Enhancing strategies to improve hydroelectricity generation

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Abstract

Renewable energy sources are evolving fundamental components of wastewater treatment plants. The intermittent and increasing adoption of renewable energy sources supports emerging studies undertaken in the demand and supply of energy. Hydropower is a significant renewable energy source globally. A sustainable application of hydropower technology requires effective planning, design and implementation to manage or mitigate challenges. In South Africa the prevalent source of energy generation is through fossil fuels and solid waste. Overdependence on energy demand based on fossil fuels for everyday capacity of the wastewater treatment plants is unsustainable. Affordability, stability, reliability, and accessibility of electricity generated by alternative renewable energy resources are fundamental for ensuring sustainability in wastewater treatment plants.

This study reviews global usage of hydropower electricity generation technologies. A key newcomer to this scenario is micro turbine technology. Data on how these micro turbines can improve saving initiatives such as operational cost, energy, at wastewater treatment plants in South Africa is evaluated. The study develops a model to support variables with design and use of micro turbines as a hydroelectricity generation technology.

A microsoft excel tool is used to conduct the multi-layer optimisation calculations and demonstrate potential micro turbine optimisation prospects through plotted graphs captured in a model. The graphs indicate the current configurations obtainable in contrast to the possible configuration opportunities. The results include possible optimisation modifications for enhancing strategies to improve hydroelectricity generation at wastewater treatment plants in South Africa. The study concludes with recommendations and possible future prospects relating to hydropower renewable energy.

Keywords:
Renewable energy, micro turbines, South Africa, wastewater treatment plants.

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List of acronyms

WWTP	Wastewater Treatment Plant
WTC	Wastewater Treatment Company
DWS	Department of Water and Sanitation
SA	South Africa
DoE	Department of Energy
GHG	Green House Gas
IEA	International Energy Agency
SLR	Systematic Literature Review
USA	United States of America
CH4	Methane
LFG	Landfill Gas
KW	Kilowatts
MW	Megawatts
Btu	British thermal unit
KWh	Kilowatts hour
Ppm	Parts per million
NOx	Oxides of nitrogen
MOGA	Multi-Objective Genetic Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm
SPEA-II	Strength Pareto Evolutionary Algorithm
MOPSO	Multi-Objective Particle Swarm Optimisation
PAES	Pareto Evolution Archive Strategy

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1 Chapter one: Introduction

This chapter introduces the context of this study, reviewing the background, problem statement, scope, objectives, limitations, and questions. This chapter also defines a structure for addressing the study objectives and questions.

1.1 Contextual Background

The intermittent and increasing adoption of renewable energy sources for electricity generation supports recent studies undertaken in this context. Numerous forms of renewable energy sources exist. These renewable energy sources include solar, hydropower, tidal, wind, wave, biomass, geothermal, hydrogen and fuel cells (Owusu, et al., 2016). This study specifically investigates hydropower as a renewable energy source. Hydropower is a renewable energy source obtained and harnessed from a water cycle (Mazzucato and Semieniuk, 2018). Hydropower describes the processes involved in transforming energy from a water cycle into electricity (Godfrey and Oelofse, 2017). The term renewable refers to a natural source not exhausted by excessive usage. Hydropower is considered a renewable source due to the continuous renewal of the water cycle by solar power (Herzog, et al., 2001). Renewable energy sources are evolving fundamental components of wastewater treatment plants. This study investigates hydropower electricity generation based on wastewater treatment plants.

Wastewater treatment plants are facilities obliged with the responsibility of converting wastewater into effluent via physical, biological and chemical processes ensuring minimal impacts on the environment. The wastewater from wastewater treatment plants can be harnessed from a water cycle to generate electricity. This process referred to as hydroelectricity consumes large quantities of energy. Generating electricity on-site at wastewater treatment plants enhances business value, reducing greenhouse gas (GHG) emissions, energy consumptions, and operating costs. The affordability, stability, reliability, and accessibility of electricity generated based on hydropower renewable energy source are fundamental for ensuring sustainability in wastewater treatment plants. This study focusses on enhancing strategies to improve hydropower electricity generation at wastewater treatment plants in the Republic of South Africa (SA). Wastewater Treatment Company (WTC) is selected to present a case study of wastewater treatment plants based in the Republic of SA. The investigation involves reviewing WTC strategies relative to hydropower electricity generation in line with existing strategies for reduction of energy usage.

WTC is a local wastewater treatment entity based in the Southern part of Africa with expertise in wastewater administration and management. WTC is obliged to enhance the municipal environments by providing an accessible, sustainable and healthy water resource cycle. WTC has an estimated wastewater capacity of 700 megalitres daily. WTC continuously defines measures to enhance hydropower electricity generation. The Department of Water and Sanitation (DWS) is an organisation in SA legislated to ensure wastewater treatment plants operates within global best practices. DWS ensures strategies developed by wastewater treatment plants aligns with global standards (DWS, 2016). DWS enforces the implementation of defined regulations by expanding the scope of regulated contaminants and lowering the maximum contaminant levels set for wastewater discharges.

A detailed search of literature establishes renewable energy sources focuses on four fundamental areas, which includes transportation, heating/cooling, electricity generation and rural energy services (Owusu and Asumadu-Sarkodie, 2016). Renewable energy sources have contributed significantly to the SA energy sector (Du Toit, 2014). The role of hydropower electricity generation in the SA energy context is enormous (Strydom, 2015). A steady supply of electricity is essential for ensuring economic, social and environmental sustainability. The power sector in SA is currently experiencing crises with electricity tariffs and restrictions on a steady increase from 2007 to present. There is an urgent need to explore strategies towards enhancing renewable energy as a source of electricity generation. The crisis experienced in the power sector justifies this present study. The crisis experienced in the power sector establishes renewable energy as a fundamental driver when evaluating the balance sheets and cost of Wastewater Treatment Plants (WWTP). Numerous factors influence the current crisis experienced in SA power sector. This includes but not limited to urbanisation, aging, and overloaded infrastructure. Urbanisation has increased electricity consumption, but limitations exist in electricity generations to meet consumers' needs as a result of the aging and overloaded infrastructures. Figure 1 illustrates the average metro baseline energy consumption per sector adapted from SA cities network (2014) publication.

The average metro baseline energy consumption of electricity across various sector shows WWTP consumes a considerable amount of energy from the South Africa energy grid. Enhancing electricity generation of WWTP becomes an important study domain.

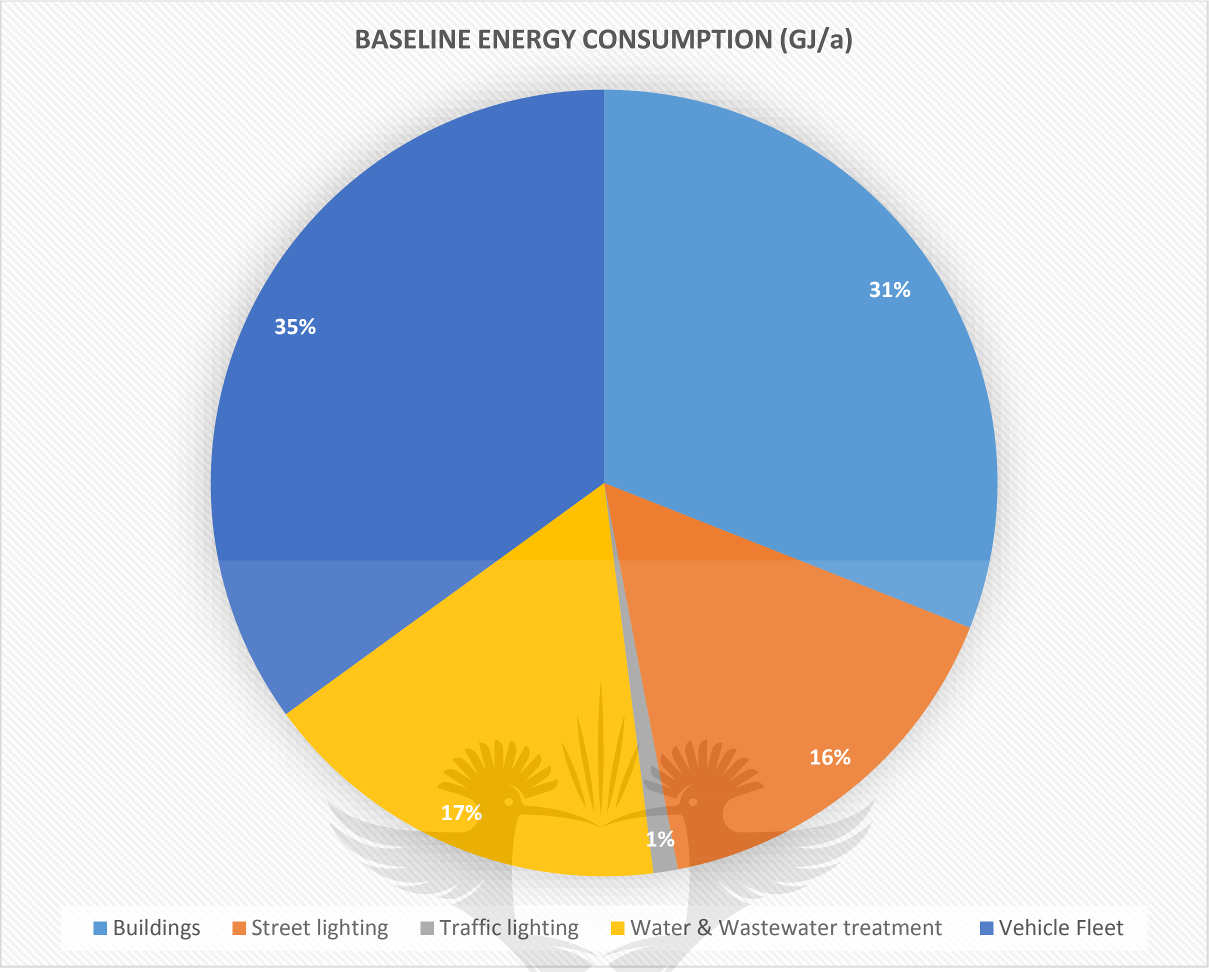


Figure 1: Average metro baseline energy consumption per sector adapted from South African cities network (2014) publication

A preliminary systematic review of literature identifies several strategies relevant to effective renewable energy sources implementations. The strategies adapted from (Logan, et al., 2013) includes but not limited to:

- Understanding consumer and relevant stakeholders' necessities, predilections, and capacity to funds and payments.
- Demonstrating the importance of effectively delivering energy services relevant to renewable energy implementations.
- Developing consumer and relevant stakeholders' trust relative to delivering energy services relevant to renewable energy implementations.
- Designing payment, funding, and financial schemes, which aligns with consumer and relevant stakeholders' budgets.
- Assessing options and identifying opportunities to collaborate.

Strategies combined with additional best practices relevant to the effective implementations of hydropower renewable energy at WWTP in SA were investigated. Based on the contextual background discussed in this section, the next section clearly defines the problem statement of this study.

1.2 Problem Statement

Intermittent renewable energy supply is unacceptable for WWTP in the current economic system relative to challenges currently experienced in the SA power grid (ERWAT, 2016). An initial review of WTC documents establishes that WTC is experiencing a high rate of power outages in recent times. Table 1 presents the total electricity consumption and power outages at WTC between July 2017 and February 2018 across the 19 wastewater treatment plants captured on a monthly basis.

Table 1: Total Electricity Consumption and Power Outages at WTC

DATE	Total Electricity used for the Month (kWh)	Total Electricity used to Process Wastewater (KW/ML)	Notified Maximum Demand	kVa Usages	Power Outages/hr
JULY 2017	9363708	9 924	24 667	15 025	23
AUG 2017	9546803	11 056	24 667	16 898	12
SEPT 2017	9426641	10 841	24 667	17 077	2
OCT 2017	8822129	9 985	24 667	16 290	29
NOV 2017	8819977	10 418	24 667	16 845	17
DEC 2017	8710184	8 019	24 667	17 976	12
JAN 2018	8720830	10 537	24 667	17 466	23
FEB 2018	8063249	9 105	24 667	17 436	21

An electrical load analysis based on Table 1 establishes WTC consumes approximately 8.8MWh per month of power set at an annual cost of R0.86/kWh excluding a yearly price increment of 8%. Electricity at WTC is the second largest operating cost, Figure 2, representing 29% of the total operating budget, Figure 2. WTC spends about of R13 Million per month on electricity. With electric pumps, motors, and other equipment operating 24 hours a day, seven days a week.

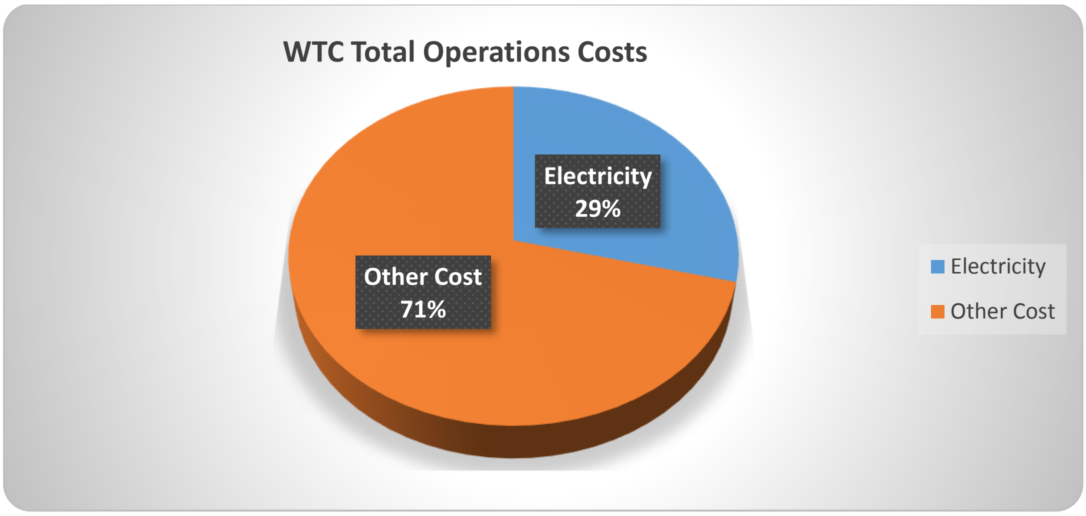


Figure 2: Total monthly operating costs

The data collected and analysed from Table 1 establishes the urgent need for WTC to enhance generation capacity via renewable energy sources. There are significant increases in power outages between July 2017 and February 2018. Though formal strategies to ensure optimal outputs of electricity generation are defined at WTC. There exist certain limitations in aligning the processes of hydropower electricity generation with global best practices. Key considerations in developing an optimal strategy might include but not limited to the type of technology, design methods, cost/budget, old infrastructures, and disposal techniques.

1.3 Impacts of hydropower renewable energy source

Coal as a source of energy, used in the 18th Century for heating buildings and smelting iron into steel resulted in the development of the first electric generator coal-powered steam engine. Prior to the development of the first electric generator coal-powered steam engine, individuals and industries, rely on muscles to generate power and energy for survival. Energy production and consumption are some of the most important activities across the globe. Renewable energy is an important source for energy production and consumption with significant economic, environmental and social impacts. Economists across the globe establish the renewable energy sector is one of the fastest growing industry in the world. Ban Ki-Moon, the secretary general of the UN reported during one of his speech at an energy conference, that global investment in zero GHG energy will reach $19 trillion by 2020". Renewable energy plays a fundamental role in WWTP and the economy of SA (Mazzucato and Semieniuk, 2018; Castillo and Gayme, 2014; Gu, et al., 2014). Ineffective strategies are identified as one contributing factor to the intermittent supply of renewable energy source relative to the generation of electricity (Ellabban, et al., 2014). Recent industry publications relative to WWTP establish the impacts of developing an effective strategy for hydropower electricity generation. Some of the impacts as adapted from (Callaway, et al., 2018; Pina, et al., 2012; Team, 2012) categorised as economic, environmental and social is detailed.

1.3.1 Economic

The power sector in SA is currently experiencing crises with electricity tariffs and restrictions on a steady increase from 2007 to present. Developing an effective strategy for hydropower electricity generation results in sustainable energy saving potential within WWTP. A steady generation of electricity via hydropower electricity generation from WWTP will enhance the generation capacity of SA energy grid. The electricity generated can be retailed to neighbouring municipalities or used onsite at the WWTP. Hydropower electricity generation is a domestic renewable source of energy, which supports different facilities generating electricity without over-dependence on international or external fuel sources. This is a positive impact on the economy of any country.

1.3.2 Environment

To address climate change as a result of global warming, there is a need for an energy revolution to protect the environment. Developing an effective strategy for hydropower electricity generation supports for a greener environment. Effectively generating energy via hydropower electricity generation produces limited or no GHG emissions reducing air pollution. Hydropower electricity generation obtained and harnessed from a water cycle results in a clean renewable energy source reducing air pollution in the environment. This is a positive impact on the environment in comparison with power plants such as natural gas or coal that burn fossil gasses. Despite the positive environmental impacts of hydropower electricity generation, hydropower facilities affect homes, land use and natural habitats, especially in the dam environs.

1.3.3 Social

An effective strategy for hydropower electricity generation maximises the potential of the water cycle to generate electricity for commercial purposes, heating, and private consumptions. This promotes a greener economy supporting the development of new industries generating employment or green jobs. Despite the positive social influences, hydropower electricity generation results in some social fears such as reduced recreational benefits of dams or rivers, poor water quality, overcrowded fish migration, and damaged wildlife habitat.

Based on the impacts of hydropower electricity generation, this study seeks to enhance strategies to enhance hydropower electricity generation of WWTP in South Africa. The next section defines the objectives investigated in this study.

1.4 Research Objectives

This study seeks to enhance strategies to improve hydropower electricity generation of WWTP in SA. Based on the problem statement discussed, this section outlines the objectives of this study.

