DEVELOPMENT OF AN EVALUATION PROCEDURE AND TOOL FOR HYDROPOWER POTENTIAL DETERMINATION AT SOUTH AFRICAN DAMS

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DISSERTATION SUMMARY

DEVELOPMENT OF AN EVALUATION PROCEDURE AND TOOL FOR HYDROPOWER POTENTIAL DETERMINATION AT SOUTH AFRICAN DAMS

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South Africa is in a critical power situation and is in dire need of additional generation capacity. Thus, renewable energy sources such as wind, solar and hydropower should be evaluated to identify high potential and cost-effective sites. South Africa, being a water-scarce country, is already heavily dammed, meaning there are no more suitable new sites for conventional hydropower generation. Instead, novel solutions such as retrofitting hydropower installations to existing infrastructure, such as at existing dams, is required.

The study focussed on the development of the University of Pretoria Retrofit Hydropower Evaluation Software (UP-RHES), a procedure and tool that can evaluate hydropower potential at South African dams. By applying the UP-RHES to 118 DWS operated dams it was found that there is indeed retrofit hydropower potential at South African dams, with a total estimated hydropower potential of 122 MW with an annual energy output of between 393 and 479 GWh.

The majority of this potential came from a select few dams with the Vaal, Blyderivierpoort and Pongolapoort Dams being economically feasible with a combined capacity of 80.22 GWh/annum or enough energy to supply 133 000 households with 50 kWh/month, which is the amount of electricity that constitutes free basic electricity, which should be sufficient for basic household needs.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

PE	Potential Energy (J)
P	Power (W)
M	Mass (kg)
g	Gravitational acceleration (m/s^2)
H	Net Head (m)
ρ	Density (kg/m^3)
V	Volume (m^3)
Q	Flow rate (m^3/s)
t_w	Temperature of water (°C)
η	Efficiency (%)
H_f	Headloss due to friction (m)
L	Length of pipe (m)
v	Velocity (m/s)
D	Pipe diameter (m)
H_l	Headloss due to local losses (m)
K	Local head loss coefficient (dimensionless)
μ	Kinematic viscosity (m^2/s)
PV	Present value of the annuity (ZAR)
A	Annuity (ZAR/annum)
i	Growth rate of annuity (%)
r	Discount rate (%)
n	Years

1 INTRODUCTION

1.1 BACKGROUND

Building upon the widespread adoption of electricity brought about by the second and third industrial revolutions, the world has entered the fourth industrial revolution, and with it, has moved into a digital age. As such, commerce, entertainment and education are all beginning to move into the digital environment. Hence, energy supply has become the basis of economic development and a reliable energy supply is required for economic growth (Barbir *et al.*, 1990). However, as of 2019, 760 million people do not have access to electricity, with most of these people living in developing Asia and sub-Saharan Africa (World Bank, 2021). This disadvantage is set to compound with the world's shift into the digital environment, as access to electricity is a pre-requisite to accessing it and the opportunities therein.

In South Africa, the majority of power stations are owned by Eskom, which supplies 95% of the country's electricity (NS Energy, 2019). However, Eskom is struggling to satisfy demand as scheduled blackouts, known as "Load Shedding", have been implemented sporadically since 2008. In an attempt to alleviate the critical power situation, the National Energy Regulator of South Africa (NERSA), announced the Renewable Energy Feed-in Tariff (REFIT) strategy in 2009.

In 2011, the Department of Energy (DoE) and the National Treasury believed feed-in tariffs amounted to non-competitive procurement and therefore the REFIT strategy was revoked. Instead, the DoE announced a competitive bidding process as a replacement to REFIT. Known as the Renewable Energy Independent Power Producer Procurement (REIPPP) programme, it is used to incentivise investment in renewable energy whilst increasing the national capacity (Eberhard and Kaberger, 2016).

The REIPPP programme has procured a total of 6 422 MW of additional renewable energy to date, predominantly from wind and solar, even though hydropower is the most widely adopted renewable energy source globally, commanding 71% of the world's renewable energy capacity (Moran *et al.*, 2018). However, according to the Department of Water and Sanitation (DWS), the contribution of hydropower as part of the government's broader initiative to stimulate an energy mix, has not been fully explored. To support sustainable power generation and supply in South Africa, a sustainable hydropower generation policy was drafted to identify the hydropower potential within DWS water management areas (DWS, 2015b).

The National Water Resource Strategy (NWRS) provides an overall framework for water resource management in the country and includes provisions for hydropower generation at DWS-owned infrastructure, specifically DWS-owned dams, with key excerpts as follows (DWA, 2013):

- "The installation of small-scale hydro-electric plants to take advantage of the head available and flow from existing dams is being considered in cooperation with the Department of Environmental Affairs (DEA), National Treasury, Eskom, the Central Energy Fund and private sector partners."
- "The Department of Energy (DoE), together with the DWS and the National Treasury (NT), commissioned an investigation of the prospects for retrofitting hydroelectric generation equipment at existing DWA dams with hydroelectric power potential. The DoE has shortlisted 14 sites for further detailed evaluation."

1.2 STUDY MOTIVATION

The DWS's goal to identify hydropower potential within their water management areas is limited by the fact that South Africa is a heavily dammed country, due to its water scarcity. Thus, there are no more suitable sites for conventional hydropower generation. Instead, novel solutions, such as retrofitting hydropower installations to existing infrastructure such as water distribution networks or at dams, is required.

This requires identification and quantification of the hydropower available at the respective infrastructure and this task is already being undertaken with the development of the South African Hydropower Atlas (Bekker *et al.*, 2021), wherein South Africa's existing dams have been identified as possible sites for renewable energy generation by means of retrofit hydropower, in accordance with the NWRS.

1.3 OBJECTIVES

The objective of this study was to develop a procedure and tool that is capable of evaluating hydropower potential at South African dams, and to use the tool to identify the total potential for retrofit hydropower at South African dams.

To achieve the objectives the following sub-objectives were set:

- Develop a procedure and tool capable of evaluating hydropower potential at South African dams.
- Estimate the total hydropower potential available at South African dams.
- Identify dams with a high hydropower potential,
- Identify locations that may benefit greatly from retrofit hydropower at dams,
- Estimate the feasibility of retrofitting South African dams with hydropower installations, and
- Compare the feasibility of retrofit hydropower to that of alternative renewable energy technologies, such as wind and solar.

1.4 SCOPE OF THE STUDY

The study focussed on the potential storage hydropower at existing South African dams and does not include pumped storage hydropower or the construction of new dams specifically for hydropower. Cascaded hydropower systems were only identified and not investigated in detail. Finally, only dams gauged by the Department of Water and Sanitation were analysed, thus privately owned dams, or dams that are owned by other government departments, were excluded from the study.

1.5 METHODOLOGY

To achieve the objective the following methodology was used:

- A comprehensive literature review was conducted on storage hydropower, specifically on hydropower evaluation and implementation in South Africa.
- The University of Pretoria Retrofit Hydropower Evaluation Software (UP-RHES) was developed using the information gathered during the literature review.
- The UP-RHES was used to evaluate the hydropower potential at each dam registered with the Department of Water and Sanitation.
- Dams with a high hydropower potential were identified and analysed in greater detail.
- The UP-RHES was used to estimate the financial feasibility of the high potential dams.

- From this an average Levelized Cost of Energy for retrofit hydropower in South Africa was determined and compared to that of alternative energy sources.
- Conclusions and recommendations developed over the course of the research were given.

1.6 ORGANISATION OF THE REPORT

The report consists of the following chapters and appendices:

- Chapter 1 serves as an introduction to the dissertation and outlines the objectives, scope, methodology and organisation of the report.
- Chapter 2 contains a comprehensive literature review on the following topics:
    - Storage hydropower.
    - Dams and storage hydropower in South Africa.
    - Hydropower evaluation
    - Hydropower implementation in South Africa
- Chapter 3 details the methodology used in the development of the UP-RHES.
- Chapter 4 gives an overview of the UP-RHES and serves as a user guide.
- Chapter 5 describes the analysis and details the results of the evaluation of hydropower potential at South African dams, using the UP-RHES.
- Chapter 6 contains conclusions and recommendations developed over the course of the research.
- Chapter 7 contains the list of references used in the research.
- Appendix A contains the source code of the UP-RHES.
- Appendix B contains a list of the expected percent of storage under very low conditions for South African dams.
- Appendix C contains the results for each dam used in the analysis.

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2 LITERATURE STUDY

2.1 INTRODUCTION

While South Africa's renewable energy focus has been on wind and solar, the benefits of hydropower should not be overlooked as storage hydropower has unique benefits that warrant consideration given the unstable power situation in South Africa. In this chapter these benefits will be outlined and a general introduction to hydropower will be given. Details on the components that comprise a hydropower scheme will be shared followed by a review of the techniques used in hydropower evaluation as well as the considerations that may affect the feasibility of a hydropower project. Finally, the chapter ends with a review of previous estimations of South Africa's latent hydropower potential.

2.2 HYDROPOWER

Hydropower is a renewable energy source that converts the energy in water to electricity without consuming the water itself. Hydropower generation began as the water wheel and over time has developed into several categories. The International Hydropower Association (IHA, 2020) has classified hydropower according to the primary method used to generate power, namely:

- Run-of-river: Diverts the flow of a river through a canal or penstock to drive a turbine, after which the water is discharged back into the river. Run-of-river projects typically have little to no storage capacity and are located on large perennial rivers.
- Storage: Uses hydraulic structures, such as dams, to store water and the potential energy or head created by the storage reservoir is used to drive turbines. Storage hydropower projects are typically large and serve multiple purposes, such as irrigation and hydropower generation.
- Pumped storage: Uses excess electricity during low energy demand periods to pump stored water from a lower storage reservoir to a higher storage reservoir. The water is then released to drive turbines during peak demand.
- Offshore: Ocean currents or tidal movement are used to drive turbines. Offshore hydropower, possess significant potential power but is technically challenging.

Additionally, categories such as riverine hydrokinetic energy and conduit hydropower are emerging as viable options. However, the majority of hydropower comes from storage and pumped storage hydropower (IHA, 2020). Nevertheless, hydropower potential exists in numerous locations, as illustrated in Figure 2-1.

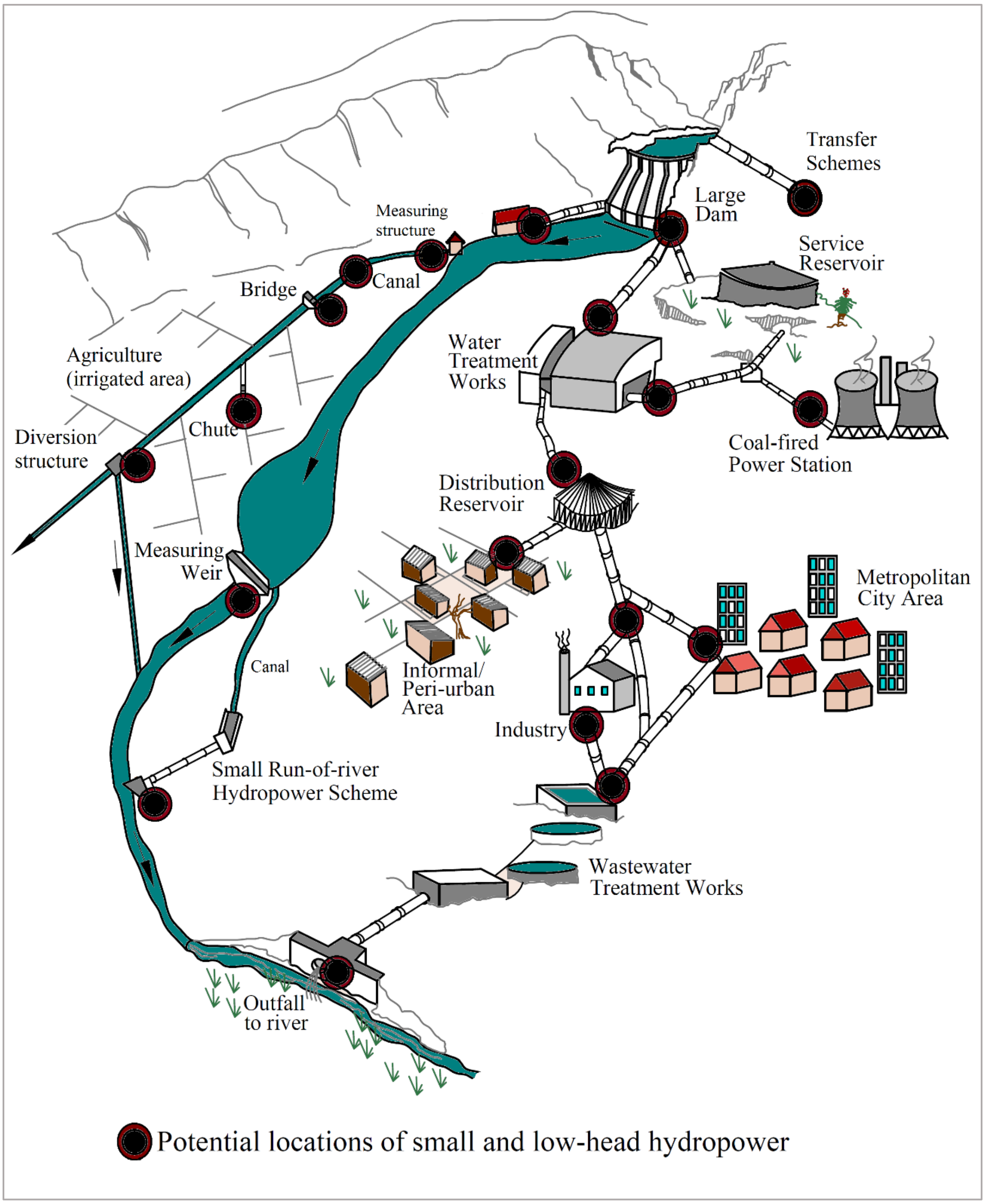


Figure 2-1: Potential locations of small and low-head hydropower (Loots *et al.*, 2015).

Internationally, hydropower capacity was built up between 1920 and 1970 in North America and Europe to serve the growing demands of the population. Recently, developing countries have been ramping up the development of hydropower to stimulate economic growth. An estimated 3 700 hydropower projects of more than 1 MW are planned or are under construction in developing countries. The Inga mega dam is one such project, with a planned capacity of 40 000 MW to be built in the Democratic Republic of Congo (DRC) (Moran *et al.*, 2018).

This aligns with the prediction that hydropower will be the resource that provides sustainable energy to parts of the world with the greatest need, such as developing Asia, Africa and South America (Bartle, 2002). This is due to the advantages of hydropower, namely (Van Dijk *et al.*, 2016; Van Vuuren *et al.*, 2011):

- A long operational life,
- High efficiency with low operating costs,
- Multi-purpose operation, with the
- Capability of quickly responding to changes in demand.

The overall high efficiency and low operating costs of hydropower is due to the technology being well developed with many years of study, leading to a general long operational life due to reduced wear. Additionally, hydropower sites may be multi-purpose as the hydraulic structures used to harness the hydropower may also provide irrigation or water for domestic use.

