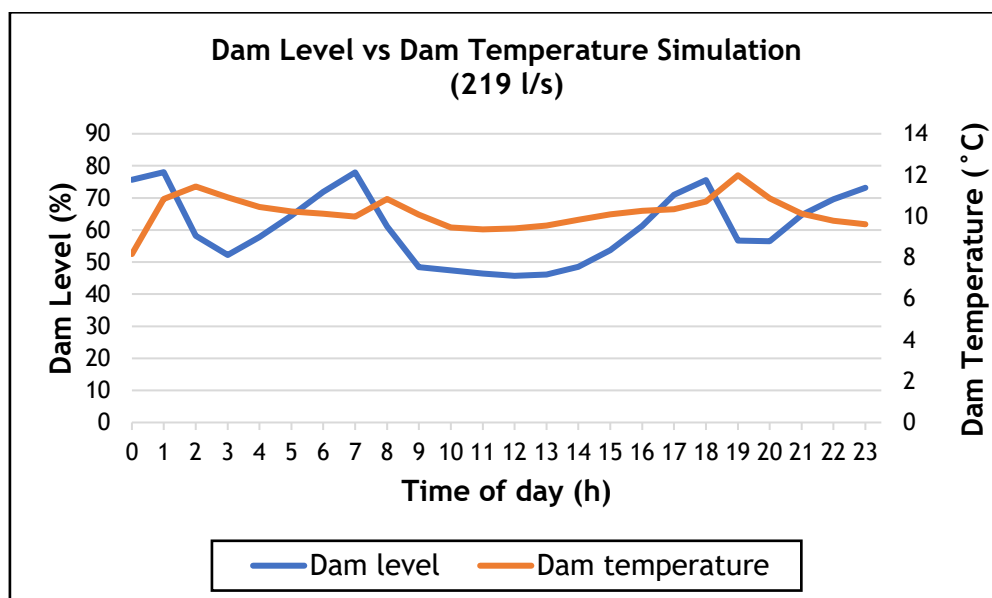


Figure 12: 110L Level and temperature comparison (Simulation)

A requirement of Mine X is to maintain 60% dam level to ensure supply at an average temperature of 11°C to ensure that mining production (ore tonnes) is not affected. The simulation was able to model an average dam level of 60.9% at an average dam temperature of 10.2°C.

Validate

The generated results have been validated in several ways as well as the main KPIs. The generated results have been validated with the turbine supplier as well numerical calculations. The model also corresponded with current conditions on 110L prior to making any adjustments and initiating the turbine.

Create a document

A comprehensive business case was completed and submitted to Mine X's management as well as a detailed report on findings, CAPEX requirements and optimum control.

Equipment sourcing

Equipment was sourced from various companies to complete the CAPEX requirements. This required to apply for capital within the next budget cycle once approved from all the committee members.

CAPEX analysis

The capital requirements were completed for two scenarios for the solution. The first solution is procuring new equipment for the project, while the second scenario, focuses on reclaiming the equipment from Mine Y, refurbishing the equipment to a perfect working order, and re-configuring some equipment to suit the application. Scenario one has a CAPEX requirement of R 9.5 million which would produce a payback period of 11 months at the calculated generated power capacity.

Table 5 tabulates the CAPEX required to execute the second scenario.

Table 5: Scenario two: Reclaiming equipment from Mine Y

Description	Cost
Generator rewind (6.6 kV to 11 kV)	R 570 000.00
Pump refurbishment and derate to a 5 stage (2 Dummy stages)	R 750 000.00
High-pressure pipes (10 inch)	R 991 000.00
0High-pressure pipe installation	R 240 700.00
Pipe supports manufacturing and installation	R 345 000.00
Low-pressure pipes and installation (10 inch)	R 228 000.00
Instrumentation	R 505 000.00
Valve refurbishment	R 354 000.00
Actuator retrofit	R 920 000.00
Total	R 4 903 700.00

Based on the theoretical calculations, if scenario two is to be implemented, a payback period of 5.6 months can be expected based on the simulation results. From the above-mentioned CAPEX details, it is recommended to recover the equipment from Mine Y as there is significant reduction in the amount of CAPEX required for the project and the machinery requires minimal re-configuring to achieve the same output as scenario one would. By doing so, the feasibility of the project improves significantly, and a larger return is promised.

3.5 Step 5: Evaluation and discussion of results

Optimal control has been established and the flow maximised to ensure maximal benefit from the turbine while not overloading the system and still adhering to production requirements. The optimal control is displayed in Figure 10 and Figure 11.

A suitable location was identified to recover gravitational potential energy by means of implementing a turbine and generator between two levels with an ideal water flow. A series of numerical and thermo-hydraulic computational simulations were calculated at various water flows. Table 6 illustrates the results comparison.

Table 6: Results comparison

Flow (l/s)	Power generated theoretical (kWh) – Single flow	Power generated simulated (kWh)	Percentage difference (%)
171	25 711	13 390	47.92
193	29 019	19 578	32.54
219.7	33 034	23 036	30.27

Ideally, a constant flow is typically used to calculate potential generation, however it is insufficient and inaccurate as displayed in Table 6. As the flow increases, the difference between the theoretical and simulated generated power decreases. The thermo-hydraulic simulation presents a low generated value as optimal control has been established encompassing the entire chilled water supply system. The thermohydraulic simulation is required for such cases due to the complex nature of the mine and water requirements.

The solution proposed has a generative capacity of approximately 23 036 kWh with considerably less CAPEX by reclaiming and re-purposing abandoned machinery. It equates to R 10.5 million p.a. using the MegaFlex 2022/2023 tariffs. The required CAPEX for the project is approximately R 4.9 million which will incur a payback period of 5.6 months.

CONCLUSION

South Africa has experienced severe increases in the cost of electricity over the past two decades, whilst Eskom who owns the monopoly within the country has resisted the idea of renewable energy sources. Within South Africa various renewable energy sources exist, however, hydropower remains the most prominent and viable, especially within the struggling mining sector. Hydropower is the most reliable and cost-effective form of renewable energy to be implemented and should be explored more intensively.

Mine X was used a case within this study to show the viability and possibility of gravitational potential energy recovery. After detailed investigations and various feasibility studies, two proposed solutions were identified. The first scenario requires the procurement of all required equipment, thus a high capital input. Approximately R 9.5 million CAPEX is required to realise the first scenario. Alternatively, the second scenario, requires R4.9 million CAPEX, which is significantly less than the first scenario. It entails reclaiming abandoned equipment from a sister mine (Mine Y) and re-purposing as well as refurbishing the equipment to a suitable operational state.

Numerical calculations were conducted showing a possible generative capacity of 33 034kWh (1.376 MW). A thermo-hydraulic simulation model was built to imitate the actual underground conditions and ensure KPIs were achieved whilst generating energy. Various flows were modelled according to the average flow of 222l/s showing the different generative potential and at different forms of control. The most optimal control and maximum output achieved was at a flow of 219.6 l/s, generating an average of 23 036kWh. The KPIs identified was to ensure the 110L dam maintained an average level of 60% at an average dam temperature of 11°C. The simulation proved an average dam level of 60.9% was achieved at an average dam temperature of 10.2°C.

Concluding, a total of R 4.9 million is required to completely fulfil the solution developed and return a payback of 5.6 months as a possible 23 036 kWh (1.007 MW) can be generated at optimum control within a 24-hour period. This equates to an approximate return of R 10.5 million p.a. The proposed solution promises to resolve a minor problem for Mine X but applied across a variety of mines may ease the cost of the electricity burden and Eskom's overall load.

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