- Discuss the expected benefits of the hydropower technology selected related to improving hydropower electricity generation at WWTP in the Republic of South Africa.
- Develop a model and investigate for optimum developments with emphasis on the applications and implementations of the hydropower technology selected.
- Discuss and propose recommendations based on the implications of the proposed optimum developments.

Results identifying the factors significant in enhancing strategies to improve hydropower electricity generation of WWTP in SA were generated. The outputs aim at contributing to the existing body of knowledge relative to WWTP in SA. The next section outlines set of questions applicable to addressing the objectives of this study.

1.5 Research Questions

To investigate if enhancing strategies of WWTP delivers an effective hydropower electricity generation; this study seeks answers to the outlined research questions.

- What emerging technology is effective to improve hydropower electricity generation at WWTP?
- What potential benefits does the hydropower technology identified have on hydropower electricity generation at WWTP?
- What variables are relevant for optimising applications and implementations of the hydropower technology selected?
- What are the implications of the proposed optimum developments related to improving hydropower electricity generation at WWTP?

Answers to the pertinent questions outlined seek to present solutions applicable in addressing the objectives of this study. The next section details the research process followed to address sets of research questions defined.

1.6 Research approach

A research approach is a plan expatiating on how the study intends to address the objectives and questions defined. This includes how the study anticipates data will be collected, designed, analysed, interpreted and make inferences (Ivankova, 2015). This section discusses and present in Figure 2 a structured approach followed to address sets of research questions defined. The structured approach is adapted from (Blumberg, et al., 2008). The applications of each research approach in this study are detailed.

1.6.1 Clarify research context

The starting point for this study is clarifying the research context. This is addressed by identifying present research gaps relative to hydropower electricity generation, defining the study objectives and defining sets of research questions. The scholar is a management employee at WTC and the belief that strategies involved in hydropower electricity generation can be improved motivates this study. The scholar, therefore, seeks global measures to improving strategies relative to hydropower electricity generation of WWTP in South Africa. The research context defined in this study is illustrated in Figure 3.

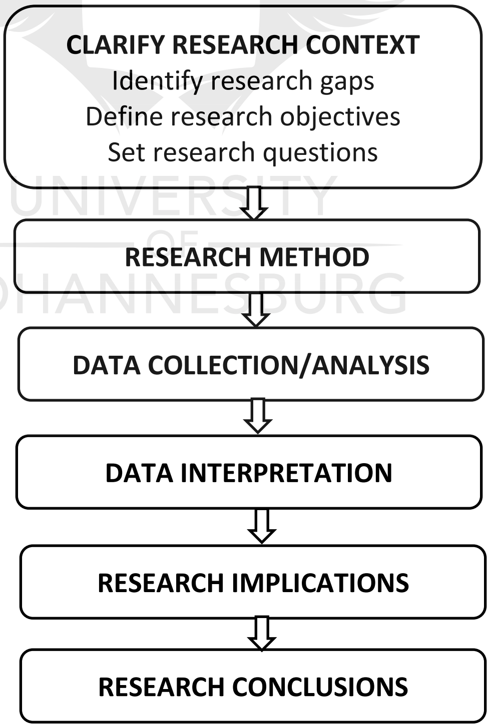


Figure 3: Research approach adapted from (Blumberg, et al., 2008)

1.6.2 Research method

When conducting a study, it is important to define a plan and method on how the research objectives and sets of questions detailed will be answered. In this study, a problem-solving approach defined by (Olivier, 2009) is adapted.

- The initial point is an assessment of what other scholars have done relative to enhancing strategies to improve hydropower electricity generation. This is achieved via a comprehensive literature search to identify present research gaps in comparison to WTC strategies.
- The next step is investigating and selecting a potential research method effective in addressing the research gaps identified. A mixed research method is proposed for investigations.

1.6.3 Data collection/analysis

The mixed research methods proposed for investigation intends to collect comprehensive data related to enhancing strategies to improve the processes involved in electricity generation via hydropower renewable energy source.

1.6.4 Data interpretation

Based on the data collected and analysed, the outputs are analysed to establish if a correlation exists between the results obtained and the objectives defined in this study.

1.6.5 Research implications

Based on the data collected, analysed and interpreted. The implications of the results are evaluated to determine how the outputs contribute to existing research. This is in relation to improving strategies relative to hydropower electricity generation of WWTP in SA.

1.6.6 Research conclusions

Based on the data collection, analysis, interpretation, and implications of the study discussed. The scholar proposes recommendations and future research directions applicable to WWTP relative to improving strategies relative to hydropower electricity generation of WWTP in SA.

Each research approach summarised is addressed via various chapters in this study. The next section presents a layout of the research report.

1.7 **Research Report Layout**

This study is structured in five chapters with each chapter commencing with a brief introduction.

- Chapter 1 introduces the context of the study defining present research gaps. This chapter defines the study objectives, questions, and methods adopted in addressing the research gaps identified.
- Chapter 2 presents a detailed literature search related to the context of the study to have an assessment of what other scholars have done relative to hydropower electricity generation.
- Chapter 3 highlights a summary of the study design, methodologies, data collection, analysis, and interpretation.
- Chapter 4 outlines the data collection and analysis of the outputs obtained.
- Chapter 5 makes inferences on the analysed data, interprets the results, present implications of the results and concludes the study.

1.8 **Conclusion**

WTC documents specific to renewable energy sources establishes although formal measures are defined to ensure optimal outputs of hydropower electricity generation. There exist certain limitations in aligning the processes involved in hydropower electricity generation with global best practices. Based on this limitation, this chapter defined objectives and questions in addressing the limitations identified. The next chapter presents a detailed literature search related to the context of this study. This presents an assessment of what other scholars have done relative to hydropower electricity generation.

2 CHAPTER TWO: LITERATURE STUDY

A comprehensive literature review assists in the gathering of in-depth knowledge for this study. This chapter presents a discussion on relevant publications and seeks answers to the following questions:

- What peer-reviewed publications are available for hydropower renewable energy specific to WWTP?
- Describe WWTP.
- What is hydropower renewable energy?
- Why hydropower renewable energy is considered important with respect to WWTP?
- What are the key components for hydropower renewable energy plants?
- What are the challenges in ensuring the sustainability of hydropower renewable energy plants?
- What best practices are obtainable globally relative to hydropower renewable energy plants?

The answers to this literature review questions serve as a guide for enhancing the strategies to improve hydroelectricity generation at wastewater treatment plants in South Africa.

2.1 **Systematic literature review**

The Systematic Literature Review (SLR) is undertaken based on four key benchmarks discussed in the next subthemes to gather relevant literature related to the context of this study. SLR evaluates what peer-reviewed publications are available for hydropower renewable energy specific to wastewater treatment plants. Scopus, a recognised academic research database, is selected for conducting the SLR. According to the SLR, China has been particularly successful at installing small hydropower projects to meet rural electrification goals.

2.1.1 Wastewater treatment plants

Wastewater treatment is any process by which municipal wastewater is collected from consumers through sewer pipes (Perrich, 2018). The wastewater gathered is treated ensuring pollution occurs at an acceptable level to a best practice defined standard. Wastewater treatment plants are facilities mandated to convert wastewater into effluent via physical, biological and chemical processes ensuring minimal impacts on the environment (Droste and Gehr, 2018). WWTP are not just waste disposal facilities, but also authorized to generate electricity via hydropower renewable energy (Wid and Horan, 2016). The effluent, sewage, and wastewater collected via wastewater disposal techniques are used for electricity generation (Stillwell, et al., 2010). Generating electricity onsite enhances business value, reducing GHG emissions, energy consumptions, and operating costs. The affordability, stability, reliability, and accessibility of electricity generated by WWTP via hydropower renewable energy are fundamental for ensuring sustainability. The electricity generated can be used onsite to operate the WWTP, in-addition supply neighbouring environs. This study specifically investigates WWTP in SA. WTC is selected to present a case of WWTP based in the Republic of SA. WTC established in 1992 delivers bulk wastewater transport, treatment, and management to thousands of businesses comprising more than 3.5 million individuals. WTC currently operates 19 wastewater treatment works releasing between 700 to 1000 megalitres to both industrial and domestic facilities daily. WTC strategic focus includes but not limited to:

- Utilise global technologies to provide effective wastewater transport, treatment and management at a prompt time to a defined geographical location.
- Provide quality, reliable, affordable and sustainable wastewater services via effective, scientific and innovative organisational practices.
- Continuously develop through research, new energy recovery and saving methods via technologies tested prior to implementations.
- Align with smart organisational practices.
- Creating competitive value for stakeholders, shareholders and promoting professional ethics.
- Continuously improve the management and utilisation of existing infrastructures and resources.

WTC aims to be recognised as a global water and energy resource WWTP providing wastewater services through collaborative and innovative initiatives with external key players. This study specifically reviews strategies obtainable globally in comparison to WTC existing strategies relative to hydropower electricity generation. The results aim at presenting existing gaps, discussions and recommend measures relative to enhancing hydropower electricity generation of WWTP in SA. The results are evaluated to determine how the outputs of this study contribute to existing literature.

2.1.2 Hydropower renewable energy

The initial keyword selected is "Hydropower renewable energy" or "Hydropower" or "Renewable energy" and “Wastewater treatment plants" or "Wastewater"or "Wastewater plants". The search is refined into publications from 2015 to 2019. The document type includes conference papers, journals, documents, books, book chapter, letter, editorial, note, short survey, and business article or press. The access types include all open and closed access publications. A total of “699” documents are identified relative to the initial keyword search selected.

The initial SLR search indicates inconsistencies of documents published per year relating to "Hydropower renewable energy" OR "Hydropower" OR "Renewable energy" AND “Wastewater treatment plants" OR "Wastewater" OR "Wastewater plants". The second SLR investigating "Wastewater treatment plants" OR "Wastewater" OR "Wastewater plants" shows consistencies of documents published per year. The third SLR investigating "Hydropower renewable energy" OR “Hydropower" OR "Renewable energy" indicates consistencies of documents published per year.

The three SLR investigations establishes the highest number of publications relating to "Hydropower renewable energy" OR "Hydropower" OR "Renewable energy" AND “Wastewater treatment plants" OR "Wastewater" OR "Wastewater plants" are from the United States and China. The results indicate limitations in the number of documents relating to the African continent, completely invisible in the 10 top ranked countries with publications.

The three SLR investigations indicates the documents identified consist more of peer-reviewed articles and conference papers in comparison with available publications. Each peer-review article and conference papers are arranged in relative magnitude of citation to carry out a detailed literature review. The three SLR investigations shows a considerable number of documents collected are from the energy, engineering, and environmental science subject areas.

The SLR gather peer-reviewed publications from conference papers, journals, documents and report to collect secondary information on the study context. The publications gathered are reviewed to investigate how to enhance strategies relative to improving hydroelectricity generation and ensuring the sustainability of WWTP. Hydropower schemes have been successfully executed in various countries including South Africa.

Hydropower is an essential renewable energy resource applicable globally (Kaunda, et al., 2012). Hydropower is a renewable energy source captured from flowing water and converted into electricity (Lee, et al., 2018). The flowing water is stored and released through a turbine from a reservoir such as valley-dammed, service and bank-side reservoirs (Kaunda, et al., 2012). The turbine spins the released water activating a generator, which produces electricity (Zarfl, et al., 2015). Hydropower renewable energy does not essentially require a large reservoir or dam. A synopsis layout of a hydropower generation plant adapted from the Colorado River storage project and International Energy Agency (IEA) is presented in Figure 4.

2.2 Biogas at Wastewater Treatment Plants

Biogas is another form of renewable energy that can be generated at WWTPs. It typically refers to a gas produced by the biological breakdown of organic matter in the absence of oxygen. The anaerobic digestion (AD) or fermentation of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plant material and crops produce biogas. Biogas comprises primarily methane (CH4) and carbon dioxide (CO2) and may have small amounts of hydrogen sulphide (H2S), moisture and siloxanes (Bharathiraja, B et al. 2018).Literature reviews that in South Africa most of the biogas generated through AD of wastewater sludge is flared and not beneficially utilised (van der Merwe-Botha et al., 2016). To date there are about 700 Biogas digesters installed in South Africa (Mutungwazi, A., Mukumba, P., & Makaka, G. 2018). Van der Merwe carried out a recent Biogas energy recovery study at Johannesburg Water Northern Wastewater Treatment Works (van De Merwe et al 2016) that produces about 1.2 Mega Watts. Sludge production is one of the current major challenges that are faced by Northern Works operation, which resulted lower volume of methane gas produced. Three of 380 kWe gas engines at Johannesburg's Northern Wastewater Treatment Works are installed. one engine is operational at a time due to small amount of gas and sludge being produced.

Literature reviews that the number of working biogas plants is still minimal. Roopnarain, A., & Adeleke, R. (2017) argues that there are major limitations when it comes to implementations of Biogas technology in Africa. These are due over-reliance to fossil fuels, cost of Biogas reactor installation, lack of political support, lack of ownership and negative impact caused by past failures of the Biogas plant. There is also a perception that maintaining the Biogas equipment is quite complex and South Africa lacks such skills. Legislative barriers and high legal fees that prevent the ease of involvement by the third part finance. (WRC Report No. TT 752/18).

Bio2Watt installed the largest 4.4 Mega Watts commercially viable plant in South Africa (Bio2Watt, 2016), supplying electricity to BMW, Rosslyn automotive manufacturing plant.Water Research Commission (WRC) and its partners funded a sludge-to-biogas project at Waterval WWTP, of which it is one of WTC wastewater treatment plants. Waterval WWTP, a 155 Ml/d biological nutrient removal (BNR) activated sludge plant that produces about 50 tDS/d combined primary and waste activated sludge (WAS) was selected as the case study plant. (WRC Report No. TT 752/18). The Biogas CHP plant at Waterval has been operational since 2007. The biogas is collected using a collection chamber with a surface area of 0.02 m^2 made from polyvinyl chloride (PVC) pipes. A co-generation plant installed at Waterval WWTP to generate electricity for digester heating to power the boilers.

2.2.1 Challenges in ensuring the sustainability of hydropower renewable energy plants

Abstract (WISA 2018) reported failures that contributed to the Biogas production at Waterval. The following contributing factors were found to the Waterval digester non-functionality : reduced solids retention times, poor mixing of digester contents, poor quality of sludge fed to the digesters, sludge temperature drops in the digesters, poor functioning of the boiler, poor heat transfer in the heat-exchangers, insufficient monitoring programme and lack of skills in operating the digester systems. This has led to compromised Biogas production (WISA 2018).

Biogas contains about 50–70% of methane (CH4) and carbon dioxide (CO2) at a concentration of 30–50% and traces of other gases (Agustini, C. B., da Costa, M., & Gutterres, M. 2020). Literature reviews that CH_4 is the second largest contributor of the Green House Gases (GHG) emitters. Some of the Biogas production plants were found to be using only 20% of the Biogas to heat up the boilers and the remaining 80% is being flared to the atmosphere. The increasing concern of the GHG emissions and the strategy to mitigate GHG emissions has not been exploited. According to environmental statistics South Africa is among the top 20 countries with the highest level of carbon dioxide emissions, also being the highest emitter of GHG emitter (USAID, 2016).

The initial cost of CAPEX of installing the Biogas plant found to high and the payback period is longer. The maintain costs of this system are extremely high when compared to the production.

2.3 Hydropower renewable energy at Wastewater Treatment Plants

Renewable energy supply in SA currently estimates between 15 to 20 percent of the total global energy demand (ERWAT, 2016). These supplies comprise mostly traditional biomass such as wood fuel used for cooking and heating (ERWAT, 2016). A report from (Sacities, 2014) establishes the heavy reliance on biogas or coal-fired plants for energy generation contributes to high carbon emissions. There is a need to explore alternative renewable energy solutions. Majority of WWTP in SA is in open land, this supports the development of alternative renewable energy sources. Alternative renewable energy sources as applicable in developing and advanced countries include hydropower, solar, wind, and geothermal energy. Hydropower has the potential to contribute a higher percentage to SA current energy grid (Yuksel, 2013). There is a need for continuous improvement strategies relative to enhancing hydropower renewable energy.

The Water Research Committee (WRC) with University of Pretoria and collaborating organisations such as Bloem Water, Ethekwini Municipality and City of Tshwane engaged in the research project to investigate and demonstrate the potential of extracting the potential of hydro power generation (WRC, 2011). The study was a reservoir (storage) hydropower schemes where it generates electricity from hydro inflows. This research study showed that it is technically viable to generate energy from existing distribution system. However, the information and the success of the implementation models about hydropower projects in SA is limited and mostly unavailable. The literature review demonstrates no studies have been implemented at outflows of the WWTPs. The next section highlights the functionalities of WWTP. WRC and Department of Science and Technology South Africa, conducted a pilot study on of a small-scale hydrokinetic (HK) project at Boegoeberg irrigation canal in the Northern Cape Province. Multiple studies have shown the untapped hydropower generation potential available , about 3700 MW of installed hydropower in South Africa (Niebuhr, C. M., Van Dijk, M., & Bhagwan, J. N. 2019). Estimating energy potential and economic viability in river-based hydrokinetic power plant project is challenging (dos Santos, I. F. S., et al 2019).

A discussion on the fundamental components of the hydropower generation plant illustrated in the layout presented in Figure 4 is detailed in the next section.

2.4 Fundamental components for hydropower renewable energy

This section presents a systematic discussion of the fundamental components for the hydropower generation plant illustrated in Figure 4. The fundamental components include storage reservoirs, trash rack, penstock, transmission tower, insulators, transformers, crane generator, valves, and turbine.

2.4.1 Storage Lake

The first fundamental component in the hydropower renewable energy layout is the storage lake. The storage lake uses a dam on a river to store flowing water in a reservoir. The storage lake functions as an intake to divert flowing water from the reservoir and deliver the required water flow into the penstocks passing through a trash rack.