However, the main advantage of hydropower over alternative Renewable Energy Technologies (RET) is that hydropower plants do not require an external power supply to begin operation. As such, they can be used to restart grids after a blackout has occurred. Additionally, storage hydropower plants can rapidly adjust supply, allowing them to help stabilise the grid during periods of fluctuating demand. Hence, hydropower compliments intermittent forms of RET, such as wind and solar, that may produce excess energy during low demand and insufficient energy during peak demand (U.S. Department of Energy, 2017).

Nevertheless, it should be mentioned that hydropower is not without flaws, and it is often mistaken for an environmentally friendly source of energy. Although it is a significant improvement compared to that of fossil fuel alternatives, hydropower may transform rivers and their ecosystems by fragmenting and altering flows, disrupting sediment dynamics and biodiversity if not designed and operated correctly. Additionally, dam construction could create social issues such as displacement and loss of livelihood of the local inhabitants during impoundment of the reservoir (Moran *et al.*, 2018).

However, the negative impacts of storage hydropower are linked to the construction of the dam's structure and not necessarily the extraction of hydropower. Furthermore, the construction of dams is often necessary in water-scarce countries, such as South Africa, to protect against water shortages. Hence, it is prudent to make full use of the opportunities at existing dams to reap the benefits of storage hydropower while minimising the negative impacts, through retrofitting. A study conducted by Bartle (2002) found that in the USA, hydropower capacity could be increased by 27% without the construction of new dams.

Fortunately, the negative environmental effects of dam construction can be remedied by mimicking the natural, pre-construction, flow regime of the river, specifically the quantity and quality of river flow by timing the releases from the dam. The standard practice is a minimum flow release, defined as a percentage of flow metrics, and the inclusion of migration paths (Renöfält *et al.*, 2010). In regards to the social impacts, the problem is more complex as the social impacts must be balanced against the benefits of improved food supply and water security.

In South Africa, hydropower has been overlooked as a power source in favour of the short term cheaper, and more abundant, coal. However, hydropower has recently been experiencing an increase in adoption under the REIPPP programme, specifically run-of-river projects in the Free State (Arnoldi, 2021).

The largest hydropower plant in South Africa is the Gariep dam with a rated capacity of 360 MW followed by the Van der Kloof dam with 240 MW (Klunne, 2021). The size of South African hydropower plants is based on their rated power capacity according to the ranges listed in Table 2-1.

Table 2-1: South African hydropower categories (Barta, 2002).

Category	Capacity
Pico	< 20 kW
Micro	20 kW - 100 kW
Mini	100 kW - 1 MW
Small	1 MW - 10 MW
Large	> 10 MW

2.3 DAMS

Dams are man-made barriers that impound the natural flow of water to create a lake or reservoir on the upstream side. In South Africa, the word dam refers to both the dam wall and the water behind it. Internationally, dam refers only to the barrier (or structure) while the impounded water body is known as a reservoir (SANCOLD, 2021).

Dams are designed to store the precipitation that falls during the wetter parts of the year, to ensure a continuous supply of water throughout the year. Dams are often multi-purpose and may provide any combination of the following uses (SANCOLD, 2021):

- Water Supply: Stored water is supplied to homes and industry.
- Irrigation: Stored water is used for irrigation of crops and water supply.
- Flood Control: High flows, that may cause damage downstream, can be stored and released in a controlled manner.
- Hydropower: Impounded water generates a large head providing an excellent opportunity for hydropower installations.
- Recreation: Stored water can be used for recreational activities such as, swimming, boating and fishing.

The volume of water stored in a dam is a function of the inflows and extractions as well as losses such as evaporation and spillage. The sequence of inflows and extractions will result in a sequence of dam levels, called a trajectory, which is bounded by a Full Supply Level (FSL) and Minimum Operating Level (MOL). FSL corresponds to the maximum volume the dam is designed to store (100% capacity), while the MOL is the level below which water can no longer be withdrawn, coinciding with the level of the release sluices or pump intakes. Therefore, the volume of water stored below the MOL is known as dead storage as it cannot be extracted. The volume stored between the MOL and FSL is known as live storage, as this is the volume that is actively extracted and replaced (Basson *et al.*, 1994).

The dam wall is designed to resist the horizontal force generated by the pressure of the water. This is accomplished through a variety of designs, such as (SANCOLD, 2021):

- Embankment dams: Embankments dams are a permeable earthen embankment with an impermeable core that resists the force of the water through the weight of the wall. Embankment dams are subdivided into earth fill and rockfill dams depending on the grain size of the material used. An example of an embankment dam is given in Figure 2-2.

Figure 2-2: Sterkfontein dam (DWS, 2021).

- Concrete gravity dams: Concrete gravity dams are concrete structures that resist the force of the water through the weight of the wall alone. An example of a concrete gravity dam is given in Figure 2-3.

Figure 2-3: Clanwilliam dam (SANCOLD, 2021).

- Buttress dams: Buttress dams are developed from gravity dams, however, less material is used by using buttresses to resists the force of the water. An example of a buttress dam is given in Figure 2-4.

Figure 2-4: Bulshoek dam (SANCOLD, 2021).

- Arch dams: Arch dams are concrete dams that are curved in the shape of an arch, to better resist the horizontal force of the water. An example of an arch dam is given in Figure 2-5.

Figure 2-5: Katse dam (LHDA, 2021).

2.3.1 Dams in South Africa

South Africa is situated in a semi-arid region of the world, with an average rainfall of about 450 mm/year. Furthermore, no large perennial river exists in the country, coupled with limited groundwater, means dams are required to provide a continuous water supply amounting to 4 457 dams registered dams (SANCOLD, 2021). The sheer number of dams is clearly illustrated in Figure 2-6, with dams owned by the DWS presented in yellow and other state-owned dams (such as the Department of Agriculture), highlighted in orange.

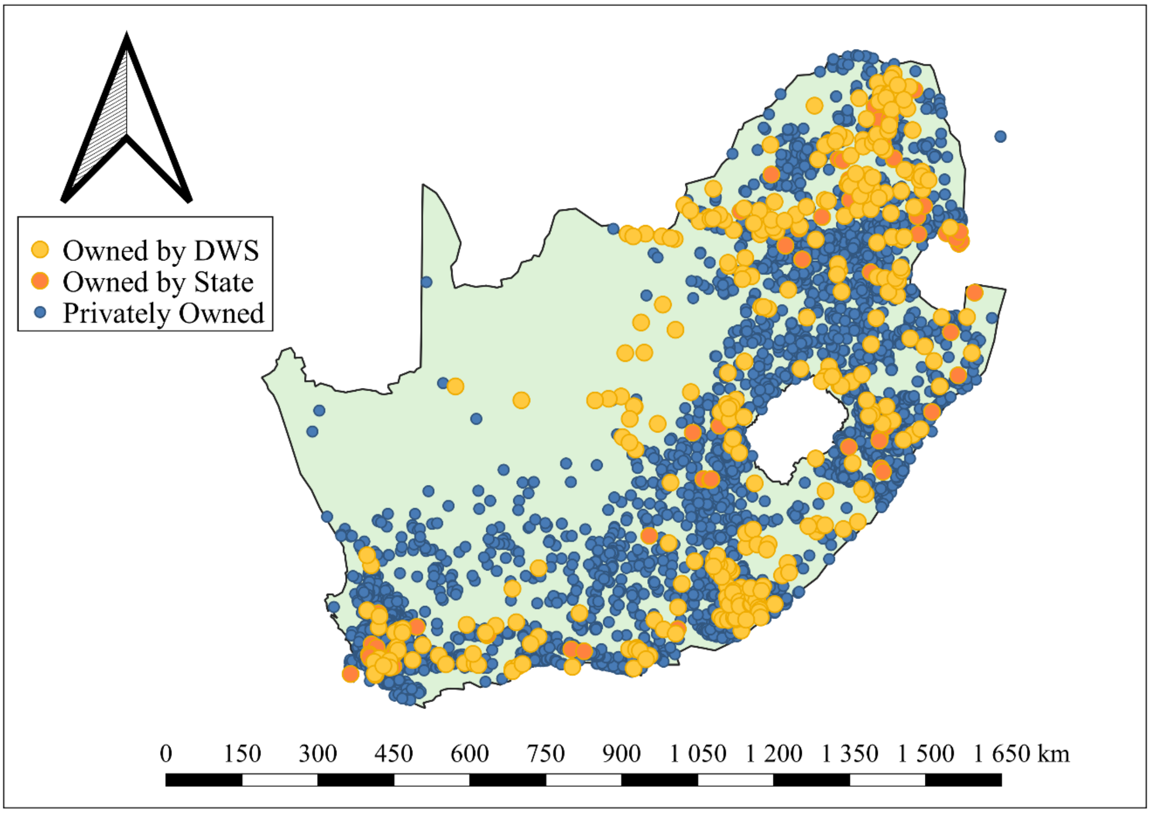


Figure 2-6: Registered South African dams.

Most of South Africa's dams were built before World War II to supply water for agriculture (Dam Safety Office, 2019). South African dams are classified by the height of the dam wall, measured from the lowest point of the foundation, as shown in Table 2-2.

Table 2-2: South African dam sizes (Van Dijk *et al.*, 2016).

Class	Count	Percentage of total (%)
Small (5 – 12 m)	3 232	73
Medium (12 – 30 m)	1 033	23
Large (> 30m)	192	4
Total	4 457	100

Although hydropower is classified based on the method of generation, it can additionally be categorised based on the head the facility operates at, as shown in Table 2-3. In the case of storage hydropower this correlates to the height of the dam wall, thus most South African dams offer low head hydropower opportunities (Loots *et al.*, 2015).

Table 2-3: Hydropower head classification (Loots *et al.*, 2015).

Classification	Head (m)
Low head	< 30 m
Medium head	30 m – 100 m
High head	> 100 m

Finally, dams in South Africa are classified into three safety categories, depending on their hazard potential, which considers the dam size, potential loss of life and the potential economic impact that may result from dam failure. These are listed in Table 2-4, with a Category I dam having the least concern for failure and a Category III, the most. In the case of Category II and III dams an Approved Professional Person (APP) must be consulted during any project that may modify the dam (SANCOLD, 1991).

Table 2-4: South African dam safety categories (SANCOLD, 1991).

Damn size	Potential loss of life		
	Low	Significant	High
Small	I	II	II
Intermediate	II	II	III
Large	III	III	III

2.3.2 Datasets and Availability

A database of every registered dam is kept by the Department of Water and Sanitation (DWS) and a database of every large dam is kept by the South African National Committee on Large Dams (SANCOLD). Additionally, the DWS's website contains verified data on South Africa's water infrastructure that is easily accessible and free to the public (Van Dijk *et al.*, 2020).

The DWS list of all the registered dams in South Africa contains the data of 323 DWS owned dams with an additional 85 dams owned by the State as well as data for the 5 228 dams not owned by the State. It should be noted that the register defines "dam" as a barrier or wall that impounds flows, as the register includes reservoirs (tanks), weirs and canals.

Data provided in the registry includes (Van Dijk *et al.*, 2020):

- Gauging station names,
- Quaternary drainage areas,
- Spillway types,
- Capacities,
- Catchment areas,
- Surface areas,
- Purpose of dams, and
- Dam owner details.

The verified data on reservoirs includes the monthly spill volume, daily average spill volume, primary flow data and corresponding level above the spillway as well as the downstream monthly volume and daily average flow (Van Dijk *et al.*, 2020).

SANCOLD's register of large dams only contains information of dams with a height of 15 m or more, from the lowest point of the foundation, or a volume of more than 3 000 000 m^3 (SANCOLD, 2021). Data provided includes the dam capacity, spillway capacity, dam wall height and the details of the owner (Van Dijk *et al.*, 2020).

2.3.3 Dams with Hydropower Installations

While South Africa may have numerous dams, only a few of its dams are fitted with hydropower generation equipment, as shown in Figure 2-7, with a total installed potential of 3 574 MW. The majority of the installed capacity at South African dams comes from its four pumped storage schemes, as listed in Table 2-5, which are supported by conventional storage facilities, as listed in Table 2-6.

The Steenbras pumped storage scheme, owned and operated by the City of Cape Town, exemplifies the benefits of local hydropower generation as it used to supplement the city's power supply while the national grid is incapable of doing so. This is done by timing the releases from the upper dam, which could be mimicked by conventional storage schemes.

Table 2-5: South African pumped storage schemes (Barta, 2017).

Scheme	Dams	Power (MW)
Drakensberg	Sterkfontein (Driekloof)	1 000
	Kilburn	
Ingula	Bedford	1 330
	Bramhoek	
Palmiet	Rockview	400
	Kogelberg	
Steenbras	Steenbras upper	180
	Steenbras lower	
Total		2 910

Table 2-6: South African storage schemes (Van Vuuren *et al.*, 2011; Barta, 2017).

Dam	Power (MW)
Collywobbles (Mbashe)	42
First falls	6
Gariep	360
Ncora	2
Second falls	11
Sol Plaatjie	3
Vanderkloof	240
Total	664

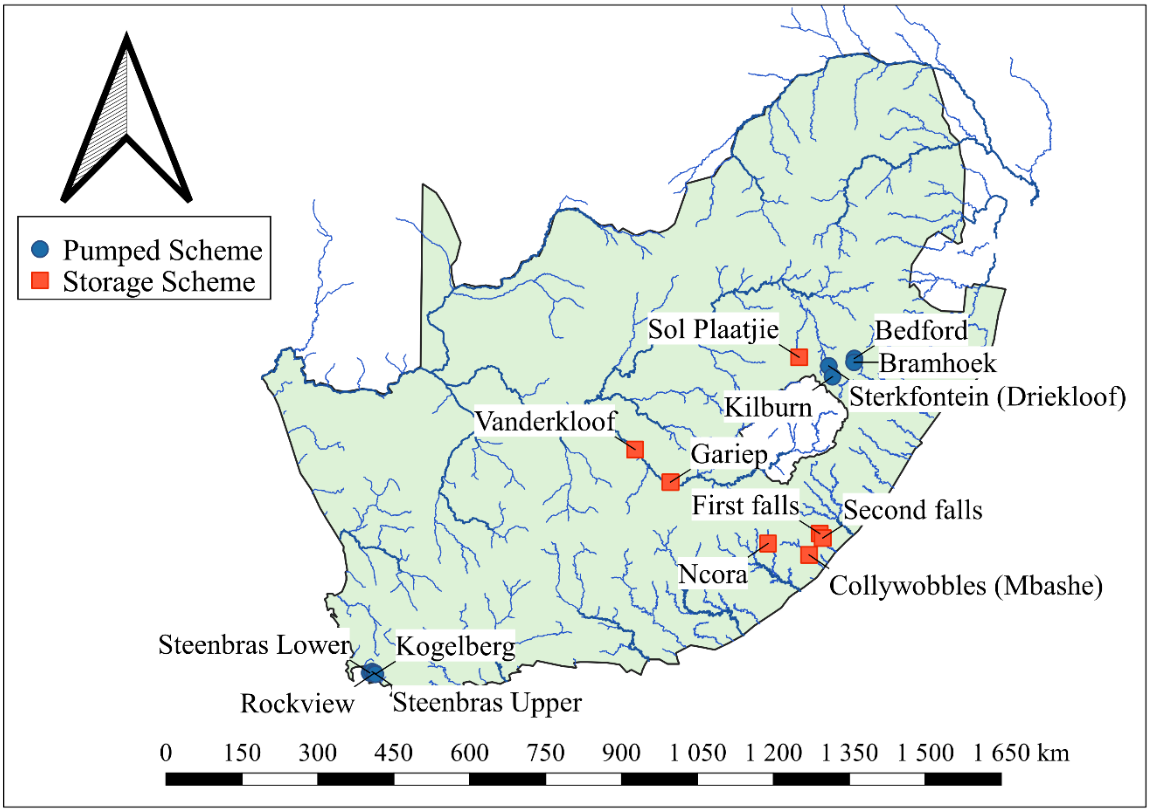


Figure 2-7: Dams with hydropower generation installations.