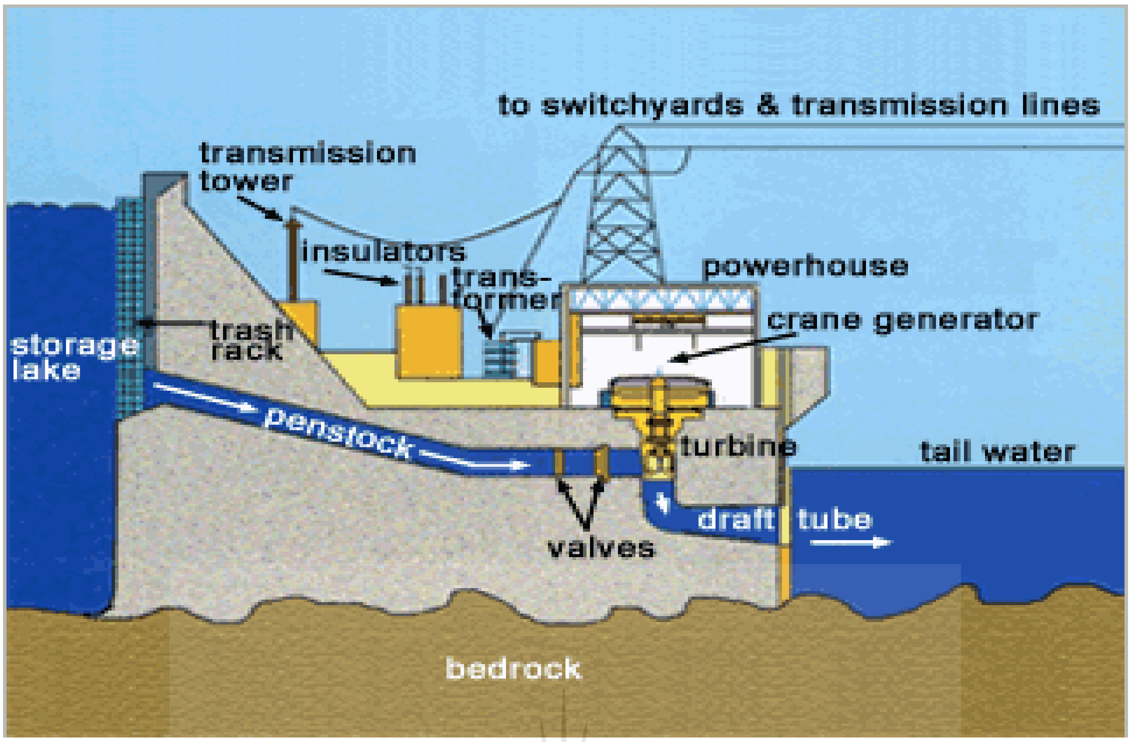


Figure 4: Hydropower generation plant layout adapted from the Colorado River storage project and International Energy Agency

2.4.2 Trash Rack

The next fundamental component in the hydropower renewable energy layout is the trash rack. The trash rack functions to protect the hydropower renewable energy plant by storing floating debris, trash and leaves from entering the turbines. Flowing water passes through the trash rack into the penstock.

2.4.3 Penstock

The next fundamental component in the hydropower renewable energy layout is the penstock. A penstock refers to a channel that controls the intake of flowing water from the forbay delivered into the hydropower renewable energy plant through the turbine.

2.4.4 Turbine

The next fundamental component in the hydropower renewable energy layout is the Turbine. A turbine transforms the kinetic energy captured from the flowing water delivered from the reservoirs into mechanical energy. The mechanical energy spins a generator transforming the mechanical energy into electrical energy. The turbine rotates high revolving speed when flowing water strikes the blades of the turbine. This results in an alternating current generated by the crane generator.

2.4.5 Transmission tower

The next fundamental component in the hydropower renewable energy layout is the transmission tower. A transmission tower is a high structure most often made of steel lattice used in high-voltage DC and AC systems to support power cables, which transmits electricity.

2.4.6 Insulators

The next fundamental component in the hydropower renewable energy layout are the insulators. The insulators do not readily allow the flow of sound and heat protecting the hydropower renewable energy plant from dangerous impacts of electricity generated.

2.4.7 Transformers

The next fundamental component in the hydropower renewable energy layout are the transformers. A transformer serves as an electrical device, which functions to transfer and convert electrical energy at high voltages between power lines and circuits at low voltages.

2.4.8 Crane generator

The next fundamental component in the hydropower renewable energy layout is the crane generator. A crane generator produces electrical energy through the mechanical energy delivered from the turbines. The shafts present at the turbine inside the generator spins a magnet generating electrical energy.

2.4.9 Valves

The next fundamental component in the hydropower renewable energy layout is the valves. The valves serve as a device to manage, start, stop and regulate the pressure of water flow into the turbine.

2.4.10 Draft tube

The next fundamental component in the hydropower renewable energy layout is the draft tube. The draft tube also referred to as tailrace functions to convert some of the kinetic energy present at the exit of the turbine into effective pressure energy.

The importance and advantages of hydropower renewable energy resource are numerous. The next section discusses some of the importance and advantages.

2.5 Importance of hydropower renewable energy

The impacts of hydropower renewable energy resource relative to the social, environmental and social influences are detailed in chapter one. This section highlights some of the importance of hydropower renewable energy adapted from (Li, et al., 2018; Callaway, et al., 2018; Huang and Yan, 2009).

- Source of electricity generation, which significantly increases the national energy grid, access, and power security.
- Produces no toxic by-products, air pollution and chemical runoffs, which limits environmental degradation and climate change.
- A clean renewable energy source fuelled from water.
- Domestic source of energy.
- Allows autonomy in the generation of electricity by states and organisations without reliance on the national grid.
- Wide areas after the reservoir source such as dam are great as water edge species for aquatic habitats.
- Hydropower renewable energy resource is self-sustaining. This creates and promotes economic opportunities.
- An effective measure for controlling flood.

Despite the numerous importance of hydropower as a renewable energy resource. The developments of hydropower renewable energy are accompanied by social and environmental limitations. The limitations include but not limited to environmental degradation and climate change. These limitations negatively influence the developments of hydropower renewable energy as a source of electricity generation. The next section details some best practices obtainable globally relating to hydropower renewable energy plants.

2.6 Best practices obtainable globally relative to hydropower renewable energy

A publication (2017) from the IEA establishes hydroelectricity generation is currently the most sustainable and common form of renewable energy resources. The IEA indicates hydroelectricity generation plays a fundamental role in global electricity generation with an estimated increase of 0.7 % in the year 2017 representing 17% of total global electricity generation. This section highlights some best practices obtainable globally relative to hydropower renewable energy. Several organisations are developed and mandated with the responsibility of improving renewable energy revolutions. In SA, the South African Department of Energy (DoE) in collaboration with the DWS are organisations mandated with ensuring sustainable and optimal use of renewable energy resources. This includes creating awareness, support, and training relative to best practice renewable energy resources innovation and solutions. Department of Energy (DoE), South Africa has established a Renewable Energy Independent Power Producer Programme (REIPPP) to contribute to meeting the national renewable energy targets and encourage foreign investment. Hydropower generation scheme is one of the technologies listed under this program and is therefore a strong motivation of the development of Hydropower generation.

The IEA establish China, Brazil, Canada and the United States of America (USA) are developed countries with the largest generating capacity of hydroelectricity. Some best practice measures obtainable in these developed countries is detailed.

2.6.1 Penstock and reservoir selection

Penstock selection is a fundamental aspect of hydroelectricity renewable energy projects. Ineffective penstock considerations might result in pipe failure during operations. The penstock selected should be strong and economically durable relative to protection against temperature and environmental conditions. The penstock selection is dependent on:

- **Size:** This classifies if the hydroelectricity renewable energy project is small or large scale, which is determined by the potential capacity of the renewable energy plant.
- **Head:** This refers to the dissimilarity in level relative to the headrace (inlet) and tailrace (outlet) of a hydroelectricity renewable energy project. Head is an important component in penstock selection determining the force or water pressure of the associated turbine output.
- **Storage:** Determines if the flowing water for hydroelectric generation is effectively stored or not. Literature presents three storage types, which include pumped storage, run-of-run, and reservoir.

Hydropower plants must define adaptation measures relative to penstock and reservoir selection. Both components in hydropower plants are effective for controlling floods limiting environmental degradation and climate change challenges.

2.6.2 Types of turbine

The type of turbine in hydropower plants is a fundamental aspect of hydroelectricity renewable energy projects. Literature present two types of turbines effective for operation in hydropower plants. This includes reaction and impulse turbines, which is dependent upon height (Purdum, et al., 2016). A synopsis of each type of turbine is presented.

- Impulse turbine uses the velocity of moving water to rotate the turbine blades and generate electricity, most often deployed in high and low flow applications (Cobb, and Sharp, 2013). The flow strikes the turbine as a jet in an open environment to create a kinetic energy which is producing the power.
- Reaction turbines generate energy using the pressure of moving water (Badhurshah, and Samad, 2015). Literature have proven theoretical performance of reaction turbines to have a better performance in low head and high flow sites (AH. Elbatrana. et al., 2015). Zeekoegat plant has recently installed the low head turbine. In South Africa, WRC has performed studies for the potential of hydroelectric generation at WWTPs.
- Table 2 indicates the turbine operational head specifications relevant for potential options adapted from a hydropower wastewater case study published by the New York energy research and development authority.

Table 2: Turbine operational head specifications

CLASS	TURBINE TYPE	HEAD RANGE (m)
Impulse	**Pelton wheel**	**200 – 1800**
	Crossflow	**2.5 – 200**
Reaction	**Francis**	**40 – 600**
	Kaplan	**15 – 50**
	Bulb	**<30**

Impulse turbines are considered less efficient in comparison with the reaction turbines. Combination of both types of turbines provides significant value and multiple benefits to WWTP, which includes high efficiency and durability (Purdum, et al., 2016). WWTP must define adaptation measures relative to the design of variable flow turbines specific to impulse and reaction turbines.

2.6.3 Turbine selection

Globally there is no universally classified sizes for hydropower scheme sizes (WRC Report No. 2219/1/16). Turbine selection charts and efficiency curves must be sourced from the manufacturers and suppliers, as the applicability of turbines from various manufacturers differs significantly. The choice of the turbine type depends on primarily on available head and the average water flow. This paper also presents several recommendations and solutions in terms of operation, overall efficiency and cost-effective points of views. Micro hydropower is frequently accomplished with a Pelton wheel for high head, low flow water supply. Figure 5 w the operating chart for different types of turbines. High-efficiency Kaplan turbines need high flow volumes of water at low head differences (Narrain, P. (2017). Kaplan type turbine was selected for Zeekoegat Plant hydropower generation case study installation (WRC Report No. TT 654/15). Tests conducted at Zeekoegat displays successful performance of low hydro electricity generation. Literature also reviews that the efficiencies of hydro turbine is directly proportional to the flows(Liu, X., Luo, Y., Karney, B. W., & Wang, W. 2015), the higher the flow rate produced , faster turbine means greater energy production.

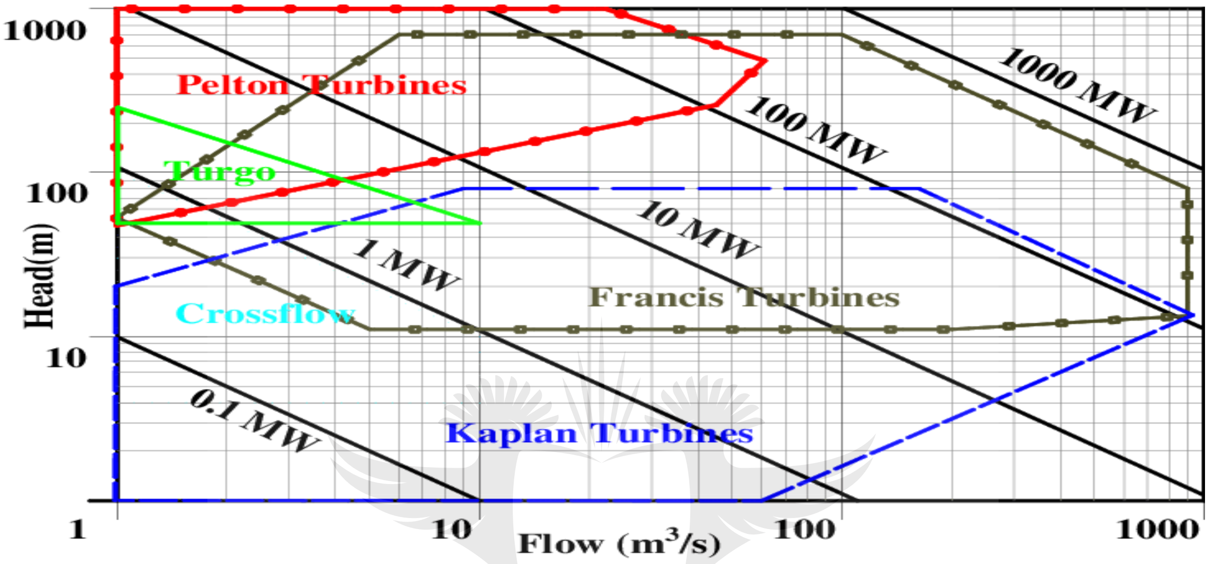


Figure 5 : **Operating area of different turbine (2010) adapted from National Hydropower Association (2010)**

2.6.4 Hydropower plant location

Wastewater treatment works are viable sources of hydropower due to the high volume of water that generally flows from such facilities. Turbines can typically be installed at wastewater treatment plant inlet or outlets to utilize either some or the entire inflow or outflow. Depending on the available space and existing infrastructure on site, several turbine options are available. The hydropower plant location is significantly dependent on proximity to dams or water reservoir. Water stored from these dams or water reservoir carries potential energy, making the storage systems an essential component of hydropower energy projects. The site location and storage systems designs are unique relative to hydropower energy implementations and technology.

Literature presents three different storage structures of hydropower plants dependent on site location, which includes subsurface, intermediate and superstructure (Chitrakar, 2004). Each storage structure is differentiated based on soil and groundwater geological structure either as surface, semi-underground or underground storage systems (Nachman-Hunt, 2001). Hydropower plants must define adaptation measures relative to flood reduction designs, topographical location, and geological structure in selecting either type of hydropower storage constructions (Mukherjee, 2018). The potential for low-head hydropower development is commonly found within the range of micro-hydropower i.e. up to or above the 100 kW installations, which can supply hydro energy to the small communities with agricultural/commercial/ manufacturing enterprises.

2.6.5 Effectively installed system, manufacturing and process component

An effectively installed system, manufacturing and process component limit issues of environmental degradation, climate change, and GHG emissions (Klunne, 2013). Hydropower plants must define adaptation measures relative to synergies between incremental power generation, clean electricity generation, climate change, and environmental degradation response.

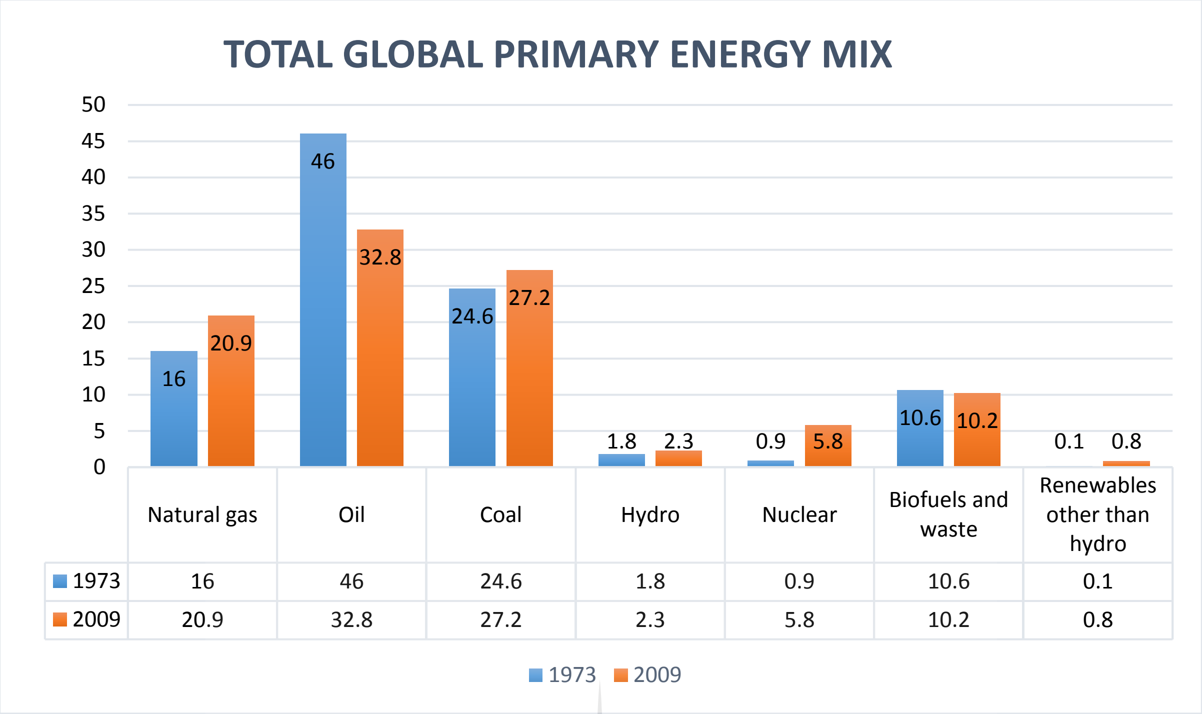
The next section details some challenges in ensuring the sustainability of hydropower renewable energy plants.

2.7 Challenges in ensuring the sustainability of hydropower renewable energy plants

This section highlights some challenges in ensuring the sustainability of hydropower renewable energy plants. A sustainable hydropower renewable energy plant requires effective planning and design. The challenges in ensuring the sustainability of hydropower renewable energy plants are structured into four categories. This includes availability, risk, technology, and cost.

2.7.1 Availability

Energy availability is one of the fundamental drivers for ensuring total global energy supply sustainability (Modi, et al., 2006). Energy availability involves not compromising the quality, reliability, affordability, and sustainability of total global energy supply in the future. Energy availability seeks for the extraction and diversification of renewable energy based on natural and localised resources. The increasing global energy demand triggered by economic and population growth establishes the need for relevant stakeholders and authors to continuously undertake research relative to renewable energy solutions. Statistics presented by IEA (2011) publication indicate the total global energy supply has been on a steady increase since 2009. A review of the publication establishes hydropower as a contributing renewable energy supply in the total global energy demand is still minimal. The total global energy supply predominantly consists of oil, coal and natural gas. The statistics of total global primary energy supply mix in 1973 and 2009 adapted from IEA is presented in Figure 6.



	Natural gas	Oil	Coal	Hydro	Nuclear	Biofuels and waste	Renewables other than hydro
🟦 1973	16	46	24.6	1.8	0.9	10.6	0.1
🟧 2009	20.9	32.8	27.2	2.3	5.8	10.2	0.8

🟦 1973 🟧 2009

Figure 6: Statistics of total global primary energy supply mix in 1973 and 2009 adapted from international energy association

Figure 5 presents statistics of total global energy supply mix in 1973 and 2009. The statistics affirm hydropower as a contributing renewable energy supply in the total global energy demand is still minimal. Considering the climate and environmental impacts of fossil fuels combined with increasing demand in energy supply. Overdependence on energy demand based on fossil fuels becomes unsustainable.

Availability of hydropower as a renewable source of energy presents a challenge requiring research from relevant stakeholders and authors. Enormous research focus on energy extraction, conversion, delivery and utilisation based on hydropower renewable energy resource is essential. This ensures the sustainability of renewable energy solutions. Sustainable energy solutions describe the extraction, conversion, delivery, and utilisation of renewable energy with minimal impacts on climate or environment change (Tsimas, et al., 2009). This includes not compromising the possibilities, quality, reliability, affordability, and sustainability of total global energy supply in the future. The availability of hydropower as a renewable energy resource limits issues related to climate and environmental challenges experienced with fossil fuels (Modi, et al., 2006). Sustainable renewable energy such as hydroelectricity generation is associated with minimal GHG emissions ensuring pollution control. Enhancing strategies to improve hydropower electricity availability and generation at WWTP in the Republic of SA limits electricity restriction challenges currently experienced in recent years. The results of this study aim to improve availability of hydropower as a renewable source of energy with attention on the optimal configuration outputs of hydropower plant technology proposed and investigated.

2.7.2 Risk

Hydropower plant projects are highly prone to risks relative to environmental degradation and climate change. Environment and climate change significantly influence global warming. The issues of global warming compel the need for an energy revolution to protect the environment. Environment degradation refers to the deterioration of resources in an environment such as water, air, wildlife and soil (Shandra, et al., 2003). Climate change describes the adjustments in regional and global climate patterns (Ebinger and Vergara, 2011). Best practice energy revolutions limit the issues of environmental degradation, climate change and global warming, which supports a greener environment. Climate changes and environmental degradation management influences financial investment decisions relative to hydroelectricity generation (Godfrey and Oelofse, 2017). Water (hydro) constitutes part of the environment, which is a source of renewable energy for electricity generation supporting life and the economy (Gamze Güngör-Demircia, 2015). Flowing water from the environment is extracted, stored in reservoirs, transported, converted to hydropower electricity and utilised. Hydroelectricity generation is a substantial source of GHG emissions. A search in literature establishes hydropower dams significantly contributes to methane (CH4) emissions resulting in environmental challenges (Anderson, et al., 2018).

Hydropower renewable energy plants affect the habitats in the water ecosystem (Bui, et al., 2018). This includes but not limited to:

- Reversing the natural conditions of water habitats by reducing water flow in summer and increasing in winter.
- Decreasing the frequency and size of large flood events.
- Weakens the flushing capacity of the dams or rivers.
- Affects procreating conditions of the water habitats.

Degradation and climatic changes have significant effects on the environment comprising living and non-living species. Aside from the habitats in the water ecosystem affected by hydroelectricity generation. Land use acts and homes present in the environs where the hydropower renewable energy plants are located can be affected. A publication from the intergovernmental panel on climate change (2007) indicates unsustainable renewable energy extraction, storage, conversion, delivery, and utilisation are fundamental contributors deteriorating the environment and climate changes. An effectively installed system, manufacturing and process component relative to hydropower renewable energy plants play a key role in limiting environmental degradation and climatic changes (Walton and Hendrix, 2012). An effectively installed system, manufacturing and process component significantly regulates total GHG emissions of hydropower renewable energy plants (Teske, et al., 2010).

The results of this study aim to reduce the risk of hydropower as a renewable source of energy with attention on the optimal operating conditions and demands of hydropower plant technology proposed and investigated.

2.7.3 Cost

Despite hydropower plants, being cost-effective in comparison with other renewable energy technologies associated with costs of fuels. Hydropower plants are associated with high investments costs. Considering the high investment costs, small-scale hydropower plants are appropriate for private economic investments, which operates as independent electricity generation companies. These small-scale hydropower plants are most suitable for developing countries with financial constraints. The small-scale independent electricity generation companies can serve as a standalone renewable energy plant for rural electricity supply or power the WWTP. This study will potentially detail a cost analysis in the results chapter based on optimal configuration outputs of hydropower plant technology proposed and investigated.

2.7.4 Technology

Hydropower uses technology to extract a specific amount of flowing water to generate hydraulic energy for electricity generation or power machinery. The working processes detailed in Figure 3 and discussed. Hydropower technology is described as one of the cost-effective electricity generation process (Locker, 2004). The flowing water presents no direct cost in comparison with other renewable energy technologies associated with costs of fuels. Hydropower technology is suggested as a base load for electricity generation company(s) for peaking purposes based on the effectiveness to respond to fluctuations in power demand. Mechanical and electrical energy are both forms of energy in high demand. Both forms of energy conversion process are associated with hydropower technology.

The challenges associated with hydropower technology ranges from configuration, cost, location, capacity, and storage. A detailed review of literature indicates micro turbines as a fundamental hydropower technology for future Landfill Gas (LFG) projects and energy recovery option (Willis, 2018). A review of micro turbines is detailed in the next section with emphasis on the hydropower challenges (availability, cost, risk, and technology) detailed.

2.8 Micro turbines

Micro turbines are effectively suited for small applications to generate electricity for onsite energy provisions and end users in relatively proximity. Micro turbines evolved from truck and automotive turbochargers, small jet engines and auxiliary power units for airplanes (Willis, 2018). Micro turbines consist of:

- Compressor: The compressor raises the pressure of air in micro turbines. The compressed air delivers high oxygen concentration for combustion in the combustion chamber.
- Combustor: The combustor functions to heat the compressed air at a constant pressure.
- Turbine: The turbine converts the compressed air heated to mechanical energy.
- Alternator: The alternator is used to charge components of the micro turbines.
- Recuperator: For capturing waste heat to improve the efficiency of the compressor stage.
- Generator: The generator produces the electrical energy in a micro turbine.

Micro turbines are effective to generate both electricity and heat rather than thrust on a moderately small scale. Figure 6 illustrates a schematic of Micro turbines. The study focuses mainly on the low-head hydropower generation turbine given its practical applications with very low discharge using water wheels. This application has the advantage that they cause slight or no impact on the environment and low head does not depend upon the amount of the flow.

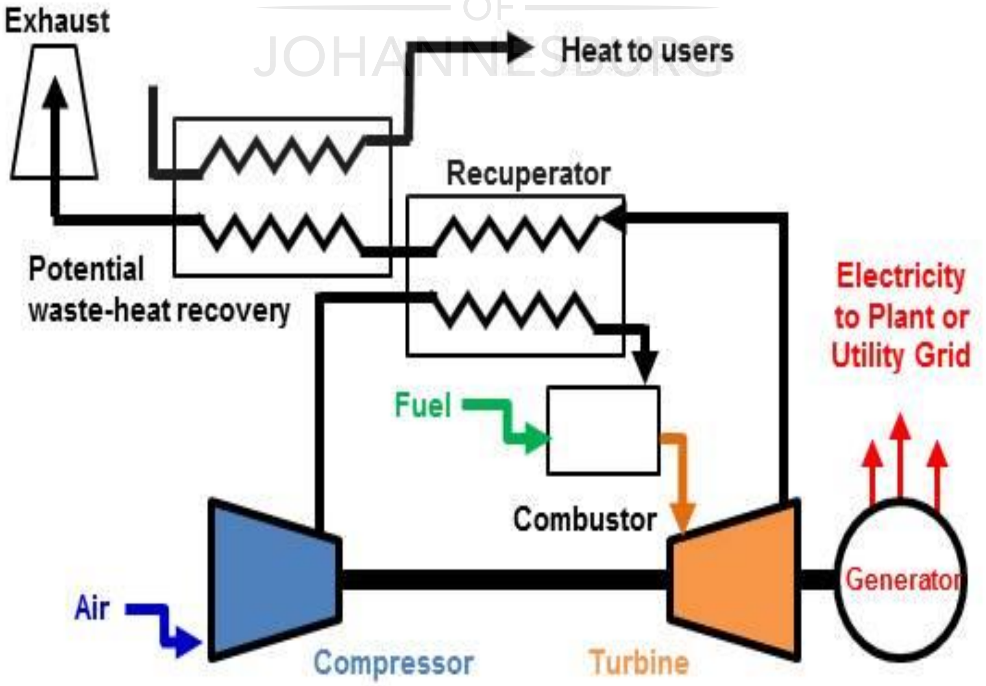


Figure 7: Micro turbine schematic adapted from a publication by Energy Solutions Center (ESC).

Other sources of energy such as solar, tidal, wind, wave, biomass, geothermal, hydrogen and fuel cells have traditionally been the choice for LFG projects 800 Kilowatts (KW) and larger (Levis and Barlaz, 2011). Conventional turbines are often considered for LFG projects 3 Megawatts (MW) and larger. The micro turbines address an important niche as an effective hydropower technology for small-scale power generation. The applicability and benefits of micro turbines in comparison to traditional electrical generation technologies adapted from (Willis, 2018; Nojavan and allah Aalami, 2015; Ebrahim, et al., 2006) is detailed.

2.8.1 Applicability of micro turbines

Literature reviews that micro turbines have proven to be the cheapest technology for rural electrification over the lifetime of a system, with high initial capital costs and low operational cost. This is diametrically opposite to for example, Biogas to energy plants, initial capital costs and operational costs are tremendously high. Micro turbines present unique applicability and advantages in comparison to traditional electrical generation technologies relating to landfills.

- Distributed generation: on-site applications and stand alone.
- Low-cost energy: The micro turbines are manufactured to support individual unit sizes ranging from 30KW to 100KW with the ability for each unit to be grouped into larger sets.
- Quality power and reliability: voltage transients, reduced frequency variations, dips, surges, or other disruptions.
- Micro turbines can be used at landfills where the gas output is too low for conventional turbines and larger engines.
- Combined heat and power (cogeneration): Landfill gas have low methane content, low gas flow, and increases in the efficiency of on-site power generation.
- Micro turbines can be used where excess gas or onsite energy requirements exist, rather than for exporting electricity.
- Landfill gas flow is low.
- Micro turbines can be operated using WWTP, LFG and numerous waste fuels.
- Micro turbines spins at much faster speeds in comparison to traditional combustion turbines.

The benefits of micro turbines in comparison to traditional sources of energy adapted from a publication from the United States environmental protection agency is detailed.

2.8.2 Benefits of micro turbines

Landfill gas micro turbines are effectively suitable and economical for a replacement of purchased electric power by self-generated electricity (retail deferral). The benefits of micro turbines in comparison to traditional LFG power technologies is detailed.

- Portable, light weight and easily sized: Modular and available in incremental capacities.
- Flexibility: Effective alternative for older and smaller landfills.
- Compact and a small number of moving parts: Minimal operation and maintenance.
- Lower pollutant emissions.
- Opportunities to utilize waste fuels.
- Effective for combusting lower-methane-content landfill gas.
- Effective to generate heat and hot water from waste heat in the exhaust replacing expensive fuel such as propane required to heat water in colder climates.

The concerns of LFG micro turbines in comparison to traditional sources of energy adapted from (Nojavan and allah Aalami, 2015) is detailed.

2.8.3 Concerns with landfill gas micro turbines

Despite the applicability and positive benefits of the LFG micro turbines certain concern exists such as:

- Capital, operating and maintenance costs.
- Long-term reliability.
- Lower efficiency consuming about 35% more fuel per KWh electricity generated.
- Sensitive to siloxane contamination requiring more pre-treatment of LFG supplied.
- Few low-flow and high-pressure compressors are available that meet the requirements of micro turbines.

The next section expands on the concerns of LFG micro turbines detailed to develop a decision framework relating to enhancing the effectiveness of the proposed hydropower technology.

2.9 Decision-support for micro turbines

Micro turbines are developed on the need for the design of a larger combustion hydropower technology used for electric power generation. A brief working principle of micro turbines adapted from a publication from the United States environmental protection agency is detailed.

- Fuel enters the combustor chamber of the Micro turbines set below 70 to 80 pounds per square inch gauge of pressure.
- Fuel and air are burned in the combustor chamber releasing heat which results in expansion of the combustion gas.
- The expanding gas powers the micro turbine simultaneously triggering operation of the generator.
- The output of 30KW micro turbine can power a 40-horsepower motor or effectively address the electricity requirements of 20 homes.

The design of micro-turbines is a multi-criteria task and dependent on variables with impacts on the operational efficiency. The variables considered for this thesis gathered from literature is detailed. Each variable is associated with enablers that facilitate a decision-support quantification for micro-turbines.

2.9.1 Cost

Cost is a significant variable in the operations of water distribution network (Babaei, 2015). This variable investigates the life cycle cost analysis of LFG micro turbines. The cost-benefit analysis potentially considers certain enablers such as the purchase, installation, commissioning, operating, maintenance, and decommissioning costs.

2.9.2 Energy

The energy consumed by LFG micro-turbines adds up to a significant proportion of costs and utilities at WWTP (Saidur, et al., 2012). The energy-reduction analysis potentially considers certain enablers such as pressure, heat rates, and fuel supply.

2.9.3 Configuration

Configuration of LFG micro turbines are a significant variable in the operations of water distribution network (Deng, et al., 2017). This variable investigates the effectiveness of the LFG micro turbines to regulate the rotational force, speed, frequency, reliability, system control, torque and environmental conditions.

The variables detailed are investigated through an optimisation decision-support framework for enhancing the operational efficiency of LFG micro turbines.

2.10 **Conclusion**

This chapter present a detailed literature review of important components and definition of hydropower plants. The review details an in-depth assessment relative to WWTP and hydropower renewable energy. The review includes the importance of hydropower renewable energy, challenges in ensuring the sustainability of hydropower renewable energy plants and best practices obtainable globally relative to hydropower renewable energy plants. The SLR establish micro turbine as a potential effective renewable energy technology. The next chapter focus on the research method identified and selected to address the defined context in this study.

3 CHAPTER THREE: RESEARCH METHOD

This chapter discusses the interrelated methods considered in addressing the objectives and questions detailed in this study.

3.1 Mixed research method

The mixed research method combines complimentary approaches for investigating and gathering an in-depth understanding relative to addressing the purpose of a study (Flick, 2018, Green and Thorogood, 2018; Richards, 2015). The data collected from a mixed research method are more descriptive and communicative (King, et al., 2018; Thomas and Magilvy, 2011; Gill, et al., 2008). This makes it easy to establish inferences from the data collected and analysed (Litosseliti, 2018; Jorgensen, 2015; Sargeant, 2012). The mixed research method can be a combination of experiments, modelling, casual-comparative research, and simulation (Bell, et al., 2018 and Bellany, 2012). This research method is empirical and numeric, focus on verifiable observation as opposed to logic and theory (Walliman, 2017). The four components of the mixed research method specific to this study is illustrated in Figure 8.

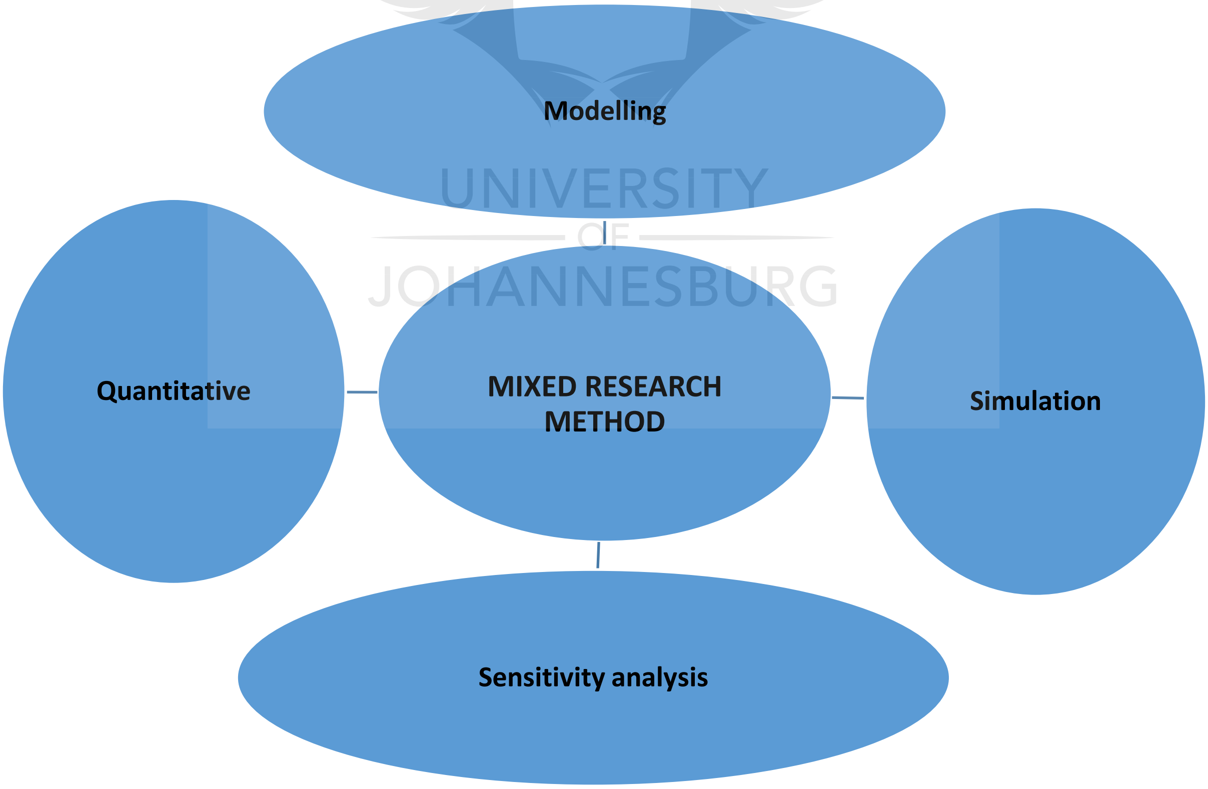


Figure 8: Mixed research method components

The initial step in the methodology design commence with a quantitative approach to extract data. The second step develops a model of potential decision-support saving variables relating to design and applications of the micro turbines. The third step simulates the model to investigate the relative magnitude of possible optimisation opportunities applicable to micro turbines. The fourth step carry out a sensitivity analysis to discuss the outputs of the optimisation model. The next sections discuss data collection of each component of the mixed research method detailed.