2.4 COMPONENTS OF A STORAGE HYDROPOWER SCHEME

A typical storage hydropower scheme consists of the components listed below, with an illustration provided in Figure 2-8. Special attention will be given to turbines and electromechanical equipment in subsequent sections as these components will have the greatest impact on retrofit hydropower evaluation (Van Dijk *et al.*, 2016):

- Dam: As explained in Chapter 2.3, a dam is used to store water and generate a head. A dam may include an emergency spillway, which prevents overtopping of sensitive embankments and migratory paths that allow aquatic fauna to pass through the obstruction caused by the dam.
- Intake: The intake is the entry point of water into the conveyance system leading to the turbine. Intakes are typically fitted with a gate or valve to control the amount of water entering the system. Trash racks and de-silting channels may prevent debris and sediment from entering the system reducing maintenance and preventing breakdowns.
- Penstock: The penstock is a system of pipes that conveys water to the turbine(s). A penstock is normally gravity-fed and cast into the dam, however in the case of retrofitting, the penstock can be fitted over the dam wall and fed by creating a siphon

using external pumps or retrofitted to environmental outlets. Penstocks can be constructed from any typical pipe material, provided that the pressure class is sufficient for the expected pressure. Design considerations include coating, lining, joining, thrust blocks and surge.

- Powerhouse: The powerhouse is a structure that supports the turbine and electromechanical equipment and protects them from theft, vandalism and the weather. Powerhouses should be designed to provide sufficient size for easy maintenance and further expansion with design considerations including flooding, buoyancy forces and thrust forces on the structure due to surge.

- Tailrace: The tailrace is used to convey water from the turbine back to the river through a pipe or canal. If the powerhouse is close to the river, direct transfer is possible. However, consideration must be given to the exit velocity of the water that may require protection, such as aprons, rip-rap or gabions, to prevent erosion.

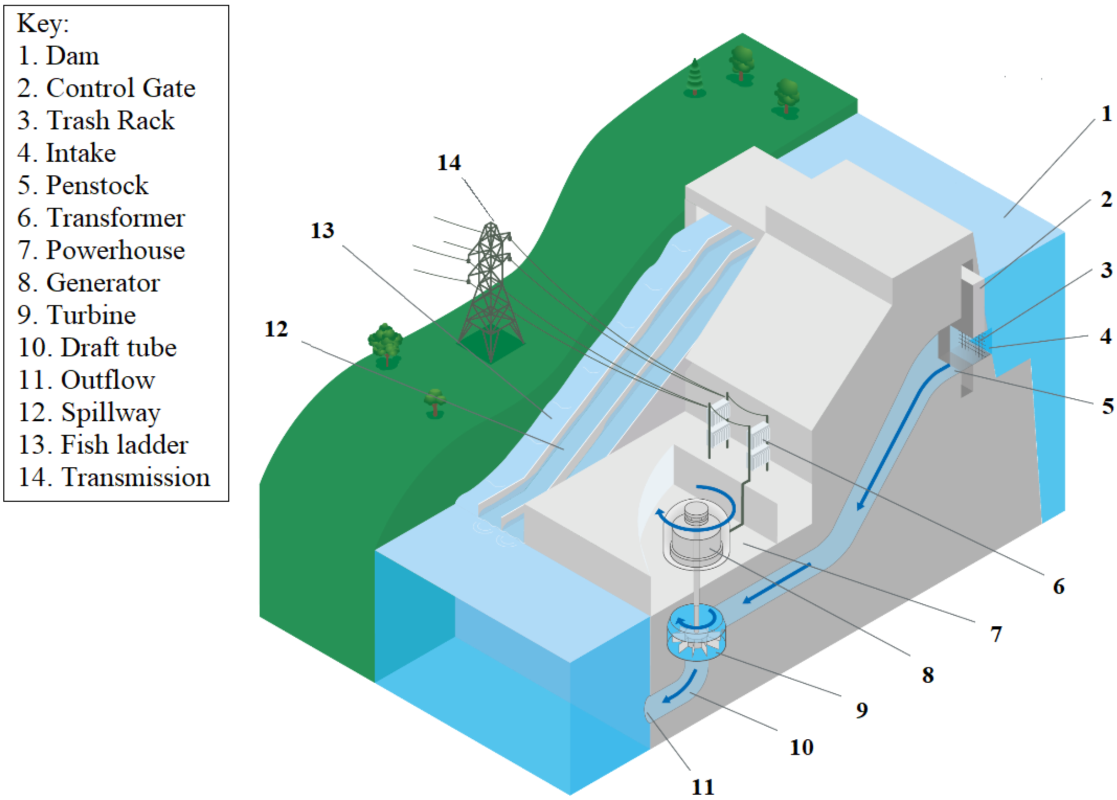


Figure 2-8: Hydropower scheme components (IHA, 2020).

2.5 TURBINES

A turbine is a mechanical device that converts the energy of moving water into mechanical power. It is the core component of a hydropower scheme and can be categorized into two groups, impulse and reaction turbines. The distinction between the two is dependent on how the runner, the rotating element of the turbine, operates.

Impulse turbines operate by directing a jet of water onto the runner thus causing rotation, while reaction turbines are fully immersed in water and use hydrodynamic forces to generate lift on the runner, causing rotation and are generally used in high head applications (Loots *et al.*, 2015).

In impulse turbines the runner is not submerged in water, and this provides unique benefits, such as high sediment tolerance, easy access and maintenance, and lower costs. According to Berrada *et al.* (2019) these benefits make impulse turbines well suited to Micro and Pico hydropower installations, such as rural electrification projects. Impulse turbines include the Pelton, Turgo and crossflow also known as Banki-Michell turbines.

Reaction turbines are designed to operate at a set flow rate, as the runner is fully submerged in water and under pressure. Thus, they are sensitive to flow rate variations and suspended sediment, which can greatly reduce their efficiency and cause issues such as cavitation and/or surge. This makes reaction turbines more costly than impulse turbines (Loots *et al.*, 2015). Reaction turbines include the Francis and Kaplan turbines as well as modified pumps as turbines.

Turbine selection is dependent on the expected head and flow at the site. Penche & de Minas (1998) used operational envelopes for turbine selection, as shown in Figure 2-9, while Natural Resources Canada (2004) only considered head in turbine selection, as shown in Table 2-7. It should be noted that at sites where the flow rate is highly variable, reaction turbines would not be appropriate and impulse turbines could provide greater long-term energy generation (Penche & de Minas, 1998).

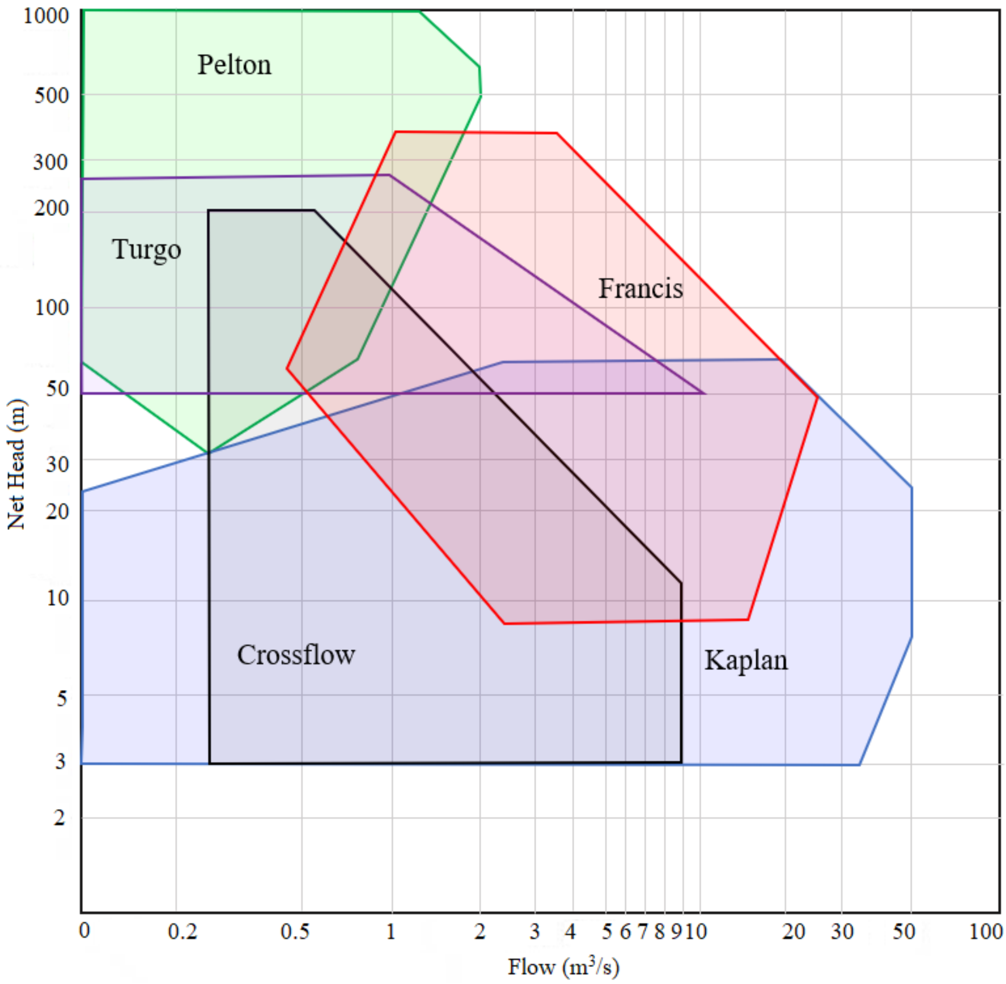


Figure 2-9: Turbine selection envelopes adapted (Penche & de Minas, 1998).

Table 2-7: Turbine selection criteria (Natural Resources Canada, 2004).

	High head	Medium head	Low head	Ultra-low head
	>100 m	20 – 100 m	5 – 20 m	< 5 m
Impulse	Pelton, Turgo	Crossflow, Multi-jet Pelton, Turgo	Crossflow, Turgo	
Reaction		Francis	Kaplan	Kaplan

Finally, the efficiency of a turbine is a function of the geometry of the turbine for a specific design head and flow. However, for an initial hydropower evaluation the dimensions of the desired turbine will not be known, therefore, extrapolated efficiencies for turbine types must be used. Table 2-8 shows general efficiencies for turbines based on the type of turbine, whilst the overall efficiency for hydropower plants can be estimated based on the size of the plant, as shown in Table 2-9.

Table 2-8: Turbine efficiencies (Van Dijk *et al.*, 2016).

Turbine type	Efficiency range (%)
Pelton	80 - 90
Turgo	80 - 95
Crossflow	65 - 95
Francis	80 - 90
Pump as Turbine (PAT)	60 - 90
Propeller	80 - 95
Kaplan	80 - 90

Table 2-9: Hydropower plant efficiencies (Van Dijk, 2021).

Rated power	Efficiency range (%)
< 20 kW	60
20 – 100 kW	60 - 70
100 – 500 kW	70 – 80
500 – 1000 kW	80 - 85
> 1000 kW	85

2.5.1 Impulse Turbines

Pelton turbines operate by directing a jet of water onto the runner, which is a set of split buckets, generating rotation. After making contact with the buckets the water then falls into the tailrace, exiting the turbine (Paish, 2002), as shown in Figure 2-10.

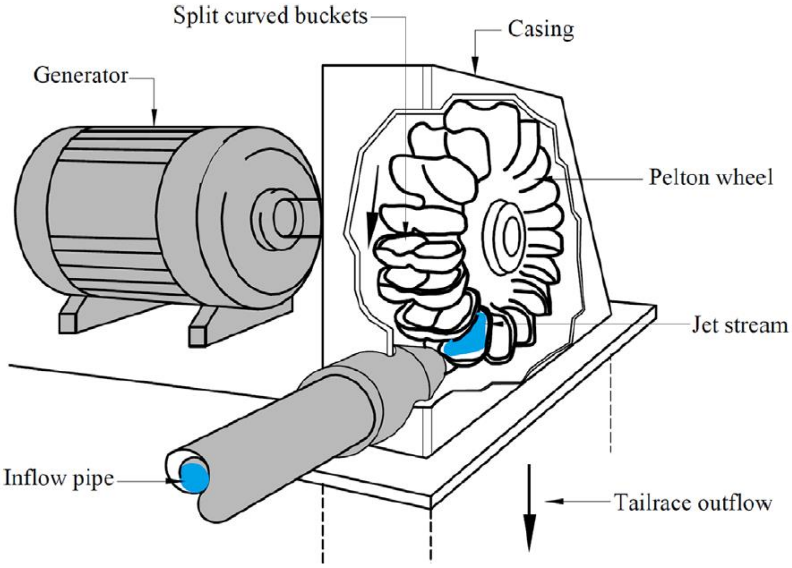


Figure 2-10: Typical Pelton turbine (Paish, 2002).

Turgo turbines are similar to Pelton turbines, however, instead of the water being deflected back towards the incoming jet, the runner guides the water to the opposite side, as shown in Figure 2-11. Thus, there is no interference between incoming and existing water. This allows a Turgo turbine to generate equivalent power to a Pelton turbine, albeit with a smaller diameter runner (Paish, 2002).

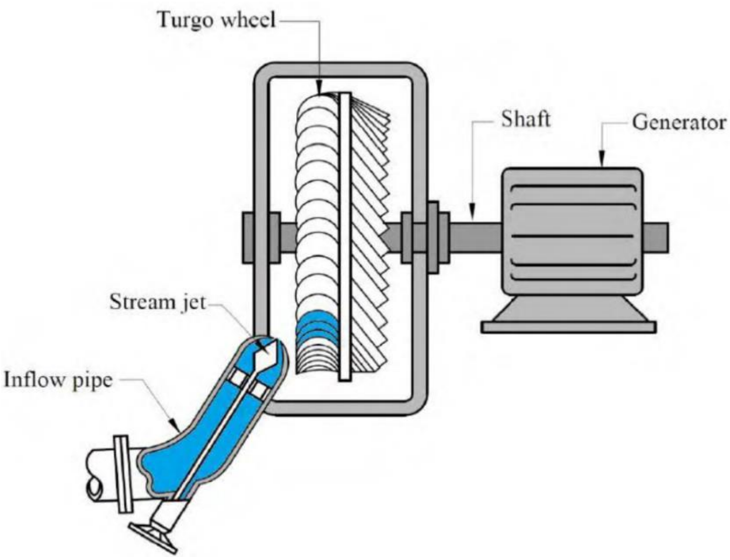


Figure 2-11: Typical Turgo turbine (Paish, 2002).