3.2 Data collection for quantitative approach

The quantitative method extracts data from database relating to hydroelectric power generation across the globe. Figure 9 Illustrates the initial 17 high ranked countries across the globe relative to hydroelectric power generation adapted from a publication detailed by the energy information agency, international energy statistics.

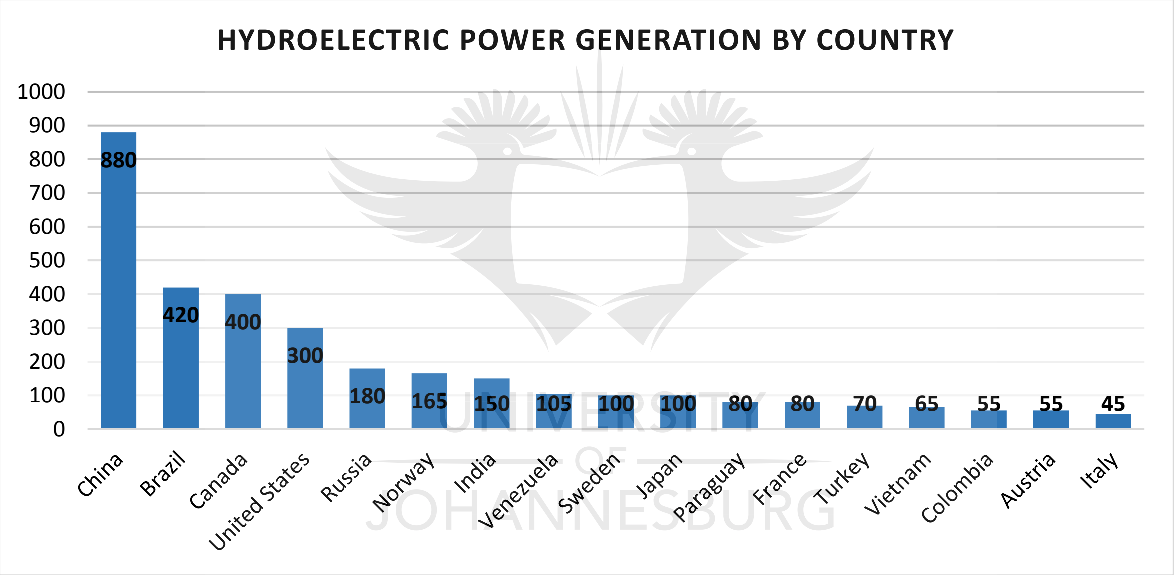


Figure 9: Hydroelectric power generation by country (2012) adapted from Energy Information Agency (EIA), international energy statistics

The applicability of LFG micro turbine projects for hydro power generation relating to the countries detailed in Figure 8 is comprehensively studied based on decision-support variables discussed in the literature review. The data collected from the quantitative approach is detailed in Table 3.

Table 3: Data collected for quantitative approach

VARIABLES	ENABLERS	VALUES
COST **(size range: 25-500KW)**	Capital cost.	$700 - $1,100/ KW.
	Maintenance interval.	5,000 - 8,000 hrs.
	Operation & Maintenance cost.	$0.005 - $0.016/ KW.
ENERGY	Heat rates.	14,000 - 16,000 Btu/KWh.
	Fuel supply/pressure (hydrogen, diesel, propane, natural gas).	70-80 pounds per square inch gauge of pressure.
CONFIGURATION	Capacity (30KW).	Power a 40-horsepower motor/electricity for 20 homes.
	Recuperated efficiency.	20-30 %.
	Unrecuperated efficiency.	< 15 %.
	Cogeneration.	50-80 degree centigrade of water.
	With heat recovery.	Up to 85 %.
	Environmental.	Low (< 9-50 ppm) NOx.

3.3 Modelling

Modelling relates to the physical representation that demonstrates functions of the components effective for potential saving variables relating to the design and applications of the micro turbines. The design and analysis of micro turbines can be challenging, due to varieties of design options, inclusive of energy demand. The Microsoft Excel tool is used to model data captured in Table 3. The modelling includes different optimisation values calculated and proposed for achieving optimum efficiency for LFG micro turbines.

3.4 Simulation

Simulation enables an experimentation scenario for the developed model to investigate the behaviour and performance of the components effective for potential saving variables relating to the design and applications of the micro turbines. The model developed in the Microsoft Excel tool is used to simulate different micro turbine configurations to determine optimum technical constraints resulting in the lowest life-cycle cost, maximum efficiency, and ideal energy savings. The simulation runs execute via multiple optimisation states under a variety of input assumptions. The results collected from simulation are used to decide through sensitivity analysis potential cost, efficiency, and energy saving opportunities for LFG micro turbines.

3.5 Sensitivity analysis

A sensitivity analysis is carried out to define inferences for cost, efficiency, and energy optimisation initiatives relating to WWTP in SA. This is based on steps defined by (Brynard et al., 2014), which include:

- Understand the data collected.
- Analyse the data collected.
- Classify the data collected resulting in a model.
- Identify and categorise patterns resulting in inter-relationships of the data collected.
- Interpret the data collected and explain the findings.

The sensitivity analysis facilitates inferences relating to the occurrences caused as a result of changes in the model inputs (variables). This delivers a cost/energy demand structure for the optimum design and implementations of LFG micro turbines. The qualitative and quantitative data collected through variables detailed are used to investigate the relative magnitude of cost and energy saving opportunities applicable to LFG micro turbines. To ensure the simulation and sensitivity analysis data collected are of good quality, several tests defined by (Noble and Smith, 2015; Brynard et al., 2014; Yin, 2009) detailed in Table 4 is performed.

Table 4: Tests adapted from (Yin, 2009)

S/N	TESTS	DEFINITION
1	Construct validity	Ensuring the precise measures and sources of information for the context undertaken in this study is used.
2	External validity	Ensuring the outputs and results are generalizable. This is achieved via a detailed literature review.
3	Internal validity	Ensuring the collated data is comprehensive and collected from multiple sources of evidence.
4	Reliability	Ensures the accuracy of inferences and measurement established via collated data.

3.6 Conclusion

This chapter highlights a summary of the study design, methodologies, data collection, analysis, and interpretation. The next chapter presents a detailed discussion of the data collected to develop a model, establish findings and interpretations of the outputs.

4 CHAPTER FOUR: CASE STUDY ANALYSIS

4.1 Introduction

Hydropower as a renewable energy source has been reviewed in evolving literature as a realistic and sustainable source for energy generation in South Africa to complement future demand and supply capacity. In order to optimally tap from the opportunities provided by hydropower energy, the technologies effective for hydroelectricity generation must be completely understood. The key considerations in hydropower energy generation is installation of the micro turbines. The literature desktop study identifies micro turbines as imperative in discussions relating to hydroelectricity generation. The impacts of hydropower projects with the use micro turbines is dependent on the cost effectiveness, installation size, facility location, and energy capacity.

This makes effective planning, design, installation, and applicability of the micro turbines a fundamental for sustainable hydropower projects. This chapter conducts a case study analysis to investigate for ideal baseline decision variables saving prospects of the micro turbines. The thin slice assessments are structured in two parts; the first component is the model development to identify and review the decision-support variables of the micro turbines from international best practices. This assist in the design, applicability, and saving initiatives of the micro turbines which is evaluated in the second part of the case study analysis.

4.2 Model development

The model development commences by extracting and assessing data from available literature relating to current design trends and practices of the micro turbines. Microsoft excel tool is used for the model development to conduct the multi-layer optimisation calculations and demonstrate potential optimisation prospects of the micro turbines. The selected decision-support variables for the design of micro turbines obtained from international best practices is detailed in Table 5. The baseline values associated with each variable is extracted from Table 3.

Table 5: Baseline decision-support variables for the design of micro turbines

VARIABLES	DESCRIPTION
Energy	Seeks to maintain an ideal pounds per square inch gauge of pressure in the design and delivery of a set of micro turbines irrespective of flow demand. It is worthy to note an operational micro turbine do nothing to alter or change the amount of energy consumption. This study seeks to optimise the design of micro turbines with energy as a decision-support variable set at minimum.
Efficiency	To allow the micro turbines maintain an ideal set of system flow from the reservoirs irrespective of the flow variance operating at an ideal state of temperature by varying flow demand. The efficiency (recuperated & unrecuperated) of the micro turbines relates to amount of energy lost to heat and friction. This study seeks to optimise the operational capability of micro turbines with recuperated efficiency as a decision-support variable set at maximum.
Cost	A strategic planning and analysis on the benefits of the micro turbines weighted against the capital, operation and maintenance costs of the micro turbines. This study seeks to optimise the capital and maintenance/operational costs of micro turbines as a decision-support variable set at minimum.
Capacity	This decision-support variable seeks for ideal volume of micro turbine output per unit time against the micro turbine design and technical attributes. This study evaluates a 30KW micro turbine effective to power a 40-horsepower motor/electricity for 20 homes. This study aims to optimise the capability of a 30 KW micro turbine driven by baseline values extracted from literature and detailed in Table 3.

4.3 **Multi-objective optimisation**

Considering the electricity restrictions in recent years, wastewater treatment plants in South Africa can explore the potentials of operating as a private and independent energy producer. This is with the suitability of the micro turbines as an imperative hydropower technology for small scale hydro power projects. The comprehensive desktop study of micro turbines indicates certain drawbacks of the micro turbines to include high energy utilization and investment cost (Jawahar and Michael, 2017). This section discusses a novel multi-objective optimisation investigation to identify ideal performance indicators relating to the decision-support variables of the micro turbines. The Pareto multi-objective optimisation techniques originally suggested by Goldberg (1889) is suitable to compute multi-objective challenges and provide optimal solutions. Several Pareto multi-objective optimisation techniques defined and adapted from (Willis, 2018) include:

- Multi-Objective Genetic Algorithm (MOGA).
- Non-dominated Sorting Genetic Algorithm (NSGA-II).
- Strength Pareto Evolutionary Algorithm (SPEA-II).
- Multi-Objective Particle Swarm Optimisation (MOPSO).
- Pareto Evolution Archive Strategy (PAES).

This study deliberates on the NSGA-II metaheuristic multi-objective optimisation method suitable to identify and develop sets of mathematical or Pareto-optimal solutions for real-world optimisation challenges (Deb, et al., 2000). The metaheuristic multi-objective optimisation is mostly applicable for optimal solutions often limited with complex information or computation capacity with features adapted from (AlSattar, et al., 2018):

- Supports non-dominated sorting.
- Allows for crowding comparison.
- Enables population variety of preserving mechanisms.
- Based on the elitist principle which allows changes in generation combinations.

Most real-life business challenges are complex and involve several objective functions which requires simultaneous optimisation. The business objective functions referred as decision-support variables in this study are mostly quantified in different units which requires competing optimisation. The NSGA-II multi-objective optimisation results in sets of Pareto-optimal solutions driven by the complex decision-support variables, rather than a single optimal solution. This is important as no singular solution is considered more significant in comparison to others with focus on comprehensive sets of simultaneous objectives. A flowchart which details steps required in NSGA-II multi-objective optimisation adapted from (Arora, et al., 2017) is illustrated in Figure 10.

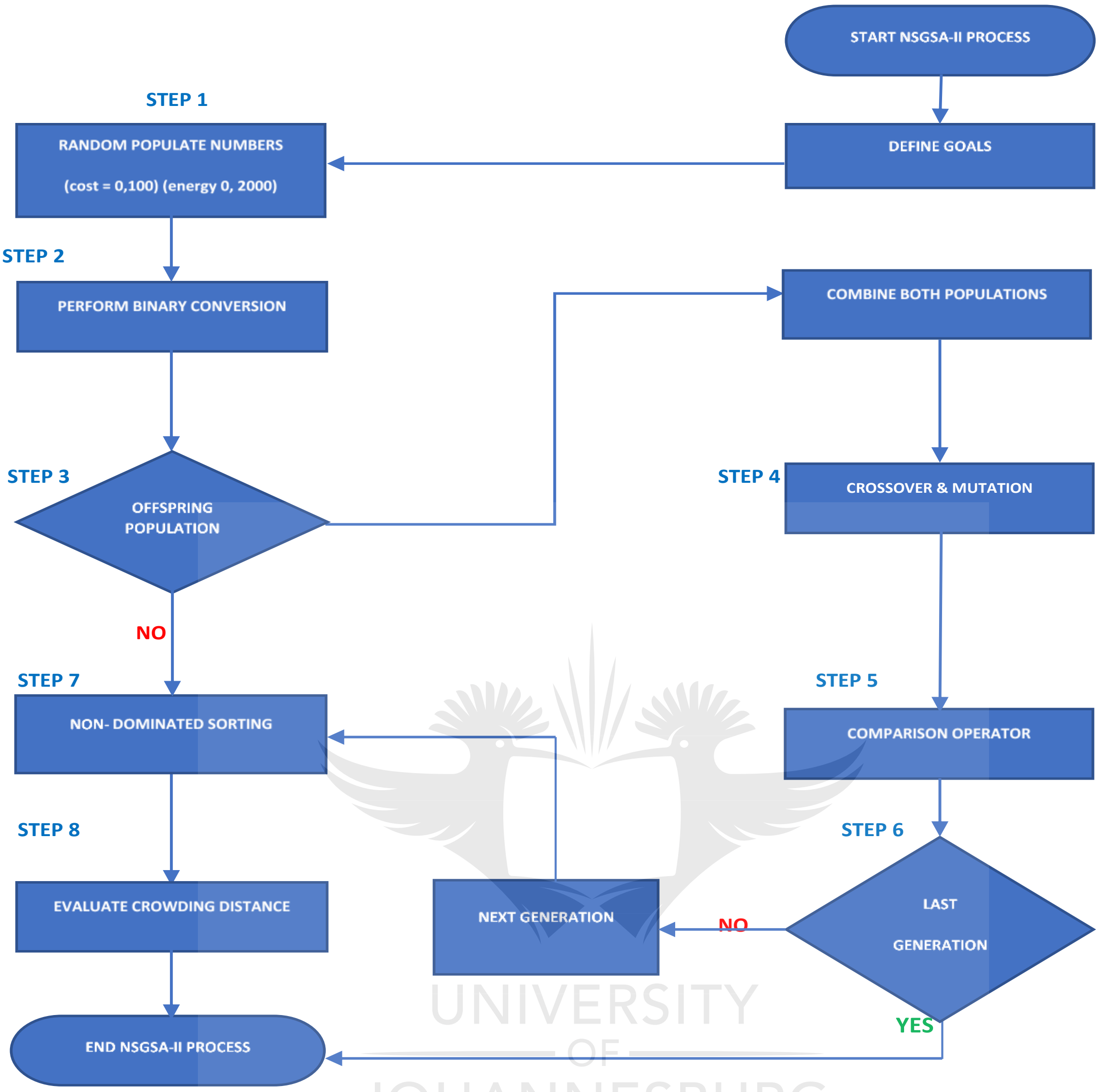


Figure 10: NSGA-II multi-objective optimisation adapted and modified from (Arora, et al., 2017)

4.3.1 Define goals

Demonstrate a multi-objective problem relating to the design and costing implications of a 30KW micro turbine driven by the NSGA-II techniques with:

- Minimum possible capital cost.
- Minimum energy.
- Maximum recuperated efficiency.
- Minimum maintenance and operational costs.

4.3.2 Define decision-support variables

This step assumes non-trivial values based on data extracted from literature on hydropower projects of micro turbines detailed in Table 3 of the methodology chapter.

Table 6: NSGA-II parameter values

NSGA-II PARAMETERS	DESCRIPTION	PARAMETER VALUES
Micro turbine capacity	Defines the size of the micro turbine considered for investigation.	30KW
Maximum limit range	The maximum limit range is used to encode genetic operations. The limit range is defined based on assumption that $1000 represents capital cost of a 30KW micro turbine and 2000Joules/minute indicates consumption for a 30KW micro turbine.	Upper limit (b) = 10 (cost) Lower limit (a) = 0 (cost) Upper limit (b) = 20 (energy) Lower limit (a) = 0 (energy)
Crossover probability	The crossover probability is used to select one-point crossover position.	0.25
Accuracy	Defines the digit accuracy of the parameter values.	2
Mutation probability	The mutation probability is used to randomly select the bits for mutation.	0.01

4.3.3 Generate initial/parent population

The parent population detailed in Table 7 is created using the random number generator available in Microsoft Excel with defined maximum limit range defined.