The Crossflow turbine, or Banki-Michell, has a drum-shaped runner constructed from two disks joined with inclined blades. This guides the incoming water such that it hits the runner twice, once upon entry and once when exiting the runner (Paish, 2002), as shown in Figure 2-12.

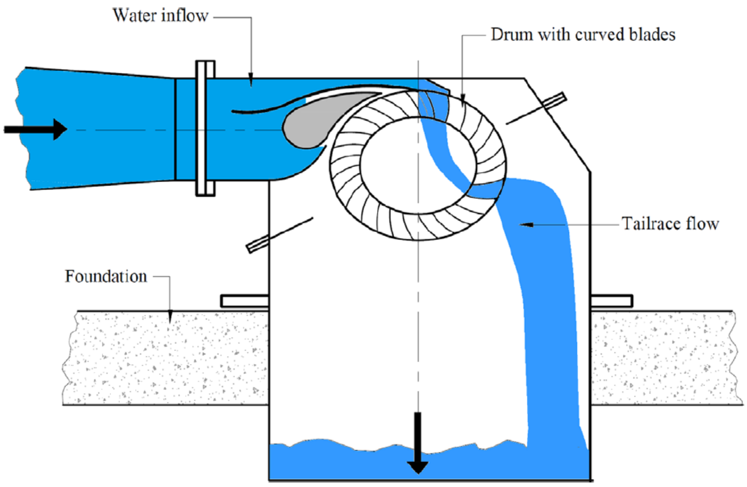


Figure 2-12: Typical crossflow turbine (Paish, 2002).

2.5.2 Reaction Turbines

Francis turbines use a spiral casing that forces the incoming water into adjustable vanes that guide the water onto the runner. The runner forces the water to flow radially inward, rotating the turbine, such that the water exists along the turbine's rotational axis (Penche & de Minas, 1998), as shown in Figure 2-13.

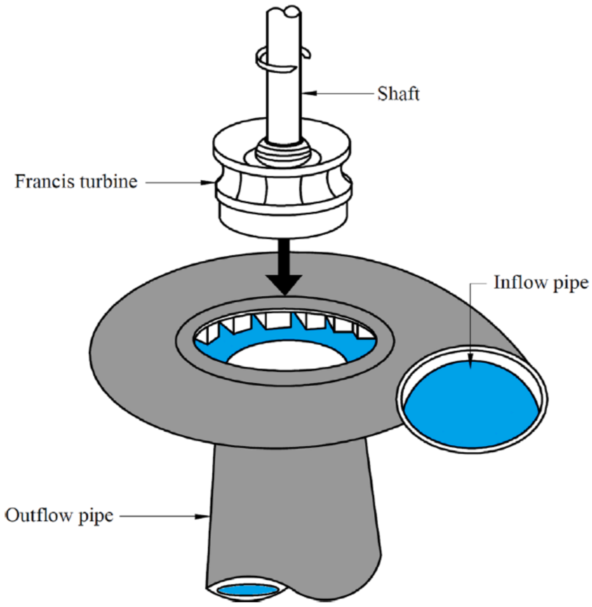


Figure 2-13: Typical Francis turbine (Paish, 2002).

Kaplan turbines act as the reverse of a ship propeller, where the turbine blades are specifically shaped to generate hydrodynamic forces, from the oncoming water, that causes the turbine to rotate (Paish, 2002), and guide vanes, upstream of the turbine, are used to ensure better efficiency (Loots *et al.*, 2015). A modified version of the Kaplan turbine, known as a siphon turbine can be used to provide an initial suction that creates a siphon over a dam wall, which passes through a turbine, which could be utilised at dams without outlet works. A typical Kaplan turbine is shown in Figure 2-14.

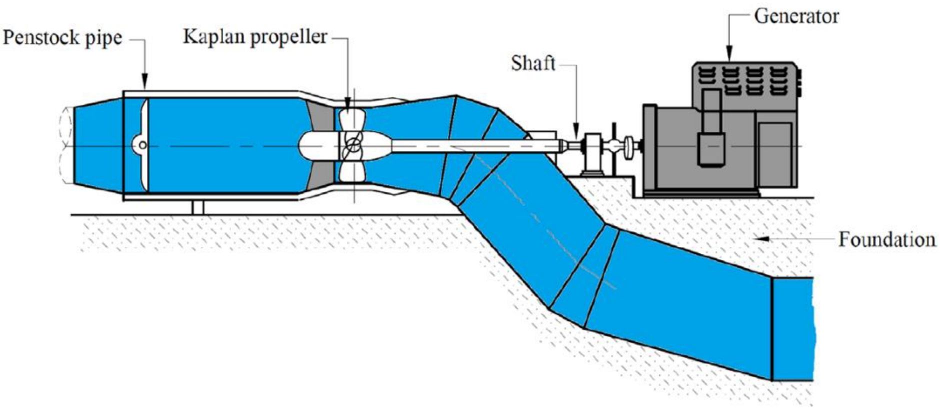


Figure 2-14: Typical Kaplan turbine (Paish, 2002).

Finally, a standard centrifugal pump can be run in reverse to act as a turbine, known as a Pump as Turbine (PAT). This is an attractive option, as pumps and parts are readily available thus are significantly cheaper than standard turbines. However, PATs are generally inefficient and are highly sensitive to variations in flow and head (Williams, 2003). An example of a PAT is shown in Figure 2-15.

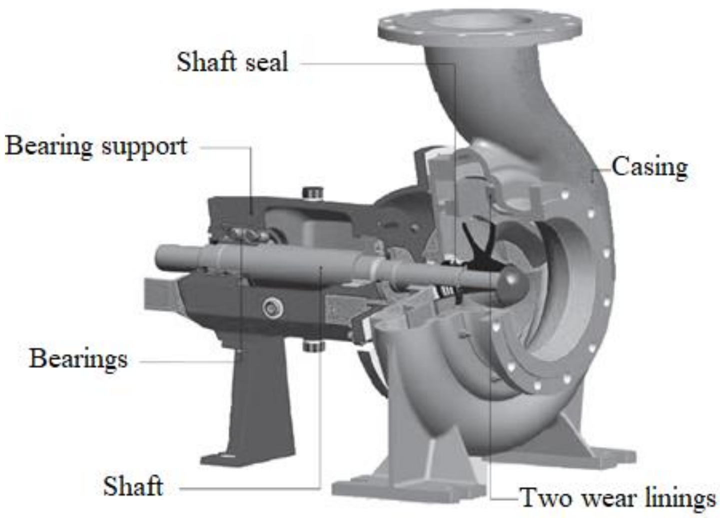


Figure 2-15: Pump as turbine (Mellacher & Fiedler, 2013).

2.6 ELECTROMECHANICAL EQUIPMENT

The electromechanical equipment of a hydropower scheme converts the mechanical torque generated by a turbine to useable electricity, the major components of which are (Penche & de Minas, 1998; Van Vuuren *et al.*, 2011):

- Generators,
- Drive systems,
- Switch gears,
- Governors, and
- Transmission systems.

2.6.1 Generators

Generators operate by taking advantage of the physical phenomena of electromagnetic induction. That is, a current can be induced in a conductor by moving it through a magnetic field. Generators are a well-developed technology and are capable of achieving high efficiencies as illustrated in Table 2-10.

Table 2-10: Generator efficiencies (ESHA, 2004).

Rated power (kW)	Efficiency (%)
10	91
50	94
100	95
250	95.5
500	96
1000	97

In generators there are two main components: a stationary set of windings, known as the stator, and a rotating set of magnets, known as the rotor. The turbine rotates the rotor, moving its magnetic field through the stator thereby creating electricity. Typically, generators have 3 sets of windings, thus creating three-phase alternating current (Penche & de Minas, 1998).

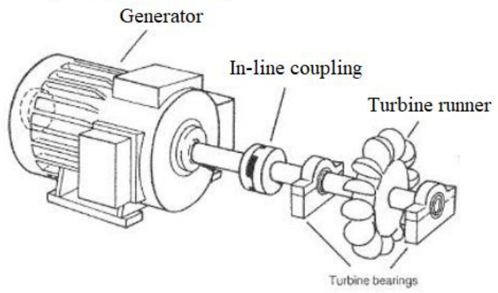
There are two main types of generators, synchronous and asynchronous, with synchronous generators being more common in power generation as asynchronous generators are usually only used in smaller systems, typically less than 5 MW (Pico, Micro and Mini) (Penche & de Minas, 1998).

2.6.2 Drive Systems

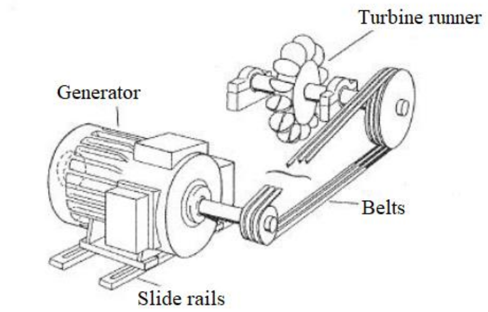
Drive systems are made from a variety of mechanisms, such as gearboxes, belts and pulleys as shown in Table 2-11. Drive systems transmit power from the turbine to the generator shaft at the correct speed (Van Dijk *et al.*, 2016).

Table 2-11: Driver systems options (Harvey *et al.*, 1993).

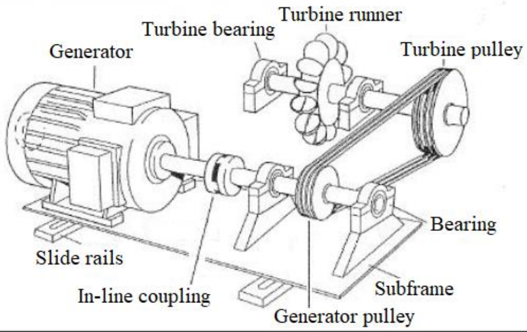
Direct coupled drive system



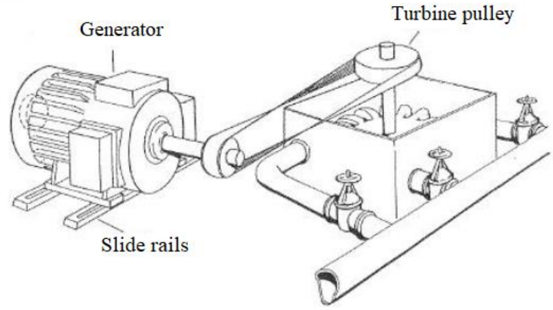
Wedge belt drive system



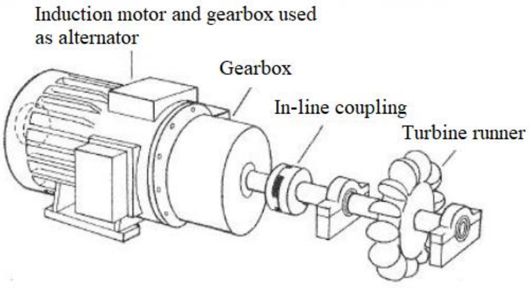
Wedge belt drive system with extra bearings



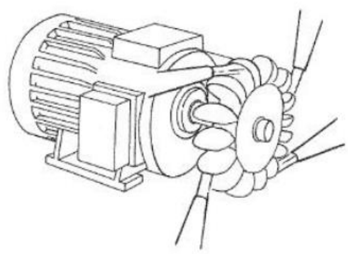
Quarter turn belt drive



Direct coupled turbine and geared motor used as alternator



Turbine rotor mounted on generator shaft



2.6.3 Switch Gear

Switchgear is the name given to the components that are used to control and transfer power from the generators. It functions as a large-scale distribution board and contains devices such as switches, circuit breakers and measuring and protection devices (Klingenberg, 2018).

Switchgear must be installed to safely isolate the generators and to interface them with a grid or an isolated load (Penche & de Minas, 1998).

2.6.4 Governors

Governors are used to control the speed of the turbine. This is critical to efficient operation as turbines are designed for a certain net head and flow, and deviations from these will result in reduced efficiency (Penche & de Minas, 1998).

The two most common forms of governors are (Penche & de Minas, 1998):

- Speed Governors operate by measuring and adjusting the flow of water to the turbine by opening and closing the inlet gate, either through electronics or mechanical means.
- Load Governors operate by measuring and adjusting the electronic load on the turbine to maintain system frequency.

2.6.5 Transmission

Transmission lines are required to transmit the electricity from the powerhouse to the users. The amount of power to be transmitted and the distance to the users will determine the size and type of transmission lines (Van Dijk *et al.*, 2016). Transmission lines can be installed above or below ground and are typically high voltage AC lines, in which case a transformer may be required to generate the appropriate voltage (Klingenberg, 2018).

2.7 EVALUATION OF HYDROPOWER POTENTIAL

The theory of generating electricity using storage hydropower is a relatively simple sequence of power conversions. It begins with the potential energy of the impounded water which is converted to a measure of power by examining the rate of change of the potential energy. In the case of water this is done by expressing the rate of change of the mass of water (flow), as illustrated in the derivation of Equation 2.1 (BHA, 2005):

$PE = mgH$

$PE = \rho VgH$

$P_H = \rho QgH$ (Equation 2.1)

Where:

PE = Potential Energy (J)

P_H = Hydraulic power (W)

m = Mass (kg)

g = Gravitational acceleration (m/s^2)

H = Net Head (m)

ρ = Density (kg/m^3)

V = Volume (m^3)

Q = Flow (m^3/s)

The hydraulic power is then converted to mechanical power through a turbine, where the efficiency of the turbine is the ratio of the power generated to the power available, as shown in Equation 2.2. The mechanical power can be used on-site however it often undergoes conversion to electrical power through a generator and further conversion to connect to the grid.

$\eta_t = \frac{P_t}{P_h}$ (Equation 2.2)

Where:

η_t = Efficiency of turbine

P_t = Power of the turbine (w)

P_h = Hydraulic power (w)

Each subsequent conversion results in further losses, due to the inefficiency of the components. Thus, the efficiency of a hydropower scheme is often given as the product of each component's efficiency (Van Vuuren *et al.*, 2011; Bortoni *et al.*, 2019). Furthermore, the density of water fluctuates with temperature according to Equation 2.3 (Bortoni *et al.*, 2019).

$$\rho = 1000.14 + 0.0094t_w - 0.0053t_w^2 \qquad \text{(Equation 2.3)}$$

Where:

t_w = Temperature of water (°C)

Thus, the potential hydropower at an existing dam is given by a simple rearrangement of Equation 2.1 that yields Equation 2.4, from which it can be seen that the two most important parameters are the flow and the net head.

$$P = \eta\rho gQH \qquad \text{(Equation 2.4)}$$

Where:

η = General efficiency

The watt-hours, or energy, produced by the plant can be calculated by simply multiplying the power calculated using Equation 2.4, by the number of hours the plant maintains that output. Assuming the plant operates at a constant power (rated power), an estimate of the annual energy output can be made by multiplying the rated power by the number of hours in a year that the plant operates. This is done with the inclusion of a load factor, or capacity factor, which accounts for downtime caused by maintenance, repairs and inoperable conditions, and is expressed as the percentage of time the plant was used compared to the total hours in a year (Van Dijk *et al.*, 2016).