Table 7: Parent population

	1	2	3	4	5
CAPITAL COST	888	213	270	279	375
ENERGY	1695	749	840	857	856

4.3.4 Define the number of bits

The number of bits is required to assist in encoding genetic operations to obtain the offspring population. The number of bits required for representing variables in binary or encoding genetic operations is defined by the equation: $\left[2^{(m-1)} < (b-a) * 10^2 < 2^m\right]$, where:

b = upper limit

a = lower limit

m = Number of bits

10^2 = Means two-digit accuracy

Substituting parameter values defined for cost decision-support variable, we have:

b = 10

a = 0

$$\left[2^{(m-1)} < (b-a) * 10^2 < 2^m\right]$$

$$\left[2^{(m-1)} < (10-0) * 10^2 < 2^m\right]$$

$[2^{(m-1)} < (10 - 0) * 10 * 10 < 2^m] = 1000$.

To satisfy the binary bits equation we have m =10bits, which results to $[2^9 < 1000 < 2^{10}]$. Therefore, 2^9 is lesser than 1000 while 2^{10} is a little greater than 1000.

Similarly, substituting parameter values defined for energy decision-support variable following same process, we have

b = 20

a = 0

m = 11bits

which represents $[2^{(11-1)} < (20 - 0) * 10 * 10 < 2^m] = 1000$.

$[2^{10} < 2000 < 2^{11}]$.

Encode the binary operations in Microsoft Excel based on the number of bits obtained to obtain six strings (S) of parent population detailed in Table 8.

Table 8: Binary operations

STRING	CAPITAL COST	ENERGY
1	1101111000	11010011111
2	0011010101	01011101101
3	0100001110	01101001000
4	0100010111	01101011001
5	0101110111	01101011000

The binary codes represent an option for each of the six strings. The next step towards obtaining the offspring population is calculating the crossover probability and mutation.

4.3.5 Crossover probability and mutation

This study considers a one-point position for crossover probability. The results for the crossover operations is detailed in Table 9.

Table 9: Crossover operators

STRING	STRING	NEW OFFSPRING	STRING NUMBER
CAPITAL COST	11011 | 11000	11011011111	1
ENERGY	11010 | 011111	1101011000	
CAPITAL COST	00110 | 10101	00110101101	2
ENERGY	01011 | 101101	0101110101	
CAPITAL COST	01000 | 01110	01000001000	3
ENERGY	01101 | 001000	0110101110	
CAPITAL COST	01000 | 10111	01000011001	4
ENERGY	01101 | 011001	0110110111	
CAPITAL COST	01011 | 10111	01011011000	5
ENERGY	01101 | 011000	0110110111	

This study considers a 0.01 probability for mutation. The results from mutation are detailed in Table 10. For binary encoding, switch randomly selected bits from 0 to1 or 1 to 0 from the new offspring binary values generated in Table 10 with 0,01 probability mutation.

Table 10: Mutation

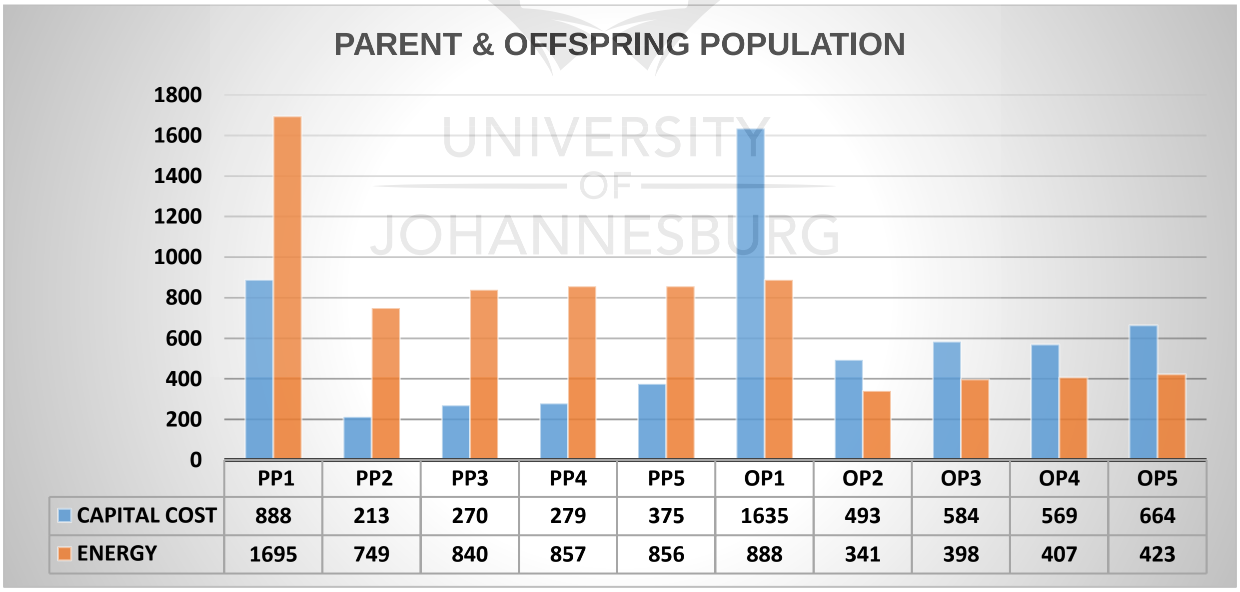
STRING	CROSSOVER PROBABILITY		MUTATION (OFFSPRING POPULATION)	
	CAPITAL COST	ENERGY	CAPITAL COST	ENERGY
1	11011011111	1101011000	11001011111	1101111000
2	00110101101	0101110101	00111101101	0101010101
3	01000001000	0110101110	01001001000	0110001110
4	01000011001	0110110111	01000111001	0110010111
5	01011011000	0110110111	01010011000	0110100111

4.3.6 Evaluate best solutions to minimise both cost and energy

This is achieved by plotting combined Parent Population (PP) and Offspring Population (OP) which gives twelve strings. The best solution evaluates for six out of the twelve strings for the next generation. This is obtained by non-dominant sorting of the combined population. The outputs of the combined strings are detailed in Table 11, where strings (1 – 5) indicates the parent population and strings (6 – 10) the offspring population.

Table 11: Combined population of outputs

STRING NO	STRING NAME	COST	ENERGY
1	PP1	888	1695
2	PP2	213	749
3	PP3	270	840
4	PP4	279	857
5	PP5	375	856
6	OP1	1635	888
7	OP2	493	341
8	OP3	584	398
9	OP4	569	407
10	OP5	664	423



	PP1	PP2	PP3	PP4	PP5	OP1	OP2	OP3	OP4	OP5
🟦 CAPITAL COST	888	213	270	279	375	1635	493	584	569	664
🟧 ENERGY	1695	749	840	857	856	888	341	398	407	423

Figure 11: Parent and offspring population

4.3.7 Analyse outputs

Based on the outputs detailed in Table 11 and Figure 11. All Pareto-optimal solutions utilizes non-dominated technique. Detailed outputs are shown in Table 11. The analysis of capital costs of hydropower can be very detailed, but for purposes of comparison and transparency, the approach used here is a simplified one. This allows greater analysis of the underlying data and assumptions, improved transparency and confidence in the analysis. The following information is inferred to determine the non-dominant (greater) fronts: 5 best strings are chosen for the next negation, using the non-dominated technique.

(a) String “2” dominates strings “1”, “3”, “4”, “5” and “6”. But string “7” dominates string “2”. String “7” dominates strings “8”, “9”, and “10”. This makes string “7” the first non-dominant front (F1).
(b) String “2” dominates strings “1”, “3”, “4”, “5”, “6”, “7”, “9”, and “10”. This makes string “2” the second non-dominating factor (F2).
(c) String “3” dominates “1”, “4”, “5”, “6”, “7”, “9”, and “10”. This makes string “3” the third non-dominating factor (F3).
(d) String “4” dominates “1”, “6”, “7”, “9”, and “10”. Strings “4” and “5” results in a non-dominant set since string “4” is more dominant than string “5” in cost and string “5” is more dominant than string “4” in energy. This makes strings “4” and “5” the fourth and fifth non-dominating factor (F4 & F5).

The collective fronts detailed in Table 12 results in the new generation which represents one iteration for the Pareto-optimal solutions for minimal capital cost and energy based on the NSGA-II algorithm techniques.

Table 12: Operational performance for cost-energy optimisation

OPTIMISED DESIGN OPTIONS (MICRO TURBINES)	OPERATIONAL PERFORMANCE	
	CAPITAL COST ($)	ENERGY (JOULES/MINUTE)
F1	493	341
F2	213	749
F3	270	840
F4	279	857
F5	279	857

A similar NSGA-II optimisation scenario is applicable for investigating the comprehensive decision-support variables discussed in the model development section for a 30KW micro turbine with the following baseline parameter values. The parameter values are defined based on data extracted from literature on hydropower projects of micro turbines detailed in Table 3 of the methodology chapter. Although this paper analyses capital costs, the data available are price indicators. The potential of the total technical hydropower resource is subjected to several critical assumptions in addition to average outflows:

- Capital cost = \$1000.
- Energy = 2000Joules/minutes.
- Recuperated efficiency = 25%.
- Operational and maintenance cost = dollar 0.0105 @ 390000 hours maintenance interval.

The results obtained for each step in the investigation is illustrated on microsoft excel spread sheet. Table 13 details the operational performance of the comprehensive decision-support variables. The levelized cost of electricity generation of hydropower varies by capital and operating costs, and the efficiency/performance of the technology. The approach used in the analysis presented in this study is based on the NSGSA-II tool. This method of calculating the cost of renewable energy technologies is based on random created values

Table 13: Operational performance for comprehensive decision-support variables

OPTIMISED DESIGN OPTIONS (MICRO TURBINES)	OPERATIONAL PERFORMANCE			
	CAPITAL COST (\$)	ENERGY (JOULES/MINUTE)	RECUPERATED EFFICIENCY (%)	OPERATIONAL & MAINTENANCE COST (%)
F1	493	341	25.0	0.0105
F2	213	749	23.6	0.0109
F3	270	840	21.8	0.0117
F4	279	857	20.4	0.0124
F5	279	857	20.8	0.0135

4.4 Sensitivity analysis

The optimisation framework discussed demonstrates a decision-support system for evaluating influences of the variables relating to the design and operations of the micro turbines. Four decision-support variables are considered, and a comprehensive technical comparative analysis is presented to analyse possible saving potentials. Table 13 details the comparative optimal operational impacts of each decision-support variable from a defined parent and offspring population of a 30 KW capacity micro turbine. Figure 11 below captures the data and relationship between the comparative optimal operational impacts of each decision-support variable.

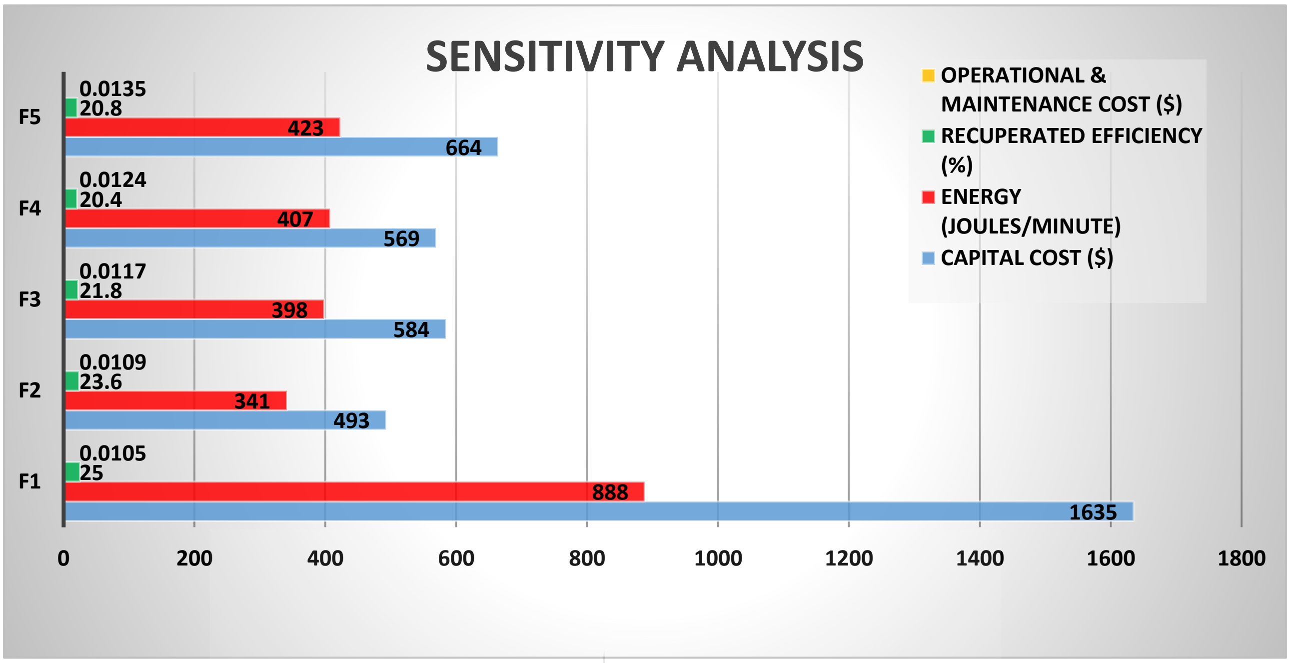
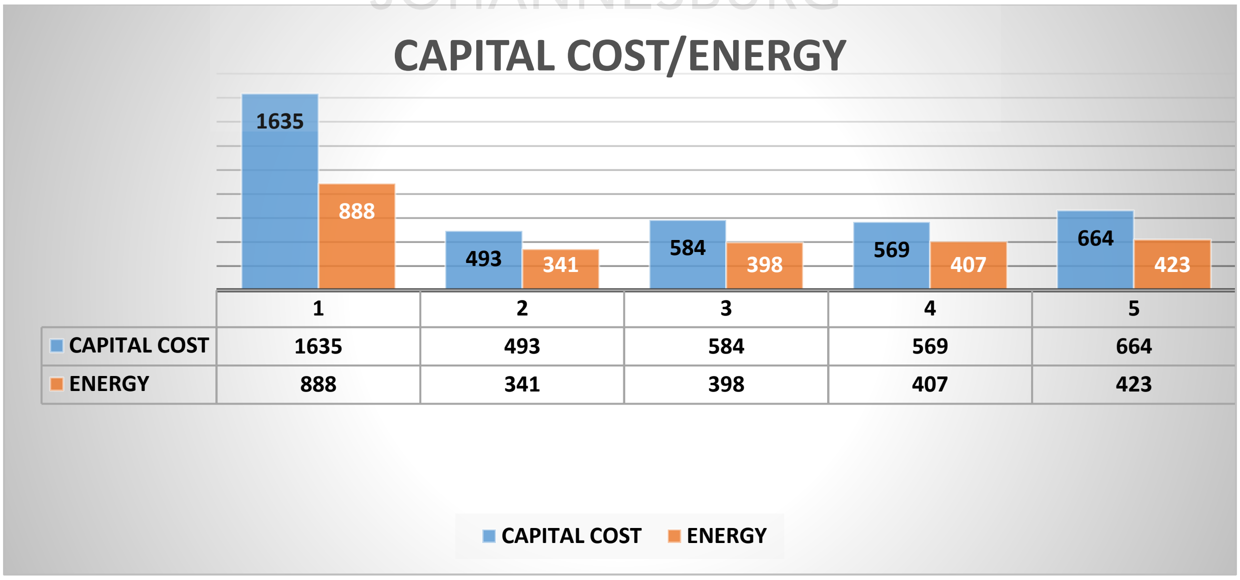


Figure 12: Graphical illustrations of optimal operational performance

From the sensitivity analysis, the greatest possible design and operational saving options from all the new generation detailed in Table 13 corresponds to Front (F1). Figure 13 indicates at minimum capital cost, energy, and operational & maintenance cost there is a comparable increase in recuperated efficiency. The operational and design results are separated in dual interactions, illustrating the relationships between the decision-support variables. The lowest capital cost is often the priority in the process of preparation of the budget in the engineering project.



	1	2	3	4	5
🟦 CAPITAL COST	1635	493	584	569	664
🟧 ENERGY	888	341	398	407	423

Figure 13: Graphical illustrations of optimal Capital Cost vs Energy

The capital cost of the 30KW micro turbine is directly proportional to the energy produced by the micro turbine. The capital cost of the 30KW micro turbine is inversely proportional to the recuperated efficiency of the micro turbine.

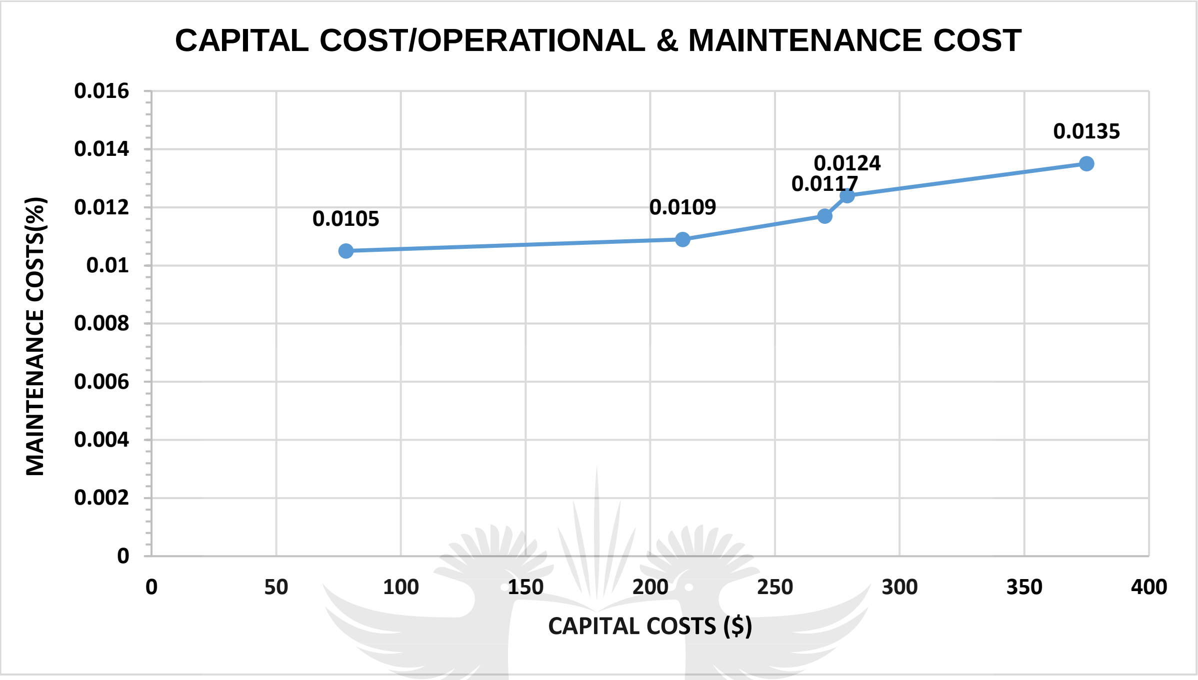


Figure 14: Graphical illustrations of optimal Capital Cost vs Maintenance Costs

As can be seen in Figure 14 that the capital costs of the 30KW micro turbine is directly proportional to the operational & maintenance cost consumed by the micro turbine.

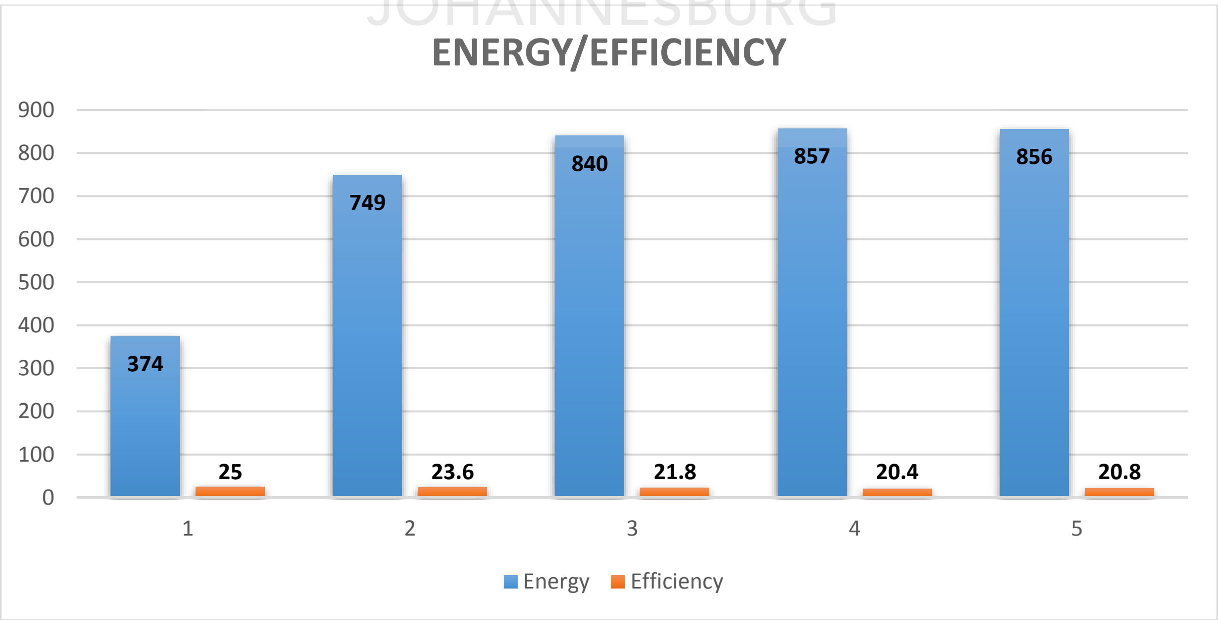


Figure 15: Graphical illustrations of optimal of Energy vs Efficiency

The energy of a 30KW micro turbine is inversely proportional to the recuperated efficiency generated by the micro turbine.

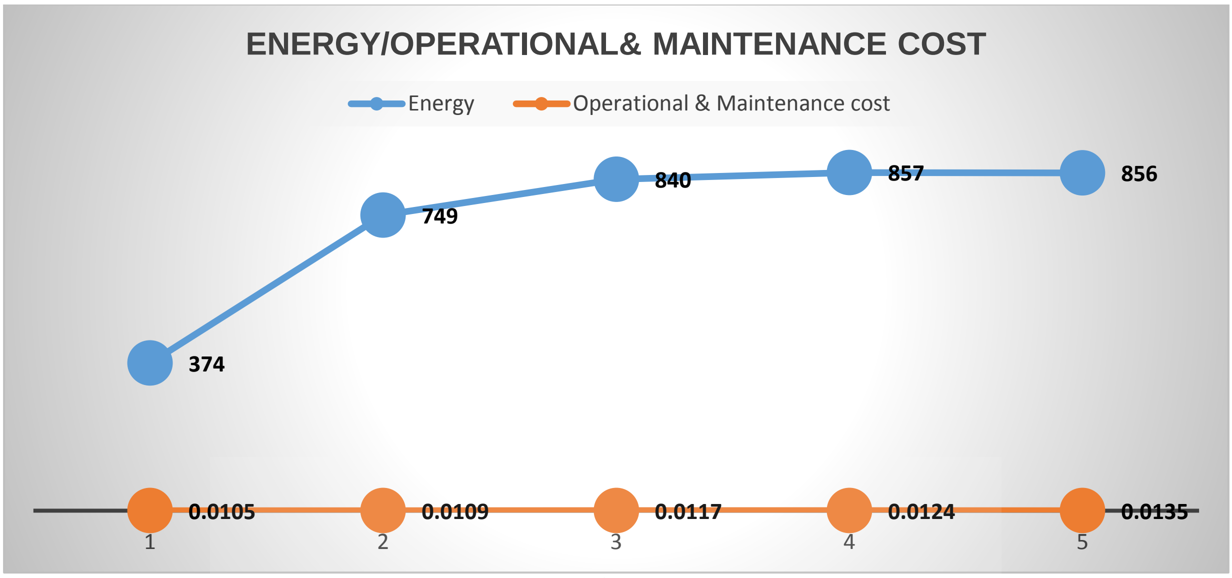


Figure 16: Graphical illustrations of optimal of Energy vs Maintenance Costs

The energy of a 30KW micro turbine is directly proportional to the operational/maintenance cost consumed by the micro turbine.

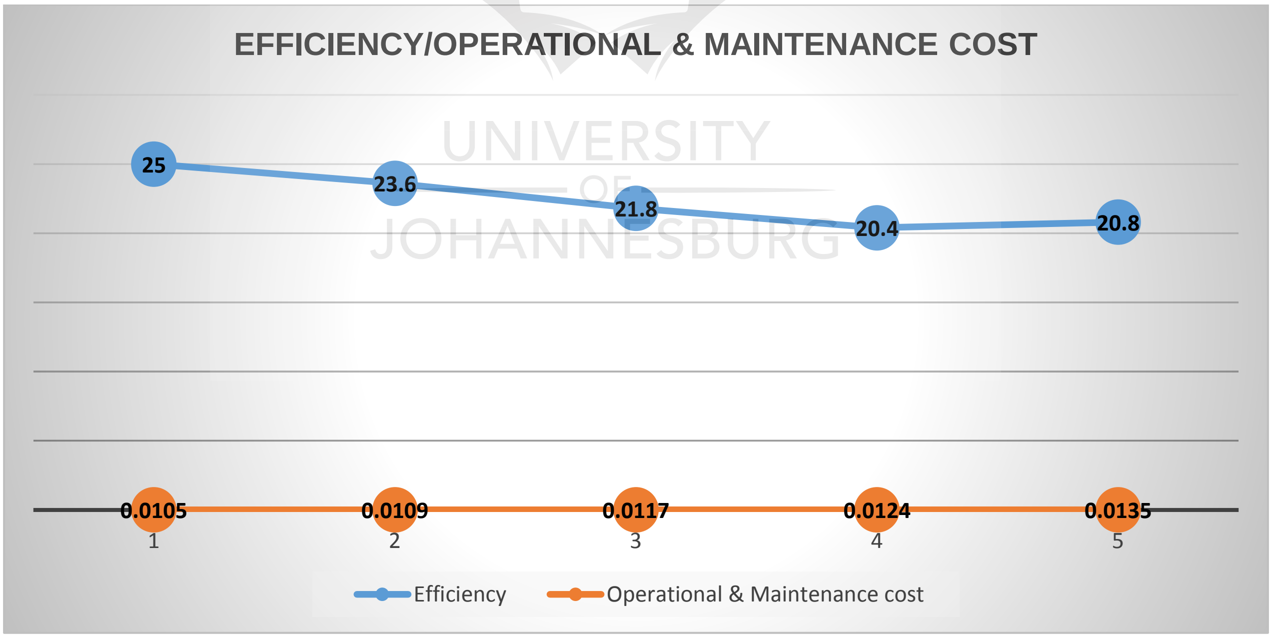


Figure 17: Graphical illustrations of optimal Efficiency vs Maintenance costs

The efficiency of a 30KW micro turbine is inversely proportional to the operational/maintenance cost consumed by the micro turbine.

4.5 **Results**

The WWTP effluent is usually released into the river system downstream. These systems convey the water via gravity allowing all the additional renewable energy to be extracted. Flow rates are provided for a potential site at the WWTP outflow. These measured volumetric flow rates are used to calculate the available hydropower potential using Equation 2(Kusakana, K. 2019). The potential sites should be chosen with adequate historical flow data records to calculate the total available flow for the potential hydropower generation.

The general formula for any hydropower system output is determined by (Stout BA. Handbook of energy). Calculations are computed using microsoft excel tool, Table 14.

$$\boldsymbol{P = \rho g Q H}\eta \qquad (2)$$

Where

P = potential generated hydropower produced at the turbine shaft in Watts

ρ = is the density of water volume (kg/m3) **(**usually 1000 kg/m3 for water)

g = acceleration due to gravity (m/s2) = 9.81

Q = flow rate passing through the turbine (m3 /s) = 68000

H = is the effective pressure head of water across the turbine (m) = 20 metres

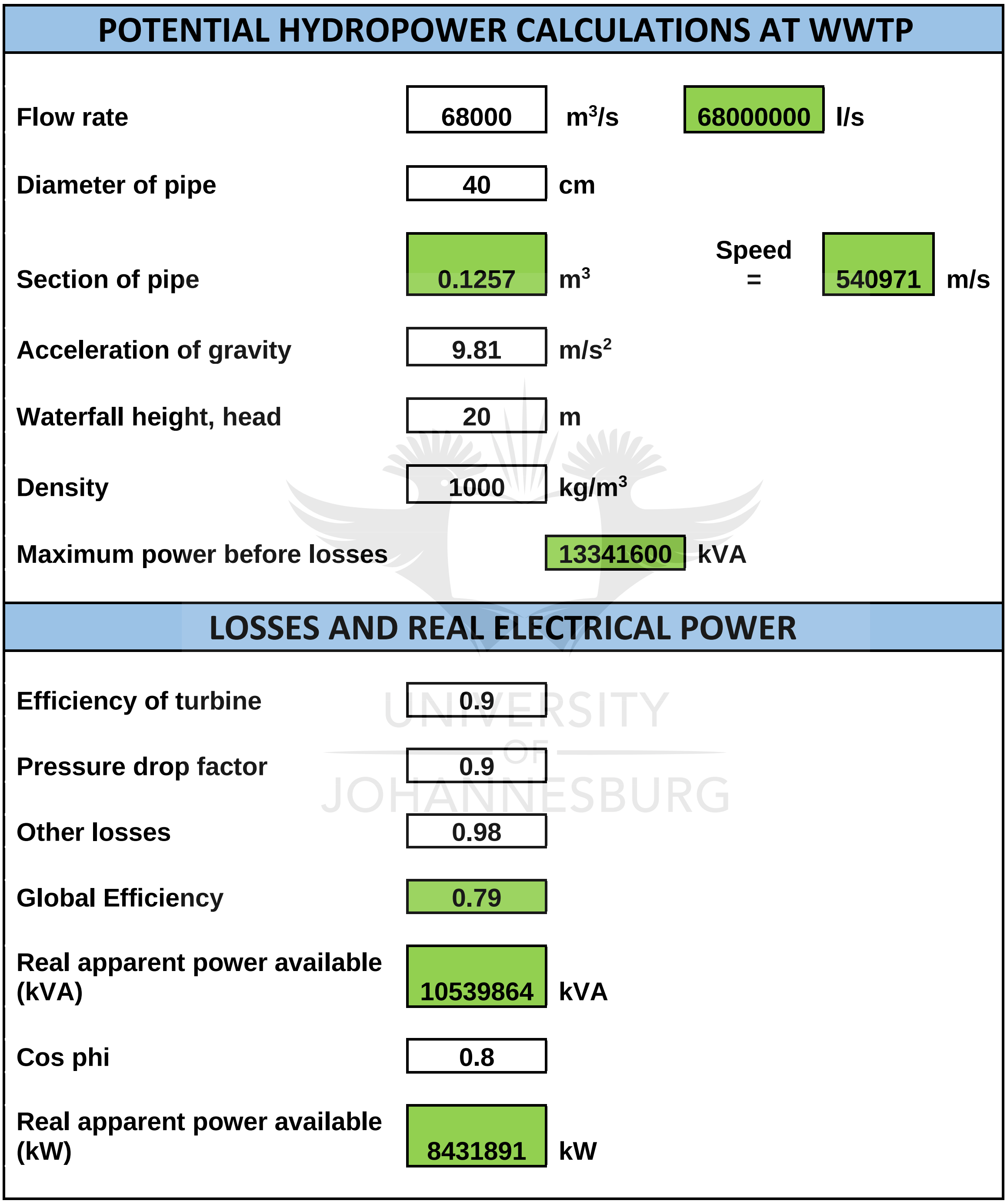
η = hydraulic efficiency of the turbine= 0.9

From the basic mathematical relationship in Equation 2, it can be noted that the potential power output is directly proportional to the flow through the turbine and the pressure head available (Bonthuys, et al., 2016).

The results presented in Table 14 demonstrates detailed potential hydropower output of a 30kW Kaplan reaction turbine. This analysis is done by using the available information in the (Infrastructure Management Query Software) IMQS information system. The energy potential for hydropower recovery with the microsoft excel tool is estimated to be 8431891 kW. This is power that will be available for use by the wastewater treatment plant.

The analysis, Table 14, shows that operating at higher head allows the possibility of increased hydro-energy generation. The selection of head is dependent of topographic conditions, which entails the selection of a different type of turbine. This improves overall operation of the system over varying speeds (C. Bousquet, et al., 2017). Literature shows that 4 technologies are commonly used for application of small hydropower schemes: the Pelton turbine, the Kaplan turbine, using a Pump as turbine (PAT) and the Archimedes screw. Studies shows that PAT-based hydropower scheme has presented bottlenecks and is not economically feasible, but has presented bottlenecks for this application. Limited literature has been performed on PAT technology in the academic published researches (Binama, et. al 2017).

Table 14 : Potential Hydropower Calculations



POTENTIAL HYDROPOWER CALCULATIONS AT WWTP					
Flow rate	68000	m^3/s		68000000	l/s
Diameter of pipe	40	cm			
Section of pipe	0.1257	m^3	Speed =	540971	m/s
Acceleration of gravity	9.81	m/s^2			
Waterfall height, head	20	m			
Density	1000	kg/m^3			
Maximum power before losses		13341600	kVA		
LOSSES AND REAL ELECTRICAL POWER					
Efficiency of turbine	0.9				
Pressure drop factor	0.9				
Other losses	0.98				
Global Efficiency	0.79				
Real apparent power available (kVA)	10539864	kVA			
Cos phi	0.8				
Real apparent power available (kW)	8431891	kW			

The developed algorithm allows for a general screening of potential for hydropower in wastewater systems in any given area. Four potential sites have been identified for generating hydropower at WWTPs; however, results may vary considerably due to assumptions made. This method should be a tool for strategic decisions and general concepts, as more detailed studies are always imperative for each site. These strategies favour the reduction of energy consumption and GHG and promote energy efficiency.

4.6 Conclusion

This chapter conducts a case study analysis to investigate for ideal baseline decision variables saving prospects of the micro turbines. The case study develops a model and conducts optimisation scenarios with the model relating to the design, applicability, and saving initiatives of the micro turbine. The benefits of the novel multi-optimisation decision-support layer include but not limited to:

- Energy efficiency: The energy consumed sums a significant percentage of the micro turbine lifecycle demand and costs.
- Reliability: Ensuring the micro turbines operate within an ideal range reducing unnecessary wear on micro turbine components, thereby increasing the operating lifecycle.
- System control: Variations in process conditions can be corrected in real-time preventing pressure or flow surges.

The study shows that there are two opportunities for hydropower generation at WWTP (Barta, et al., 2015) namely:

- installation at the inlet works (raw water) and
- the at the WWTP outflow (treated effluent) or discharge point.

The next chapter concludes this study with a summary of the discussions and recommendations.

5 CHAPTER FIVE: SUMMARY AND RECOMMENDATIONS

5.1 Introduction

This study contributes to the South Africa energy sector specifically investigating hydroelectricity generation as a renewable energy source at wastewater treatment plants. The study evaluates the role and maturity of micro turbines to enhance strategies in improving hydroelectricity generation at wastewater treatment plants in South Africa. Cost, efficiency, and energy saving opportunities of the micro turbines are discussed. The results present optimisation insights relating to the applications and design of the micro turbines for hydro electricity generation. The next section highlights the findings of this study.

5.2 Findings

The outputs of this study demonstrate the possible benefits of the micro turbine as a hydro electricity generation technology for wastewater treatment plants. Although, fossil fuels and solid wastes are prevalent renewable energy sources in wastewater treatment plants, this is unsustainable. The importance of hydro energy as a complimentary renewable source has been established. The findings in relation to the objectives of this study is detailed.

- Undertake a detailed literature review relevant to renewable energy sources with specific attention directed to hydropower renewable energy.

A comprehensive literature study is conducted on hydropower renewable energy and suitability of the micro turbines for hydro electricity generation. Google Scholar and Scopus database present available publications which provides data and information on micro turbines as an emerging hydro technology. The literature review addresses the first research question which states "What emerging technology is effective to improve hydropower electricity generation at WWTP?"