2.7.1 Head

The gross head is calculated as the difference between the headwater, the elevation of water in the dam, and the tailwater, the elevation of water downstream of the dam. A maximum potential can be estimated by approximating this value to the height of the dam wall.

By subtracting headlosses from the gross head, the net head or the head across the turbine can be calculated (Bortoni *et al.*, 2019). Headlosses will result mainly from friction against the pipe wall, however local losses due to turbulence, caused by a change in pipe geometry, will also contribute to headloss. It should be noted that this method calculates the instantaneous power and does not account for the fluctuations in water level throughout the year, which will influence the expected power capacity and as such is only used for a basic first order assessment.

Friction losses can be calculated using the Darcy-Weisbach equation, Equation 2.5, with methods for approximating the pipe friction factor, λ, shown in Table 2-12 and local losses are generally expressed as a factor of the kinetic energy in the flowing water, shown in Equation 2.6 (Chadwick *et al.*, 2013):

$$h_f = \frac{\lambda L v^2}{2gD} \qquad \text{(Equation 2.5)}$$

Where:
h_f = Headloss due to friction (m)

L = Lenght of pipe (m)

v = Velocity (m/s)

D = Pipe diameter (m)

and

$$h_l = K\frac{v^2}{2g} \qquad \text{(Equation 2.6)}$$

Where:
h_l = Headloss due to local losses (m)

K = Local head loss coefficient

Table 2-12: Friction loss methods for turbulent flows (Chadwick *et al.*, 2013).

Method	λ
von Kármán - Prandtl	$\frac{1}{\sqrt{\lambda}} = 2\log\left(\frac{3.7D}{k_s}\right)$
Colebrook-White transition	$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.7D} + \frac{2.51}{Re\sqrt{\lambda}}\right)$
Barr	$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k_s}{3.7D} + \frac{5.1286}{Re^{0.89}}\right)$
Moody	$\frac{1}{\sqrt{\lambda}} = 0.0055\left(1 + \left(\frac{20000k_s}{D} + \frac{10^6}{Re})\right)^{1/3}\right)$

Table 2-12 assumes the flow to be turbulent, this assumption must be checked by calculating the Reynold’s number, as shown in Equation 2.7, and comparing to the ranges in Table 2-13 (Chadwick *et al.*, 2013).

During preliminary evaluations, the length and material of the pipe may not be known, thus headloss calculations will not be accurate. Therefore, a percentage of the gross head could be used as an estimate for the headlosses, such as 95% or 5% headloss (Chadderton & Niece, 1983).

$$Re = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{vD}{\mu} \qquad \text{(Equation 2.7)}$$

Where:

μ = Kinematic viscosity $\left(\frac{m^2}{s}\right) = 1.14*10^{-6}$

Table 2-13: Reynold’s number (Chadwick *et al.*, 2013).

Classification	Range
Laminar flow	Re < 2000
Transitional flow	2000 < Re < 4000
Turbulent flow	4000 < Re

2.7.2 Flow

The evaluation of the flow available for hydropower generation at existing dams can be done through a variety of methods, namely:

- Monthly power computations,
- Duration curve analysis, and a
- Known abstraction.

Monthly average flows as well as the difference between monthly average headwater and tailrace elevations were used by Chadderton & Niece (1983) to calculate the hydropower potential at an existing dam in the USA. This provided the average hydropower potential for each calendar month, which may give a better representation of power generation throughout the year.

Duration curve analysis is frequently used in hydropower evaluation, with Loots (2013), Bonthuys (2016) and (Van Dijk *et al.*, 2016) all making use of some form of duration curve analysis. Duration curves are used in hydropower evaluation as a single measurement of flow has little value in evaluating the long-term potential of a site. Flow duration curves relate a flow to an exceedance probability. That is, to show the likelihood that a given flow rate will be equalled or exceeded. This allows for the design flow rate to be determined for a required confidence, such as 50, 90 or 95% (Van Dijk *et al.*, 2016).

Flow duration curves are generated by ranking a historic sequence of flow records and tabulating the number of times a given flow is exceeded. This is then repeated for higher flows until the maximum recorded flow is met with an exceedance probability of 0% (Gulliver & Arndt, 1991). A typical flow duration curve is given in Figure 2-16.

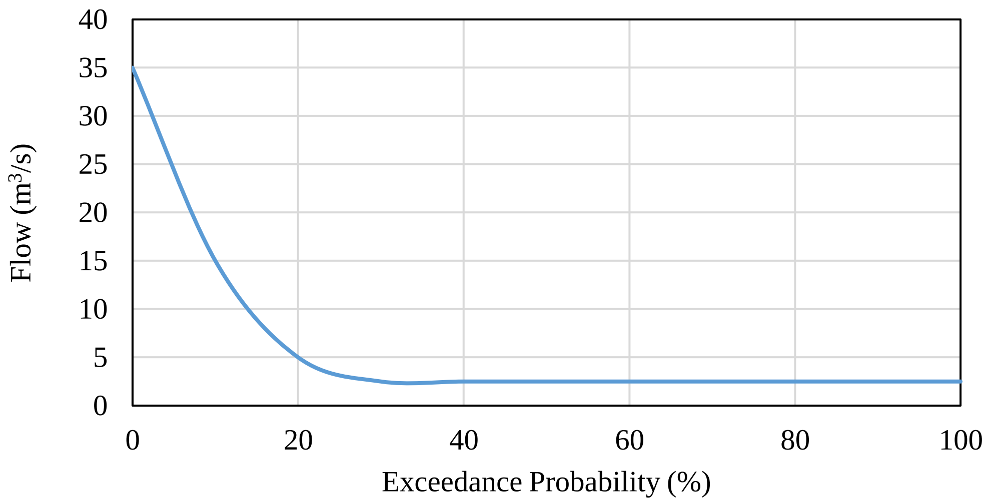


Figure 2-16: Typical flow duration curve.

Known abstractions were listed by Sule *et al.* (2018) as a hydropower evaluation method for existing dams, in which an optimisation model with an objective function of maximising the annual energy output is used to calculate the theoretical available power for a given inflow exceedance probability, subject to the constraints of irrigation, water supply and ecological releases. This method requires significantly more data than the two alternatives as values for dam abstractions must be known. Furthermore, this method, if implemented, changes the operation of the dam which conflicts with the reasoning of Chadderton & Niece (1983) that the installation of a hydropower scheme should not affect the normal operation of a dam.

2.8 FEASIBILITY CONSIDERATIONS

Hydropower potential at a site is the primary requirement for a successful hydropower scheme, however the feasibility of a site cannot be inferred from potential alone, thus this section lists the considerations that will influence the feasibility of a hydropower scheme.

The hydropower development sequence was listed by Gulliver & Arndt (1991) as follows:

- Power production screening,
- Preliminary feasibility study,
- Review of financing, environmental and regulatory considerations,
- Comprehensive feasibility study, including:
    - Hydraulic and hydrologic analysis,
    - Formulation of alternatives,
    - Cost estimates for equipment and construction,
    - Analysis of plant operation strategies,
    - Computation of expected energy production,
    - Analysis of energy value and markets,
    - Financial analysis,
    - Analysis of environmental and social impacts, and
    - Strategy development for project implementation.
- Permit applications,
- Purchase negotiations,
- Facility design,
- Construction,
- Operation.

The objective of this study was to develop a tool to evaluate hydropower potential at South African dams. Thus, only the first two points fall within the scope of this study, while the remainder should be investigated if the site is deemed feasible.

2.8.1 Environmental and Social Considerations

Retrofitting hydropower to existing dams avoids many of the environmental and social impacts traditionally associated with storage hydropower, due to most of the impacts arising from dam construction. However, the process of retrofitting will include construction and operation of mechanical equipment in and around of sensitive areas such as rivers, lakes and dams.

Therefore, the environmental impacts of constructing and operating a hydropower project need to be identified and mitigated for the project to be feasible and sustainable. Furthermore, it is important that the public benefit from the project and are not negatively affected in any way. This, while good for society, also increases public acceptance and reduces vandalism (Van Dijk *et al.*, 2016).

Van Vuuren *et al.* (2011) investigated, detailed and developed a method to evaluate the various environmental and social considerations associated with retrofitting hydropower facilities to South African dams. Both environmental and social considerations were firstly identified, after which, the importance of each issue was calculated based on factors such as the area, duration and severity.

A complete list of the environmental and social issues expected during the construction and operation of a retrofit hydropower project are listed in Table 2-14, 2-15 and 2-16. Positive social impacts were considered by Van Vuuren *et al.* (2011) separately by use of a simple checklist, to see whether the project will promote sustainable development in the surrounding region. The checklist was as follows:

- Will roads be built or upgraded that can serve the surrounding community?
- Will other types of infrastructure or services be built or upgraded to the benefit of local residents?
- Will there be potential for electricity provision in local areas from the power produced or construction of new transmission lines that could benefit the community?
- Will the project result in emission reductions?
- Will investment be stimulated in the region?
- Will jobs be created during the construction?
- Will jobs become created after the construction?

Table 2-14: Possible environmental impacts (Van Vuuren *et al.*, 2011).

Process	Affected party	Nature of impact	Minimum importance	Maximum importance
Geological	Wildlife	Noise	Insignificant	Medium
Removal of existing	Natural vegetation	Modifying natural habitat	Insignificant	Medium
Road upgrading or expansion	General public	Opportunity creation	Low	High
	Wildlife	Modifying natural habitat	Low	Very high
		Noise	Low	Very high
	Vegetation	Modifying natural habitat	Insignificant	Medium
Excavation and earthmoving	Local hydrogeology	Modifying groundwater movement	Low	Very high
	Local geology	Slope stability	Low	High
Dredging of watercourse	Aquatic habitats	Modifying natural habitat	Low	High
Temporary river diversion	Aquatic habitats	Modifying natural habitat	Low	Very high
Use of construction equipment	Wildlife	Noise	Low	High
	General public	Noise	Insignificant	Medium
Presence of humans on site	Wildlife	Noise	Insignificant	Medium
	General public	Noise	Insignificant	Medium

Table 2-15: Possible social impacts (Van Vuuren *et al.*, 2011).

Process	Affected party	Nature of impact	Minimum importance	Maximum importance
Road upgrading or expansion	Local community	Damage to cultural and historical heritage sites	Low	Very high
Excavation and earthmoving	Local community	Damage to cultural and historical heritage sites	Low	Very high
	Immediately adjacent residence	Noise	Insignificant	Medium
Dredging of watercourse	Local community	Damage to cultural and historical heritage sites	Low	High
Temporary river diversion during construction	Local community	Damage to cultural and historical heritage sites	Low	High
	Dependent farmers	Change in available flow	Low	Very high
	Community adjacent to River	Change in available flow	Low	Very high
Use of construction equipment	Immediately adjacent residence	Noise	Insignificant	Medium
	Local community	Loss of traditional values and practices	Low	Very high
Operation of electromechanical components	Immediately adjacent residence	Noise	Low	High
Permanent structures in riverbed	Local community	Loss of cultural and historical heritage sites	Low	High
	Community adjacent to river	Change in available flow	Low	Very high
	Local community	Loss of cultural and historical heritage sites	Low	High

Process	Affected party	Nature of impact	Minimum importance	Maximum importance
Permanent river diversion	Dependent farmers	Change in available flow	Low	Very high
	Community adjacent to river	Change in available flow	Low	Very high
New overhead power lines	Local community	Loss of cultural and historical heritage sites	Low	Very high
Alteration of flow rates	Community adjacent to river	Health related problems	Low	Very high
Influx of workers from other areas	Local community	Loss of traditional values and practices	Low	Very high

Table 2-16: Possible impacts during operation (Van Vuuren *et al.*, 2011).

Process	Affected party	Nature of impact	Minimum importance	Maximum importance
Generation of renewable energy	General public	Reduction of pollutants	Low	Very high
Permanent structures in riverbed	Aquatic habitats	Modifying natural habitat	Low	Very high
	General public	Negative visual impact	Low	High
Permanent river diversion	Aquatic habitats	Modifying natural habitat	Low	Very high
New overhead power lines	General public	Negative visual impact	Low	Very high
	Wildlife	Negative visual impact	Low	Very high
Alteration of flow rates	Aquatic animals	Modifying natural habitat	Low	Very high
	Vegetation	Modifying natural habitat	Low	Very high
	Farmers	Irrigation	Low	Very high
	General public	Altering recreational activity	Low	Very high
Operation of electromechanical	General public	Noise	Insignificant	Medium
	Wildlife	Noise	Insignificant	Medium

As part of the National Environmental Management Act (Act 107 of 1998) (NEMA) either an Environmental Impact Assessment (EIA) and a scoping report or a Basic Assessment Report (BAR) is required before any construction project can commence. The environmental sensitivity, as well as the scale of projects, dictates the type of assessment required and an Environmental Management Plan (EMP) may be required as part of the BAR or EIA, that addresses how the following issues will be handled (Van Dijk *et al.*, 2016):

- Integrity of existing operation regime,
- Public health and safety,
- Air quality during construction,
- Noise management during construction,
- Water quality management during and post construction,
- Waste management during construction,
- Disaster management, and
- Environmental rehabilitation.

Klingenberg (2018) provided a summary of the possible activities, related to the refurbishment or construction of a new hydropower plant, that will require either a BAR or EIA, as shown in Table 2-17.

Table 2-17: Summary of applicable activities (Klingenberg, 2018).

BAR		EIA	
Activities listed in government Notice 544 of 18th June 2010		Activities listed in government Notice 545 of 18th June 2010	
1	The construction of facilities or infrastructure for the generation of electricity where: i. The electricity output is more than 10 megawatts but less than 20 megawatts; or ii. The output is 10 megawatts or less, but the total extent of the facility covers an area in excess of 1 hectare.	1	The construction of facilities or infrastructure for the generation of electricity where the electricity output is 20 megawatts or more.

BAR		EIA	
Activities listed in government Notice 544 of 18th June 2010		Activities listed in government Notice 545 of 18th June 2010	
10	The construction of facilities or infrastructure for the transmission and distribution of electricity i. Outside urban areas or industrial complexes with a capacity of more than 32 but less than 275 kilovolts; or ii. Inside urban areas or industrial complexes with the capacity of 275 kilovolts or more.	8	The construction of facilities or infrastructure for the transmission and distribution of electricity with a capacity of 275 kilovolts or more, outside an urban area or industrial complex.
52	The expansion of facilities and infrastructure for the transfer of water from and to or between any combination of the following : i. Water catchment; ii. Water treatment works; or iii. Impoundments; Where the capacity will be increased by a 50 000 cubic meters or more per day but excluding water treatment works where water is treated for drinking purposes.	10	The construction of facilities or infrastructure for the transfer of 50 000 cubic meters or more water per day, from and to or between any combination of the following: i. Water catchment; ii. Water treatment works; or iii. Impoundments; Excluding treatment works with what is to be treated for drinking purposes
55	The expansion of the dam where: i. The highest part of the dam wall, as measured from the outside toe of the wall to the highest part of wall, was originally 5 meters or higher and where the height of the wall is increased by 2.5 meters or more; or ii. With a high-water mark of the debt will be increased with 10 hectares or more.	19	The construction of the dam, where the highest part of the dam wall, as measured from the outside toe of the wall to the highest part of the wall, is 5 meters or higher or where the high-water mark of the dam covers an area of 10 hectares or more.

2.8.2 Regulatory Considerations

The regulatory considerations of a hydropower project can be complex and can compromise the feasibility of a project. Thus, all the regulatory considerations for a project must be identified in advance and completed. Firstly, to avoid misinterpretations, an understanding of the definitions pertinent to hydropower development are given in Table 2-18.

Table 2-18: South African regulatory definitions (Van Dijk *et al.*, 2020).

Term	Definition
Generator	A legal entity who generates electricity by any means.
Embedded generator	A legal entity that operates a generating plant that is or will be connected to the national distribution network.
Independent Power Producer (IPP)	A legal entity that operates a generating plant in which the government, or any organ of the state, does not hold a controlling ownership.
Own use	Electricity generation that is used only by the operator or owner of the facility. (Can be grid connected).
Islanded use	Electricity generation that is completely independent of either national or municipal distribution networks.

The following licences or legislative assessments may be required for the construction and implementation of a small-scale hydropower plant.

- NERSA licensing or registration,
- Water use licensing or general authorisation, or an
- EIA or BAR.

<u>NERSA licensing</u>

The regulations and procedures for obtaining NERSA licensing are outlined in the Energy Regulation Act (Section 8 of Act 4, 2006) which stipulates that an electricity generation licence is required for any of the following activities (Klingenberg, 2018; Van Dijk *et al.*, 2020; Engineering News, 2021):

- Operate any generation transmission or distribution facility.
- Import or export any electricity or,
- Be involved in the trading of electricity.

With the exceptions of:

- Any plant constructed and operated for demonstration purposes only and not connected to an interconnected power supply.
- Any generation plant constructed and operated for own use.
- Non-grid connected supply of electricity except for commercial use.
- Own use generators if the generation capacity is less than 100 MW.

In which case only registering with NERSA will be required.

Water-use licence

The regulations and procedures for water-use licensing are stipulated in the National Water Act (Act 36 of 1998). Water use licences are required in the following cases (Klingenberg, 2018; Scharfetter & Van Dijk, 2017):

- Taking water from a water resource,
- Storing water,
- Impeding or diverting the flow of water in a water course,
- Engaging in a stream flow reduction activity,
- Discharging waste, or water containing waste, into a water resource through a pipe, canal, sewer, sea outfall or other conduit,
- Disposing of waste in a manner which may detrimentally impact a water resource,
- Disposing in any manner of water which contains waste from, or which has been heated in any industrial power generation process,
- Using water for recreational purposes,
- Altering the bed, banks, course or characteristics of a watercourse, or
- A power generation activity which alters the flow regime of a water resource.

However, in section 22 of act 36 (1998), an exception is made whereby a water-use licence is not required if the use is an extension of an existing lawful use, i.e., a licence is already held. Furthermore, small scale, non-grid connected hydropower plants between 10 and 300 kW will only require general authorisation (Klingenberg, 2018).

2.8.3 Financial Considerations

The financial feasibility of a hydropower project can be determined by first quantifying the expected life cycle costs of the project and comparing these to the potential income. Methods of comparison are separated into either static or dynamic methods, as shown in Table 2-19.

Table 2-19: Financial analysis methods (Penche & de Minas, 1998).

Static methods		
Method	Formula	Determines
Payback method	$Period = \frac{Initial\ investment}{Annual\ income}$	Number of years until invested capital has been returned
Return on Investment (ROI)	$ROI = \frac{Annual\ income}{Initial\ investment} * 100$	The income generated as a percentage of the initial investment
Dynamic methods		
Method	Formula	Determines
Net Present Value (NPV)	$NPV = PV(Benefits) - PV(Costs)$	The difference between the present value of benefits and the present value of costs.
Benefit-Cost ratio (BC)	$BC = \frac{PV(Benefits)}{PV(Costs)}$	The ratio of the present value of benefits to the present value of costs. The ratio must exceed 1 to be viable.
Internal rate of return (IRR)	Iterative variation of discount rate such that NPV or BC returns 0 or 1, respectively.	The discount rate at which the present value of benefits equals the present value of costs.
Levelized Cost Of Energy (LCOE)	$LCOE = \frac{PV(Costs)}{Lifetime\ energy\ output}$	The average cost for a unit of energy produced.

The static methods provide an easily understandable value that may be beneficial in negotiations and presentations. However, they fail to account for the time value of money and thus are not accurate for projects lasting longer than a few years. The dynamic methods are more accurate but require further detail, including, the expected life of the infrastructure, listed in Table 2-20, the discount and interest rates as well as an estimate of the benefits and costs.

The Levelized Cost Of Energy (LCOE) is commonly used to compare different methods of electricity generation as it represents the cost of producing a single unit of energy (ZAR/kWh). This allows for direct comparison between sources such as coal, gas, wind, solar and hydropower, with typical ranges provided in Table 2-21 Shen *et al.* (2020) with a conversion rate of 15 ZAR/USD and 17 ZAR/Euro.

Table 2-20: Expected life of hydropower scheme assets (Van Vuuren *et al.*, 2014).

Asset	Expected useful life (Years)
Dams/weirs	50 - 100
Buildings	50
Access roads	20
Turbines	25
Valves	45
Penstocks (Steel)	50
Generators	20
Transformers	20
Transmission lines	30
Electrical controls	15
Telemetry	15
Security components	10

Table 2-21: Levelized cost of energy (Ram *et al.*, 2018; IEA, 2020; Shen *et al.*, 2020).

Generation type	Global aggregates		South African aggregates	
	LCOE ($/kWh)	LCOE (ZAR/kWh)	LCOE (€/kWh)	LCOE (ZAR/kWh)
Solar PV	0.09-0.199	1.35-2.985	0.070 – 0.115	1.19 – 1.955
Solar thermal	0.12-0.452	1.8-6.78	-	-
Onshore wind	0.04-0.115	0.6-1.725	0.075	1.275
Offshore wind	0.08-0.258	1.2-3.87	0.13	2.21
Hydropower	0.07-0.109*	1.05-1.635*	-	-
Biomass	0.09-0.144	1.35-2.16	-	-
Geothermal	0.08-0.098	1.2-1.47	-	-
Wave	0.562	8.43	-	-
Tidal	0.479	7.185	-	-
Coal	-	-	0.047	0.799

*LCOE for hydropower does not distinguish between types and it is assumed retrofitting would be cheaper than conventional hydropower installations.

Van Vuuren *et al.* (2011) investigated and detailed the various costs associated with retrofitting hydropower facilities to South African dams, noting that the following costs may be incurred:

- Planning costs, including licence fees and preparation costs,
- Connection fees,
- Construction costs,
- Operation and maintenance costs, and
- Water usage costs.

Planning costs include all costs that may be incurred during the planning phase of the project (pre-construction). This includes costs for studies and negotiations, design fees, legislative fees and environmental and social assessment costs. Table 2-22 provides an estimate for the separate costs that make up the planning costs, including, negotiations fees with the dam owner and the preparation of documents for a water use licence from the DWS and a generation licence from NERSA.

Additionally, and of particular importance to the costing of a hydropower project is the cost of the transmission lines. Local or on-site use may not require a significant investment. However, if the site is remote the significance of transmissive lines is greatly increased (Van Dijk *et al.*, 2016).

Table 2-22: Estimated planning costs (Van Vuuren *et al.*, 2011).

Authority	Reason	Cost (ZAR)
Dam Owner	Permission to use the dam for power generation.	10 000
DWA (DWS)	Water use licence.	50 000
NERSA	Electricity generation licence	20 000
Buyer (Eskom)	Power purchase agreement	10 000
DEA	BAR/EIA	200 000
	EIA	1 000 000

Construction costs will include the civil works and electromechanical equipment costs. The cost of civil works is typically country dependant, while the cost of electromechanical equipment follows world market prices. Because of this, Cavazzini *et al.* (2016) stated that the cost of civil works cannot be estimated through a generic formula and thus are not included in preliminary analyses.

This contradicts the findings of Van Vuuren *et al.* (2011) who found that costing functions developed by Saini & Singal (2008) from Indian hydropower projects, accurately predicted the costs of a retrofit project in South Africa. Table 2-23 lists the costing functions converted to ZAR in 2011.

Table 2-23: Civil works costing functions (Saini & Singal, 2008; Van Vuuren *et al.*, 2011).

Component	Cost (R/KW)
Intake	$C_1 = 2792(10^{-3}P)^{-0.2368}H^{-0.0598}$
Penstock	$C_2 = 952(10^{-3}P)^{-0.3722}H^{0.3866}$
Powerhouse	$C_3 = 12084(10^{-3}P)^{-0.2354}H^{-0.0587}$
Tail-race	$C_4 = 5468(10^{-3}P)^{-0.376}H^{-0.624}$
Total	$C_{CW} = 1.13(C_1 + C_2 + C_3 + C_4)$

Instead Cavazzini *et al.* (2016) argued that in the case of retrofit hydropower the cost of the electromechanical equipment will be the main investment cost. Thus, they proposed an aggregate model that could predict the total cost of a project as a function of power and head.

This method of cost estimation has been used frequently with several studies being conducted on it, with the general form of the model being first proposed by Gordon & Penman (1979) as Equation 2.8:

$$C = aP^bH^C \qquad \text{(Equation 2.8)}$$

Where:
C = Costs

P = Power

a, b, c = Coefficients

In which the coefficients are derived from statistical analysis of available datasets. This idea was finalised by Ogayar & Vidal (2009) who noted that the cost of the electromechanical equipment is heavily dependent on the type of turbine. As such, Equation 2.8 was separated into three models for Pelton, Francis and Kaplan turbines respectively.

Cavazzini *et al.* (2016) extended the model of Ogayar & Vidal (2009) to be a function of power, head and flow. The model, as shown in Equation 2.9 and Table 2-24, was slightly more accurate than that of Ogayar & Vidal (2009), with mean errors of 9.2%, 9.8% and 18.2% for Pelton, Francis and Kaplan installations respectively.

$C = aH^b + cQ^d + eP^f + g$ (Equation 2.9)

Where:

C = Costs (€, 2016)

H = Net head (m)

Q = Design flow rate (l/s)

P = Design power (kW)

a, b, c, d, e, f and g = Coefficients

Table 2-24: Coefficients per turbine (Cavazzini *et al.*, 2016).

	Pelton	Francis	Kaplan
a	1358677.67	190.37	139318.161
b	0.014	1.27963	0.02156
c	8489.85	1441610.56	0.06372
d	0.515	0.03064	1.45636
e	3382.1	9.62402	155227.37
f	0.416	1.28487	0.11053
g	-1479160.63	-1621571.28	-302038.27

The latest addition to the topic of hydropower costing functions was conducted by Filho *et al.* (2017), in which the total cost of a project was estimated to be a function of the aspect factor of a turbine. The aspect factor is a unit derived from the specific speed of the turbine, which in turn is a function of the rated head and power. The model performed worse than both Ogayar & Vidal (2009) and Cavazzini *et al.* (2016) with a mean error of 21.33% compared to real world installations.

Operation and maintenance costs are an important part of the annual cost of a hydropower plant. These costs are generally expressed as a percentage of the total cost of works associated with that component. Bonthuys (2016), provided the most comprehensive list for the South African context based on industry standards, as listed in Table 2-25.

Table 2-25: Annual operation and maintenance costs (Bonthuys, 2016).

Component	Percentage of cost
Civil works	0.25% of Civil costs
Transmission	0.8% of Transmission costs
Operation	0.4% of Total costs, excl. planning costs
Insurance	0.3% of Total costs, excl. planning costs
Electromechanical	2.0% of Electromechanical costs

Furthermore, a water usage tariff will be due to the DWS for hydropower generation exceeding 1 MW and up to 20 MW. Costs will include an annual fixed cost and a variable cost per kWh produced, as shown in Table 2-26. In the case of plants exceeding 20 MW, rates must be negotiated with the DWS while plants less than 1 MW are exempt from charges (DWS, 2015a).

Table 2-26: Water use tariffs (DWS, 2015a).

	Hydropower plant integrated within DWS's infrastructure at the dam.	Hydropower plant developed downstream of DWS infrastructure and downstream of dam wall.
Fixed	R10.00/kW per annum	R5.00/kW per annum
Variable	R0.01/kWh	R0.01/kWh

Once the costs of a hydropower project have been calculated the financial benefits can simply be estimated based on the expected price of electricity. The price of electricity should be competitive, thus Eskom's listed tariffs can be used to estimate income. Table 2-27 includes the tariffs for Eskom's Ruraflex package as this was believed to be most appropriate and the times for Peak, Standard and Off-peak are given in Table 2-28 as P, S and O respectively.

Table 2-27: Ruraflex Gen (Non-local authority) tariffs (Eskom, 2021).

Average active energy charge (c/kWh) Vat incl.					
High demand season (Jun-Aug).			Low demand season (Sep-May)		
Peak	Standard	Off-peak	Peak	Standard	Off-peak
501.98	152.07	82.59	163.75	112.69	71.5

Table 2-28: Peak/Standard/Off-peak weekday timing (Eskom, 2021).

Demand	AM												PM											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
High	O	O	O	O	O	P	P	P	S	S	S	S	S	S	S	S	P	P	S	S	S	O	O	O
Low	O	O	O	O	O	S	P	P	P	S	S	S	S	S	S	S	S	P	P	S	S	O	O	O

2.9 HYDROPOWER DEVELOPMENT TOOLS

In this section an overview of current hydropower development tools will be given. Doing so will illustrate common aspects used in the development of tools and aid in the development of a tool that is capable of meeting the objective of the research.

2.9.1 Hydropower Retrofitting Model

Van Vuuren *et al.* (2011) developed the Hydropower Retrofitting Model (HRM) which can be used in the initial phases of a project to determine feasibility. The model does not generate a design but rather ascertains financial, environmental and social feasibility at a pre-feasibility level.

The model performs a basic power evaluation based on the inputs of MOL, FSL, minimum and maximum flows as well as the daily operational hours. A suitable turbine is automatically selected based on the inputs and the costs are estimated using costing functions, with the following rates:

- Contingencies of 10% to 15% of the cost of civil works.
- Preliminary costs of 25% of civil works costs.
- Insurance costs of 0.15% to 0.25% of civil and mechanical costs.
- Operation and maintenance cost based on industry standards.

The potential income is then calculated and a final recommendation is given by considering the sections of environmental, social and financial viability. The project is deemed viable so long as all of the following criteria are met:

- None of the environmental impacts have a rating of very high.
- Less than half of the environmental impacts have a rating of high.
- None of the social impacts have a rating of very high.
- Less than half of the social impacts have a rating of high.
- The IRR of the project is greater than 10%.