- Investigate and discuss existing challenges relevant to hydropower renewable energy implementations at WWTP in the Republic of South Africa.

The desktop study identifies a research gap which relates to optimising the cost, efficiency, and energy opportunities offered by the micro turbine technology for electricity generation at wastewater treatment plants. A quantitative approach is applied in developing a multi-optimisation layer. The optimisation framework supported by NSGA-II techniques is developed in Microsoft Excel. The optimisation layer evaluates and demonstrates possible benefits relating to the design and operational demand expected from the micro turbines. This objective addresses the second research question which states “What potential benefits does the hydropower technology identified have on hydropower electricity generation at WWTP?”

- Identify an emerging technology effective to improve hydropower electricity generation at WWTP globally.

A comprehensive desktop study is conducted on the suitability of the micro turbine technology identified from the literature review. Critical decision-support enablers suitable to improve operational demand of the micro turbines are identified and discussed. This objective addresses the third research question which states “What variables are relevant for optimising applications and implementations of the hydropower technology selected”.

- Discuss the expected benefits of the hydropower technology selected related to improving hydropower electricity generation at WWTP in the Republic of South Africa.

This study present detail discussions on the possible opportunities relating to the suitability, applicability and operational demand of the micro turbines for improving hydro electricity generation at wastewater treatment plants. This objective addresses the fourth research question which states “What are the implications of the proposed optimum developments related to improving hydropower electricity generation at WWTP?”

- Develop a model and investigate for optimum developments with emphasis on the applications and implementations of the hydropower technology selected.

A novel optimisation decision-support model is developed in Microsoft Excel demonstrating ideal operational possibilities of the micro turbines. NSGA-II technique is specifically applied in the optimisation of the operational demand of the micro turbines.

- Discuss and propose recommendations based on the implications of the proposed optimum developments.

This study concludes with a discussion on the importance of the novel multi-optimisation decision-support layer. Recommendations, limitations and possible future directions based on outputs of this study are detailed.

5.3 Recommendations and Limitations

5.3.1 Recommendations

- Invest in energy effective micro turbine as a hydro electricity generation technology at wastewater treatment plants.
- Size micro turbines to operate at closest proximity for optimal efficiency.

5.3.2 Limitations

Lack of operational data or information relating to the adaptability of micro turbines at wastewater treatment plants. Therefore, for the purpose of discussing potential implementation and modification prospects of micro turbines for hydro electricity generation at wastewater treatment plants, available data for current configurations in hydro projects obtainable is extracted for contrast to the possible configuration opportunities.

5.4 Conclusion and Future Research

The dominant source of electricity generation in South Africa is coal and thermal power. The increasing demand and supply of energy is not sustainable. This study argues the prospects provided by the micro turbines to improve hydropower as a source of electricity generation at wastewater treatment plants in South Africa. The study demonstrates hydropower generation through micro turbines has the potential to support the current rate of electricity production. The study details the applications, reliability and maturity of micro turbines across developed countries. The results detail possible cost-energy prospects of the micro turbines. The results discuss the role of the micro turbines as a possible integral technology of the wastewater treatment plants in South Africa.

Therefore, micro turbines can considerably contribute to the increasing demand and supply of hydro energy in South Africa. Micro turbine designs should incorporate implementation and modification measures. Future studies can focus on implementation strategies of the micro turbines at wastewater treatment plants based on optimisation modifications detailed.

References:

Agustini, C. B., da Costa, M., & Gutterres, M. (2020). Biogas from Tannery Solid Waste Anaerobic Digestion Is Driven by the Association of the Bacterial Order Bacteroidales and Archaeal Family Methanosaetaceae. *Applied biochemistry and biotechnology*.

AH. Elbatrana, OB. Yaakob Yasser M. Ahmed, H.M. Shabara (2015) Operation, performance and economic analysis of low head micro-hydropower turbines for rural and remote areas.

AlSattar, H. A., Zaidan, A. A., Zaidan, B. B., Bakar, M. A., Mohammed, R. T., Albahri, O. S., and Albahri, A. S. (2018). MOGSABAT: a metaheuristic hybrid algorithm for solving multi-objective optimisation problems. Neural Computing and Applications, 1-15.

Anderson, E. P., Jenkins, C. N., Heilpern, S., Maldonado-Ocampo, J. A., Carvajal-Vallejos, F. M., Encalada, A. C., and Salcedo, N. (2018). Fragmentation of Andes-to-Amazon connectivity by hydropower dams. Science advances.

Arora, R., Kaushik, S. C., and Kumar, R. (2017). Multi-objective thermodynamic optimisation of solar parabolic dish Stirling heat engine using NSGA-II and decision making. International Journal of Renewable Energy Technology, 8(1), 64-92.

Babaei, N., Tabesh, M., and Nazif, S. (2015). Optimum reliable operation of water distribution networks by minimising energy cost and chlorine dosage. Water SA, 41(1), 149-156.

Badhurshah, R., and Samad, A. (2015). Multiple surrogate based optimization of a bidirectional impulse turbine for wave energy conversion. Renewable energy, 74, 749-760.

Bell, E., Bryman, A., and Harley, B. (2018). Business research methods. Oxford university press.

Bellamy, C. (6). P. (2012) Principles of Methodology: Research Design in Social Science., London: SAGE.pp.1.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S., & Iyyappan, J. (2018). Biogas production–A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and sustainable Energy reviews*, *90*(C), 570-582.

Binama, M., Su, W. T., Li, X. B., Li, F. C., Wei, X. Z., & An, S. (2017). Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 79, 148-179.

Blumberg, B., Cooper, D. R., and Schindler, P. S. (2008). Business research methods (Vol. 2). London: McGraw-Hill Higher Education.

Brynard, D. Hanekom, S. Brynard, P. (2014) Introduction to Research .3rd ed. Pretoria: Van Schaik Publishers, pp56-61.

Bui, K. T. T., Bui, D. T., Zou, J., Van Doan, C., and Revhaug, I. (2018). A novel hybrid artificial intelligent approach based on neural fuzzy inference model and particle swarm optimization for horizontal displacement modelling of hydropower dam. Neural Computing and Applications, 29(12), 1495-1506.

C. Bousquet, I. Samora, P. Manso, L. Rossi, P. Heller, A .J. Schleiss (2017) Assessment of hydropower potential in wastewater systems and application to Switzerland.

Callaway, D. S., Fowlie, M., and McCormick, G. (2018). The variable value of renewable energy and demand-side efficiency resources. Journal of the Association of Environmental and Resource Economists, 5(1), 39-75.

Castillo, A., and Gayme, D. F. (2014). Grid-scale energy storage applications in renewable energy integration: A survey. Energy Conversion and Management, 87, 885-894.

Chitrakar, P. (2004). Micro-hydropower design aids manual. Small Hydropower Promotion Project (GTZ) and Mini-Grid Support Program, Alternate Energy Promotion Centre, Government of Nepal.

Cobb, B. R., and Sharp, K. V. (2013). Impulse (Turgo and Pelton) turbine performance characteristics and their impact on pico-hydro installations. Renewable Energy, 50, 959-964.

Deb, K., Agrawal, S., Pratap, A., and Meyarivan, T. (2000, September). A fast-elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. In International conference on parallel problem solving from nature (pp. 849-858). Springer, Berlin, Heidelberg.

Deng, X., Mecrow, B., Wu, H., and Martin, R. (2017). Design and development of low torque ripple variable-speed drive system with six-phase switched reluctance motors. IEEE Transactions on Energy Conversion, 33(1), 420-429.

dos Santos, I. F. S., Camacho, R. G. R., Tiago Filho, G. L., Botan, A. C. B., & Vinent, B. A. (2019). Energy potential and economic analysis of hydrokinetic turbines implementation in rivers: An approach using numerical predictions (CFD) and experimental data. *Renewable Energy*, *143*, 648-662.

Droste, R. L., and Gehr, R. L. (2018). Theory and practice of water and wastewater treatment. Wiley.

Du Toit, L. (2014). Promoting renewable energy in South Africa through the inclusion of market-based instruments in South Africa's legal and policy framework with reference to the feed-in tariff (Doctoral dissertation, University of Cape Town).

East Rand Water Care (2016). Newsbeat Development. website from www.erwat.co.za/about-erwat.

Department of Water Sanitation website from www.dws.gov.za. Accessed August 2018.

Ebinger, J, and Vergara, W. (2011). Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation, Energy Sector Management Assistant Program (ESMAP) of theWorld Bank.

Ebrahim, M., Lakov, G., and Oliver, S. (2006). U.S. Patent No. 7,045,913. Washington, DC: U.S. Patent and Trademark Office.

Ellabban, O., Abu-Rub, H., and Blaabjerg, F. (2014). Renewable energy resources: Current status, prospects, and enabling technology. Renewable and Sustainable Energy Reviews, 39, 748-764.

Energy Solutions Center (ESC). Understanding CHP. https://understandingchp.com/overview-2/system-schematics/micro-turbine-schematic/. Accessed April 2019.

Flick, U. (2018). An introduction to qualitative research. Sage Publications Limited.

Gamze Güngör-Demircia (2015) Spatial analysis of renewable energy potential and use in Turkey.

Gill, P., Stewart, K., Treasure, E., and Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. British dental journal, 204(6), 291.

Godfrey, L., and Oelofse, S. (2017). Historical review of waste management and recycling in South Africa. Resources, 6(4), 57.

Gorshkov, V and Makarieva, A. (2005). Knowledge of the Environment. Quality of Human Resources Volume 1, UNESCO Encyclopaedia of Life Support Systems.

Green, J., and Thorogood, N. (2018). Qualitative methods for health research. Sage.

Herzog, A. V., Lipman, T. E., Edwards, J. L., and Kammen, D. M. (2001). Renewable energy: a viable choice. Environment: Science and Policy for Sustainable Development, 43(10), 8-20.

http://sawic.environment.gov.za/documents/8641.pdf. Accessed February 2018.

http://www.energy.gov.za/files/coal_frame.html. Accessed March 2018.

http://www.sacities.net/wp-content/uploads/Annual_Report/SACN-Annual-Report-2014-WEB.pdf. Accessed July 2018.

https://wisa.org.za/document/?document-year=2018&document-conference=wisa2018

https://www.eia.gov/beta/international . Hydroelectric power generation by country adapted from energy information agency, international energy statistics. Accessed August 2018.

https://www.usbr.gov/uc/rm/crsp/. Colorado River storage project. Accessed March 2019.

I. Loots, M. van Dijk, B. Barta, S.J. van Vuuren, J.N. Bhagwan (2015) Review of low head hydropower technologies and applications in a South African context

Intergovernmental Panel on Climate Change (2007), Climate Change: Working Group 1—The Physical Science Basis, Cambridge University Press, Cambridge, UK.

Ivankova, V. (2015). Mixed Methods Application in Action Research, From Methods to Community Action. London: Sage.pp4.

Jawahar, C. P., and Michael, P. A. (2017). A review on turbines for micro hydro power plant. Renewable and Sustainable Energy Reviews, 72, 882-887.

Jorgensen, D. L. (2015). Participant observation. Emerging trends in the social and behavioural sciences: An interdisciplinary, searchable, and linkable resource, 1-15.

Kaunda, C. S., Kimambo, C. Z., and Nielsen, T. K. (2012). Hydropower in the context of sustainable energy supply: a review of technologies and challenges. ISRN Renewable Energy, 2012.

King, N., Horrocks, C., and Brooks, J. (2018). Interviews in qualitative research. SAGE Publications Limited.

Klunne, W. J. (2013). Small hydropower in southern Africa-an overview of five countries in the region. Journal of Energy in Southern Africa, 24(3), 14-25.

Kusakana, K. (2019, December). Hydropower Energy Recovery from Wastewater Treatment Plant: Case of Zeekoegat Plant. In *2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)* (pp. 1-5). IEEE.

Lee, U., Han, J., Elgowainy, A., and Wang, M. (2018). Regional water consumption for hydro and thermal electricity generation in the United States. Applied energy, 210, 661-672.

Levis, J. W., and Barlaz, M. A. (2011). Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model. Environmental science & technology, 45(13), 5470-5476.

Li, X. Z., Chen, Z. J., Fan, X. C., and Cheng, Z. J. (2018). Hydropower development situation and prospects in China. Renewable and Sustainable Energy Reviews, 82, 232-239.

Litosseliti, L. (Ed.). (2018). Research methods in linguistics. Bloomsbury Publishing.

Liu, X., Luo, Y., Karney, B. W., & Wang, W. (2015). A selected literature review of efficiency improvements in hydraulic turbines. *Renewable and Sustainable Energy Reviews*, *51*, 18-28.

Locker, H. (2004). Environmental Issues and Management for Hydropower Peaking Operations, United Nations, Department of Economic and Social Affairs (UN-ESA).

Logan Yonavjak, Emily Norford, Athena Ballesteros, Tom Nagle and Susan Alzner. (2013). Implementation strategies for renewable energy services in low-income rural areas.

Mazzucato, M., and Semieniuk, G. (2018). Financing renewable energy: Who is financing what and why it matters. Technological Forecasting and Social Change, 127, 8-22.

Modi, V., McDade, S., Lallement, D., and Saghir, J. (2006). Energy and the Millennium Development Goals, The Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project, and World Bank, New York, NY, USA.

Mukherjee, A. (Ed.). (2018). Groundwater of South Asia. Springer.

Mutungwazi, A., Mukumba, P., & Makaka, G. (2018). Biogas digester types installed in South Africa: A review. Renewable and Sustainable Energy Reviews, 81, 172-180.

Nachman-Hunt, N. (2001). Small Hydropower Systems: Energy Efficiency and Renewable Energy Clearinghouse (No. DOE/GO-102001-1173; NREL/BR-810-29065). National Renewable Energy Lab., Golden, CO (US).

Nardi, P. M. (2018). Doing survey research: A guide to quantitative methods. Routledge.

Narrain, P. (2017). Low head hydropower for local energy solutions. CRC Press.

Niebuhr, C. M., Van Dijk, M., & Bhagwan, J. N. (2019). Development of a design and implementation process for the integration of hydrokinetic devices into existing infrastructure in South Africa. *Water SA*, *45*(3), 434-446.

Noble, H., and Smith, J. (2015). Issues of validity and reliability in qualitative research. Evidence-based nursing, 18(2), 34-35.

Nojavan, S., and allah Aalami, H. (2015). Stochastic energy procurement of large electricity consumer considering photovoltaic, wind-turbine, micro-turbines, energy storage system in the presence of demand response program. Energy conversion and management, 103, 1008-1018.

Owusu, P. A., and Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues, and climate change mitigation. Cogent Engineering, 3(1), 1167990.

Owusu, P. A., Asumadu-Sarkodie, S., and Ameyo, P. (2016). A review of Ghana's water resource management and the future prospect. Cogent Engineering, 3(1), 1164275.

Perrich, J. R. (2018). Activated carbon adsorption for wastewater treatment. CRC press.

Pina, A., Silva, C., and Ferrão, P. (2012). The impact of demand-side management strategies in the penetration of renewable electricity. Energy, 41(1), 128-137.

Purdum, H., Downs, W., and Downs, L. V. (2016). U.S. Patent No. 9,255,478. Washington, DC: U.S. Patent and Trademark Office.

Richards, L. (2015). Handling Qualitative Data: A Practical Guide. 3rd ed. London: SAGE, pp.1.

Roopnarain, A., & Adeleke, R. (2017). Current status, hurdles and future prospects of biogas digestion technology in Africa. Renewable and Sustainable Energy Reviews, 67, 1162-1179.

Saidur, R., Mekhilef, S., Ali, M. B., Safari, A., and Mohammed, H. A. (2012). Applications of variable speed drive (VSD) in electrical motors energy savings. Renewable and sustainable energy reviews, 16(1), 543-550.

Sargeant, J. (2012). Qualitative research part II: Participants, analysis, and quality assurance.

Shandra, J. M., London, B., and Williamson, J. B. (2003). Environmental degradation, environmental sustainability, and overurbanization in the developing world: A quantitative, cross-national analysis. Sociological Perspectives, 46(3), 309-329.

Stillwell, A., Hoppock, D., and Webber, M. (2010). Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. Sustainability, 2(4), 945-962.

Strydom, J. (2015). Energy and security: The role of renewable energy in South Africa (Doctoral dissertation, University of Pretoria).

Team, G. W. (2012). Global energy assessment: toward a sustainable future. Cambridge University Press.

Teske, S., Pregger, T., Simon, S., Naegler, T., Graus, W, and Lins, C. (2010). "Energy revolution 2010—a sustainable world energy outlook," Journal of Energy Efficiency, vol. 4, no. 3, pp. 409–433.

The department of water and sanitation, (2016).https://www.vukuzenzele.gov.za/department-water-and-sanitation. Accessed March 2018.

Thomas, E., and Magilvy, J. K. (2011). Qualitative rigor or research validity in qualitative research. Journal for specialists in pediatric nursing, 16(2), 151-155.

United States environmental protection agency, (2002). Office of Air and Radiation (6202J), EPA430-F-02-012.

Walliman, N. (2017). Research methods: The basics. Routledge.

Walton M, and Hendrix, L. (2012). The Promise of Renewables: Recent Success and Challenges of Getting to Scale—Commentary, The Geopolitics of Cleaner Energy, Centre for Strategic and International Studies, Washington DC, USA.

Wid, N., and Horan, N. J. (2016, June). Anaerobic digestion of wastewater screenings for resource recovery and waste reduction. In IOP Conference Series: Earth and Environmental Science (Vol. 36, No. 1, p. 012017). IOP Publishing.

Willis, H. L. (2018). Distributed power generation: planning and evaluation. Crc Press.

Yuksel, I. (2013). Renewable energy status of electricity generation and future prospect hydropower in Turkey. Renewable Energy, 50, 1037-1043.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., and Tockner, K. (2015). A global boom in hydropower dam construction. Aquatic Sciences, 77(1), 161-170.