2.9.2 Conduit Hydropower Development Tool

Developed by Loots (2013), the Conduit Hydropower Development Tool (CHDT) starts as a series of flow diagrams that guide the user through the relevant factors of conduit hydropower assessment, including hydropower potential, financial, environmental and social and regulatory considerations. The tool is used in conjunction with a spreadsheet which performs the relevant calculations. The tool consists of three phases, with each containing its own flow diagram:

- First phase: Pre-feasibility
- Second phase: Feasibility
- Third phase: Detailed Design

A modification of the CHDT was developed by Van Dijk *et al.* (2016) that simplifies and broadens the tool to all hydropower types, known as the Low Head Hydropower Assessment Model.

2.9.3 Hydropower Development Assistance Tool

Klingenberg (2018) developed the Hydropower Development Assistance Tool (HDAT) which supports the evaluation of existing or decommissioned hydropower plants in South Africa, to either refurbish, renew or replace.

The model is implemented over three stages:

- Criteria based assessment which scores the infrastructure of a site to estimate the overall condition of the site.
- Plant assessment of non-quantifiable criteria such as run to failure period, automated failure analysis, hydropower potential and power demands.
- Financial evaluation which performs a life cycle costing analysis.

2.9.4 Hydro Help

Hydro Help is a spreadsheet-based tool that aids in the initial assessment and selection of a turbine for a hydropower site. The tool selects a turbine based on a database of operating envelopes of commercially available turbines greater than 1 MW. The tool is also capable of estimating the costs of the related infrastructure of the turbine installation, such as crane capacity and concrete quantity (IEA, 2008).

2.9.5 RET Screen

Renewable Energy Technology (RET) Screen Clean Energy Project Analysis is a spreadsheet-based software, developed and distributed by the Government of Canada. The software can evaluate the technical and financial viability of various types of renewable energy solutions such as solar, wind, hydro and biomass, as well as combinations of these. The analysis is conducted in five steps including an energy model, cost analysis, submission analysis, financial analysis and sensitivity and risk analysis (IEA, 2008).

2.9.6 Peach

PEACH is a decision-making tool that can be purchased from the French consulting firm ISL of Paris and Montpelier. The tool is a preliminary analysis tool that assesses the potentials, dimensions and economic and financial viability of a hydropower project (ISL, 2021).

2.9.7 USBR

The United States Department of the Interior Bureau of Reclamation (USBR) developed a tool to assess hydropower potential at dams. The tool is used for preliminary hydropower potential evaluation and uses a cost function to determine the benefit-cost ratio and internal rate of return of the project. The tool requires the following, continuous flow, defined head and tailwater levels and the distance to transmission lines (USBR, 2011).

2.9.8 Plant Cost Estimator

Plant cost estimator is a spreadsheet-based tool developed by the U.S. Department of Energy. The tool is applicable to conventional hydropower plants and estimates the costs of development as well as operation and maintenance. The tool is applicable to new sites, existing dams without generation facilities and to the expansion of existing dams with generation facilities (Hall *et al.*, 2003).

2.9.9 HPP-Design

HPP-design is an online service which determines and sizes an optimal turbine using a given head and flow. The tool is used for the preliminary design of a hydropower plant to minimise losses and optimise energy yield. The tool offers 50 free sizings up to power rating of 50 kW, after which clients may purchase additional sizings (HPP-Design, 2021).

2.9.10 Summary

This section illustrates that numerous hydropower tools have been developed and are available for commercial use. New tools are developed to accommodate new findings from literature or include functions and considerations other tools have failed to include, such as co-generation with other RET or expansion of construction costs.

Commonly, the tools estimate a potential for the site based on the available combination of head and flows, recommend a turbine type and perform a financial assessment. However, most of these tools were not designed for retrofit hydropower evaluation in the South African context, with the exception of the Hydropower Retrofitting Model (HRM), in which, the methodology used to estimate hydropower potential was basic and can be improved.

2.10 CASE STUDIES

In this section, case studies of retrofit hydropower evaluations at South African dams will be detailed. Firstly, Van Vuuren *et al.* (2011) applied the HRM to two dams: a) Sol Plaatjie, which has been retrofitted and b) the Vaal dam, which has been subject to previous estimations. Secondly Ottermann & Barta (2012) evaluated the hydropower potential of the Hartbeespoort dam and finally, two separate studies were conducted that evaluated the hydropower potential of South Africa as a whole.

2.10.1 Sol Plaatjie Dam

The evaluation of Sol Plaatjie was conducted by Van Vuuren *et al.* (2011), who used the difference between the FSL and Tail Water Level (TWL) as the head (11.46 m) and the average flow (27 m^3/s) as inputs. In hydropower estimation flow is not normally fixed, however the model recommended a 3.2 MW Kaplan turbine which correlated well to the actual installation that used a similar size Kaplan turbine with an error of 7%. However, the cost estimate was 18 million rand larger than that of the actual installation. Van Vuuren *et al.* (2011) stated that this was due to the HRM using a costing function derived from European suppliers while the actual installation used an Indian sourced turbine. Finally, both the civil works costs and annual operation and maintenance costs correlated well to the actual values with an error of 7.4 % and 9% respectively.

In regard to a financial evaluation, the site was deemed feasible with an IRR of 10.87%, which compared well to the real value of 11.4%. Table 2-29 provides a full breakdown of the costs estimated for the project.

2.10.2 Vaal Dam

The Vaal dam was also evaluated by Van Vuuren *et al.* (2011) due to its importance in the South African water supply system. The head was calculated using the difference between the FSL and TWL levels (33 m) and a minimum and maximum flow of 12.5 m^3/s and 20 m^3/s were used respectively. The model recommended a Kaplan turbine with a minimum and maximum power rating of 2.54 MW and 5.83 MW, respectively. This aligned well with a previous estimation made in the Vaal hydro report, furthermore the financial analysis yielded a similar IRR of 18.11% compared to the real value of 17.83%, with comparable total costs as shown in Table 2-30.

Table 2-29: Financial analysis of Sol Plaatjie dam (Van Vuuren *et al.*, 2011).

Parameter		Estimated value (ZAR)	Actual value (ZAR)
Costs during construction	Technical	58 539 746	45 050 000
	Legislative	70 114	70 114*
	Environmental/Social	800 000	800 000*
	Design	4 567 211	Not available
Costs during operation	Operation & maintenance	2 538 781	2 314 500*
	DWAF (DWS) cost	218 768	204 204*
	Insurance	106 170	75 000*
Total cost		66 840 790	48 513 818
Income	Income	9 886 447	9 228 275
Evaluation	IRR	10.87%	11.40%

*Estimated based on capital costs

Table 2-30: Financial analysis of Vaal dam (Van Vuuren *et al.*, 2011).

Parameter		Estimated value (ZAR)	Actual value (ZAR)
Costs during construction	Technical	77 454 944	78 069 700
	Legislative	70 114	70 114
	Environmental/Social	175 000	200 000
	Design	5 659 565	Not available
Costs during operation	Operation & maintenance	2 877 269	3 006 678
	DWAF (DWS) cost	356 888	356 888*
	Insurance	122 364	131 503*
Total cost		86 716 144	81 834 883
Income	Income	16 355 196	16 355 196
Evaluation	IRR	18.11%	17.83%

*Estimated based on capital costs

2.10.3 Hartbeespoort Dam

Four opportunities were identified at the dam by Ottermann & Barta (2012) namely, Left Bank one and two (LB1 & LB2) and Right Bank one and three/four (RB1 & RB3/4).

RB3/4 was a proposed site with an estimated head of 30 m and a flow of 5 m^3/s. The difference between RB3 and RB4 was the nature of the penstock, with a non-pressurised channel proposed for RB3 and a pressurised pipe for RB4. The estimated power was 1.5 MW with an annual energy output of 8 GWh and load factor of 61%.

LB1 was an inline opportunity where a turbine could be fixed to an outlet pipe. The head was estimated to be between 14 m to 16.7 m with a design flow of 3 m^3/s. The estimated power was 0.5 MW with an annual energy output of 4.2 GWh and load factor of 95%.

LB2 presented an opportunity to harness seasonal flows over the spillway of the Hartbeespoort dam. Using a head and flow of 42 m and 25 m^3/s respectively, resulted in an estimated power of 4.2 MW to be used for 50 – 80 % of the rainy season. This would result in an annual energy output of 12 GWh with a load factor of 33%.

Of the four sites, only RB3/4 and LB2 were deemed feasible, with the following financial considerations (Ottermann & Barta, 2012):

- Estimated unit cost of 17 000 to 20 000 ZAR/kW.
- Operating unit cost of 80 ZAR/kW.
- Interest rate of 14%.
- Tax rate of 30%.
- 2-year construction period.
- Life span of 20 years.

A financial analysis was conducted for several unit costs of electricity, specifically the average Ruraflex rate of 90 c/kWh and the NERSA rate cap for hydropower of 103 c/kWh (Ottermann & Barta, 2012).

2.10.4 General Evaluation

A pilot study was conducted by Barta (2002) and yielded an overall assessment of South Africa's hydropower potential, as summarised in Table 2-31.

Additionally, Thompson & van Dijk (2012), analysed the hydropower potential of 109 South African dams. Analysis was conducted by calculating the theoretical daily power, using daily average flows with corresponding water levels, for data sets with a length of at least 20 years. Floods were filtered out of the daily average flows and an efficiency of 75% was assumed. The theoretical daily power was then plotted on a cumulative frequency curve and a total energy potential of 447 GWh was estimated for South Africa with 80% reliability.

Table 2-31: Estimated hydropower potential for South Africa (Barta, 2002).

Hydropower category	Installed capacity (MW)	Potential for development	
		Firm (MW)	Long-term (MW)
Pico (< 20 kW)	0.02	0.10	60.20
Micro (20 kW - 100 kW)	0.1	0.40	3.80
Mini (100 kW – 1 MW)	8.1	5.50	5.00
Small (1 MW – 10 MW)	25.70	63.00	25.00
Subtotal (< 10 MW)	33.92	69.00	94.00
Run-of-river (>10MW)	-	1200	150
Diversion fed (>10MW)	-	3700	1500
Storage regulated head (>10MW)	653	1271	250
Total for hydropower in South Africa	687	5160	1994

2.11 SUMMARY

In conclusion, the literature review showed that retrofit hydropower may have potential within South Africa, based on the benefits of hydropower including:

- A long operational life,
- High efficiency with low operating costs,
- Multi-purpose operation, with the
- Capability of quickly responding to changes in demand.

Furthermore, retrofit hydropower avoids many of the negative aspects of hydropower linked to the construction of dams by making use of existing dams that are required for water supply. To evaluate this potential, two techniques of hydropower evaluation were identified namely: a) monthly power computations, which evaluated the average monthly power available at a dam and b) duration curve generation and analysis which is used to predict the likelihood of a given potential based on the dam's historic flow record.

The numerous factors that may affect the feasibility of a site were examined including environmental, social and financial considerations with a breakdown of the expected costs that constitute the latter being detailed.

It was discovered that several tools for hydropower estimation have been developed and are available for commercial use, however the majority of these tools were not designed for retrofit hydropower evaluation in the South African context, with the exception of the Hydropower Retrofitting Model (HRM), in which, the methodology used to estimate hydropower potential was basic and can be improved.

Lastly, it was found that several estimations have already been conducted on retrofit hydropower potential in South Africa, which will be applied in Chapter 3 for comparison and calibration.

3 DEVELOPMENT OF THE UNIVERSITY OF PRETORIA RETROFIT HYDROPOWER EVALUATION SOFTWARE

3.1 INTRODUCTION

Hydropower evaluation is dependent on the estimation of the available head and flow. This can be done in a variety of methods such as: monthly power computations, duration curve generation and analysis, as well as through optimisation models. However, the objective of a potential hydropower installation must be known before a full evaluation can be done and can be broadly categorised into two categories: energy generation or peak clipping/grid stabilisation.

Peak clipping is an objective wherein the design of the hydropower installation is focused on maximising the available power. This allows the installation to rapidly supply energy during peaks in demand, for stabilisation of grids primarily supplied by a separate source of energy, such as coal. This objective is restricted to large scale hydropower installations.

Energy generation is an objective of hydropower generation wherein the main design consideration is the maximisation of the energy produced, which is not necessarily equivalent to a large power potential. Instead, hydropower installations with this objective maximise energy output by designing their installed capacity (power) to harvest as much of the available energy as possible. This is done through careful selection of the number and size of the turbine units under the constraint of the amount of time they can be used. This objective is shared by both large- and small-scale hydropower installations, however it should be the primary objective of small-scale installations and a secondary objective of large installations.

During the development of the University of Pretoria Retrofit Hydropower Evaluation Software (UP-RHES), it was found that South African dams have small-scale hydropower potential. Thus, the procedure and tool were refined to identify and evaluate the maximum energy available at South African dams, using their current discharge volumes without considering changing the current operation of the dams.

3.2 THE UP-RHES

The UP-RHES is a set of five tools developed using Python 3, which is a programming language commonly used in data analysis and scientific work. Python was selected as the programming language as it is free, open source and compatible with multiple operating systems.

To create a user-friendly environment, each tool is presented using a User Interface (UI) designed with the standard Python UI toolkit, tkinter. Furthermore, only standard Python libraries were used in the development of the UP-RHES to ensure that the tools will run regardless of differences in Python installations. Refer to Chapter 4 for installation instructions and Appendix A for the source code.

The tools that comprise the UP-RHES are as follows:

- An initial screening tool that considers some of the environmental and social impacts that may make a site unfeasible,
- A dataset downloader that automates the process of downloading datasets from the DWS website,
- A rapid assessment tool,
- A scenario assessment tool, and
- A Life Cycle Costing Analysis (LCCA) tool that determines the financial feasibility of a site at a pre-feasibility level.

The UP-RHES identifies and evaluates the maximum energy available at South African dams at a pre-feasibility level through a four-step procedure, illustrated in Figure 3-1. The procedure begins by identifying a dam and a release point from said dam, which is then screened using the initial screening tool to determine whether further investigation of the site is worthwhile. This is followed by a rapid assessment of the hydropower potential at the site, using monthly power computations, which can be used as starting point for the scenario assessment tool or indicate that the site is unfeasible. Finally, the scenario assessment tool and LCCA tool are used in tandem to evaluate and maximise the financial feasibility of retrofitting the site through iterative adjustments of the design scenario.

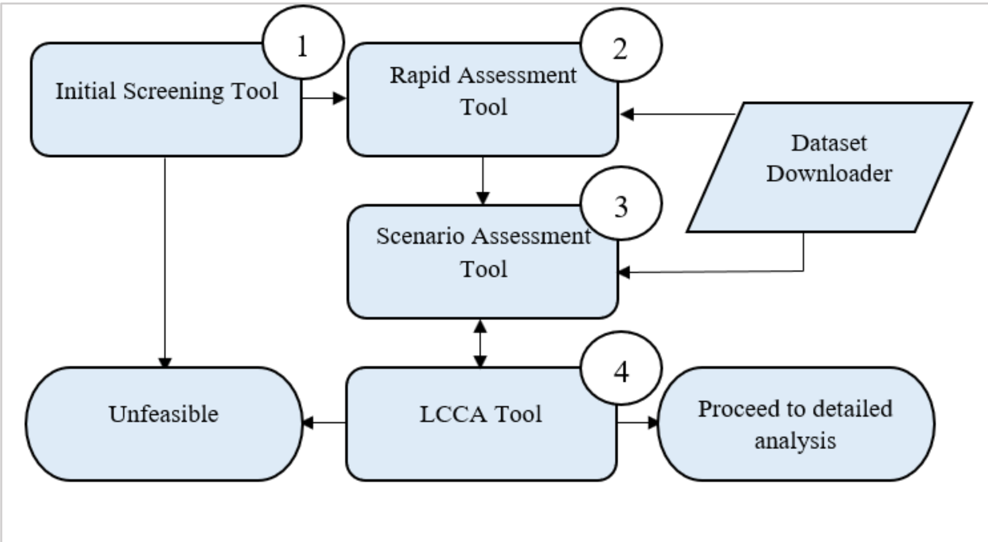


Figure 3-1: UP-RHES procedure.

3.3 INITIAL SCREENING TOOL

The initial screening tool rapidly determines whether further investigation of a site is worthwhile by eliminating unfeasible sites. This is done by asking the user four sets of questions that determine whether the proposed site is worth further investigation, as illustrated in the flow diagrams in Figures 3-2 and 3-3.

The first set of questions is obvious in nature, such as if there is a demand for electricity at the site and whether an agreement can be made with the dam owner. The second set of questions is a check list of positive impacts that may be achieved during hydropower development. Finally, the third and fourth set of questions are check lists of the possible environmental/social impacts that may be experienced during and after construction of a hydropower station.

This procedure eliminates sites with very high, or a large amount of high severity environmental/social impacts and was based on the environmental and social viability procedure developed by Van Vuuren *et al.* (2011), specifically for retrofit hydropower installations at South African dams.

The site is deemed feasible so long as all of the following criteria, defined in Chapter 4, are met:

- There is at least one positive impact,
- None of the environmental/social impacts have a rating of very high, and
- Less than half of the environmental/social impacts have a rating of high.

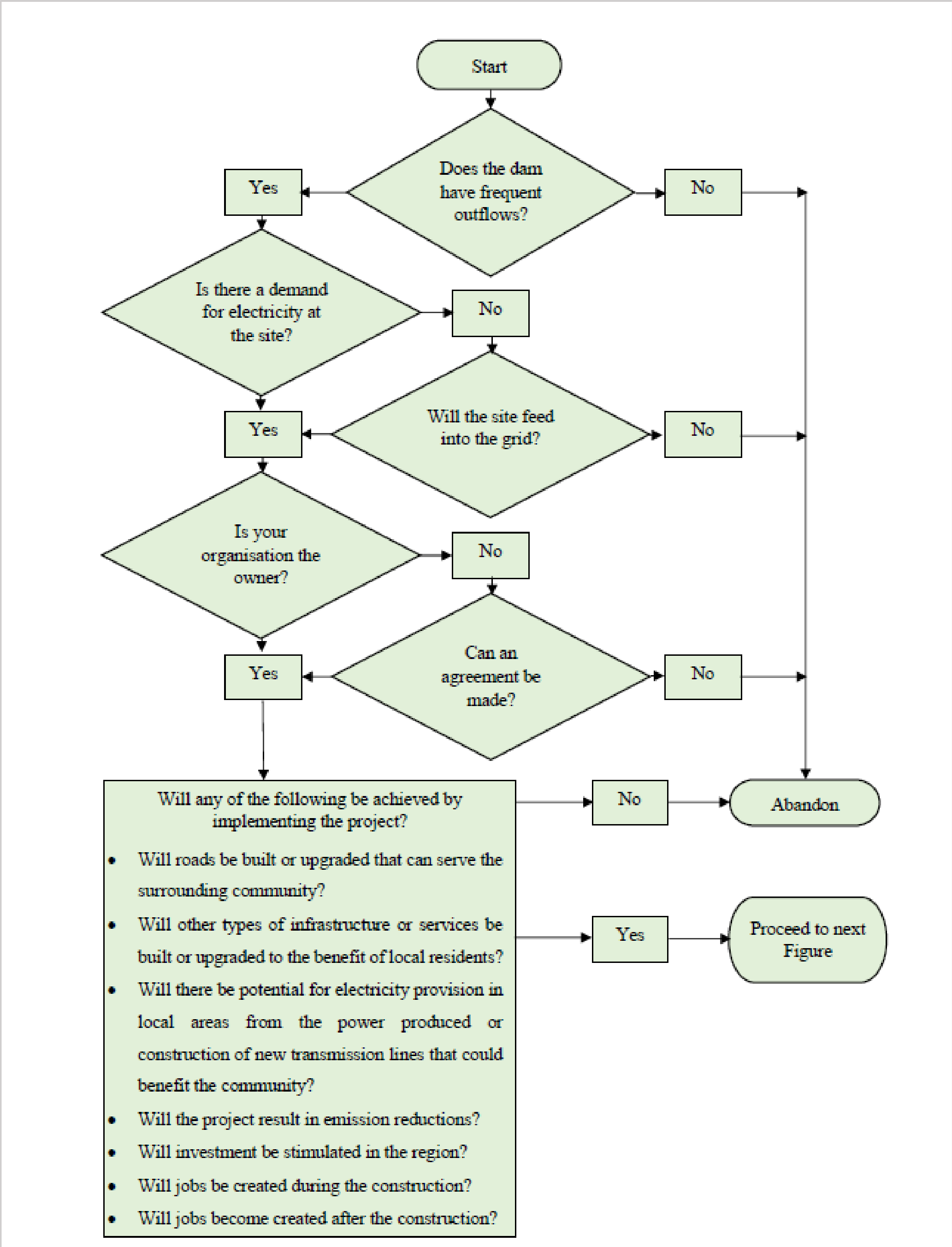


Figure 3-2: Initial screening tool: Diagram 1.

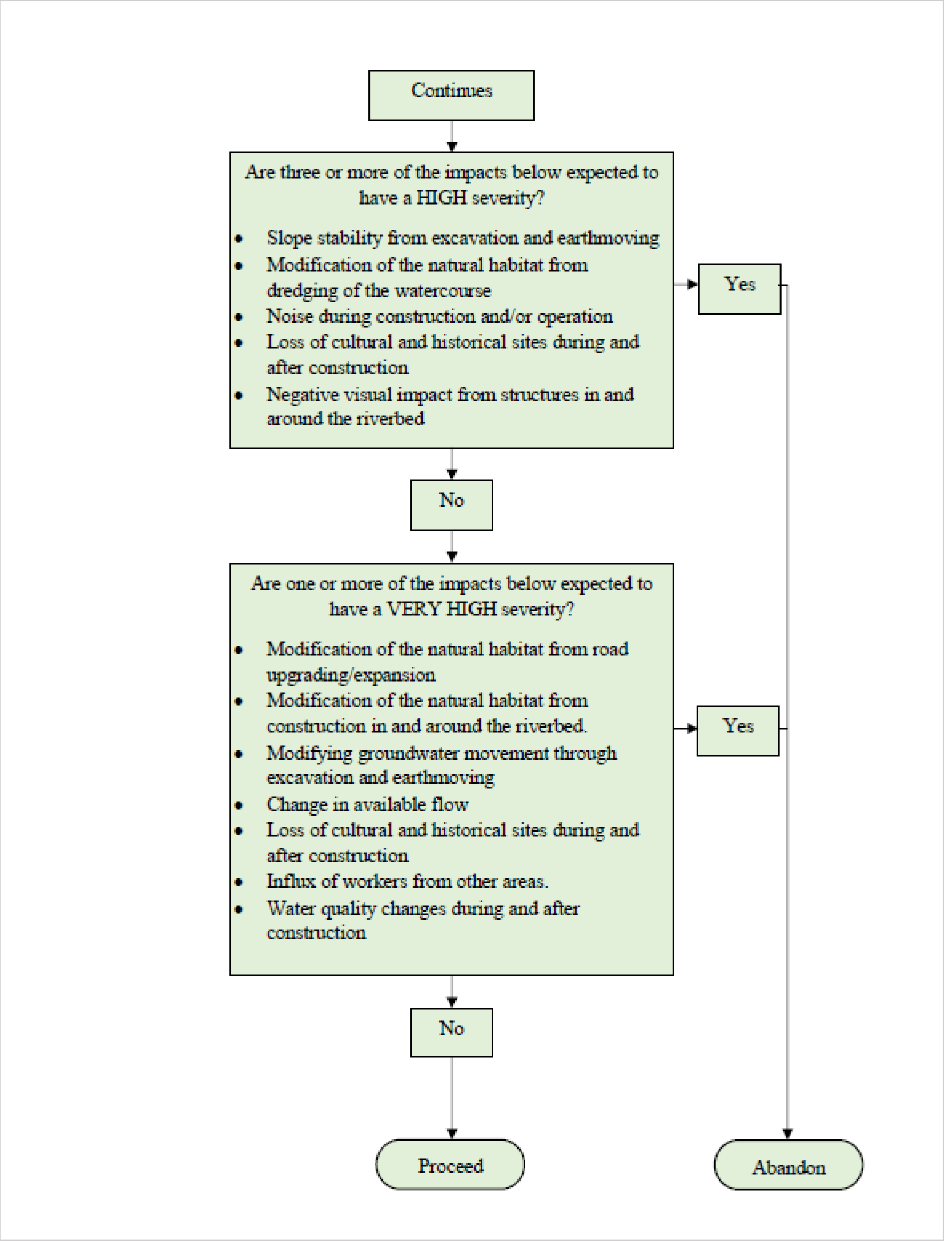


Figure 3-3: Initial screening tool: Diagram 2.

3.4 DATASET DOWNLOADER

During the development of the UP-RHES, a problem arose that drastically limited the speed and ease of use of the software. This occurred while downloading datasets from the DWS website, on which each request is limited to 7000 records, to limit server overheads and download times. In the case of monthly data, downloading the entire dataset is quick, as it can be completed in a single request. However, for daily and primary data, acquiring the entire dataset can be tedious.

Therefore, the dataset downloader was developed to automate the process of downloading datasets from the DWS. To accomplish this, two functions that make up the dataset downloader tool, were defined:

- A single request function and,
- A next day function.

When making a request using the DWS website, the inputs specified by the user are used to generate a Uniform Resource Locator (URL) that opens a web page containing the required dataset. The URL generated has a form as illustrated in Figure 3-4.

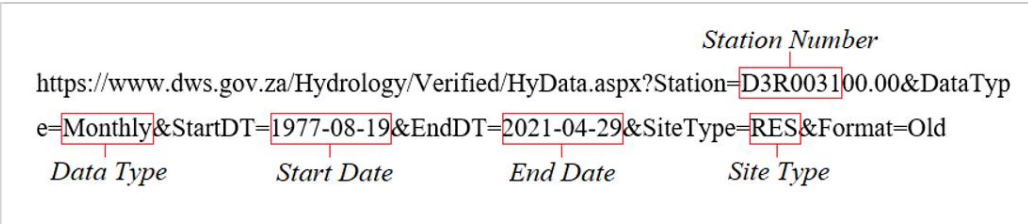


Figure 3-4: DWS URL.

By manipulating the separate components of the URL, the dataset for any combination of site, date and datatype can be requested and stored. The single request function takes advantage of this, by converting the requested webpage to a string, in which the index of the required data is hard-coded based on the datatype (monthly, daily and primary).

Using this, the string is spliced and the desired data is written to a '.txt' file based on the user's inputs. Finally, the last date in the dataset for the specific request is found and used as an input into the next day function.

The next day function, as the name implies, finds the date following an input date. This is done by first determining whether the year is a leap year, using the method presented below. Using this, the number of days for the given month can be determined and the next date calculated, accounting for both days that fall on the end of a month and the end of a year.

The procedure used to determine whether a year is a leap year was as follows:

- If the year is divisible by 400 then it is a leap year,
- Else, if it is divisible by 100 then it is not a leap year,
- Else if it is divisible by 4 then it is a leap year, and
- All other cases are not leap years.

Finally, the dataset downloader creates a loop that requests the data for a single request, finds the last date in that request and then requests the data for the day following that date. The data for each request is appended to the '.txt' file to create the entire dataset, until the following stop conditions are met:

- Monthly datatype has been selected and a single request has been made, or
- The URL returns the message "No data for requested period".

The URL may return the message "No data for requested period", in two situations. First when the downloader is requesting data for a date that exceeds the last date that data is available for and secondly when there is significant data gap that results in no data being available for that period. In the second case the downloader must be restarted using the next available date, refer to Chapter 4 for further details.

The decision to not automate the process of handling data gaps was deliberate, as recognising the frequency of data gaps in a dataset is important in determining the quality of the dataset and thus if the error is frequently encountered for a station, it suggests that the quality of the dataset may be poor.

3.5 RAPID ASSESSMENT TOOL

3.5.1 Introduction

The rapid assessment tool is the first of the two stages of hydropower evaluation used in the UP-RHES and estimates the hydropower potential at a dam using monthly power computations, as proposed by Chadderton & Niece (1983).

Average monthly power computations provide a useful breakdown of the expected hydropower available throughout the year and are calculated using the monthly average volume that flow through an abstraction/release point of a dam, and the average monthly water level, as a percentage of the height of the dam wall.

During the procedure the tool assumes the density, gravitational acceleration, efficiency and annual load factor, which are set to the values listed in Table 3-1 by default, however these can be changed by the user. The density of water is calculated using Equation 2.3 based on the assumed water temperature and the efficiency was based on the values reported by Van Dijk, (2021).

The annual load factor is set to 100% by default as the flow, and thus the power estimated by the rapid assessment tool, was assumed to be constant throughout each month, which should result in an intentional overestimation of the available hydropower to avoid false negatives. This was done as the objective of the rapid assessment tool is to determine whether or not the site should proceed to further stages of analysis and thus erroneously deeming feasible sites as unfeasible was unacceptable.

Table 3-1: Default assumptions.

Assumption	Value
Water temperature	20 °C
Gravitational acceleration	9.81 m/s^2
Efficiency	85 %
Annual load factor	100 %

3.5.2 Calculation Procedure

The tool begins by importing the dataset from the specified directory and storing the monthly values to a matrix. The value, imported as a string, is converted to a float (rational number), however, should the value contain any non-numeric characters, such as '#' or '+', that indicate approximated or missing values, the value is replaced with '#' and is excluded from further calculations.

Using the generated matrix, the average volume, in Mm^3, for each month is calculated and converted to flow, in m^3/s, by assuming that the flow is constant throughout the month. While the assumption fails to account for the timing of the releases it does provide a first-order estimate of the available power, which may aid in identifying high potential sites.

The power for each month is then calculated using Equation 2.4 using the flow and the dam wall height, as well as the assumptions, as inputs to generate an initial estimate of the hydropower available. The maximum power found during the initial estimate does not consider the average water levels, instead assuming it to be 100%. This is done to maximise the power as this step is done to determine high potential sites.

A high potential site was determined to be any site that is capable of generating 100 MW of power under optimum conditions. In this case the site is deemed capable of supplying peak clipping power and the initial estimate holds. This distinction is made, as power is a measure of the rate of energy transfer and as such, sites with a maximum power that exceeds 100 MW are expected to be able to operate at the maximum estimated power of that site, albeit infrequently, quickly supplying power to the national grid. However, sites smaller than 100 MW are not expected to be able to operate at their maximum theoretical power and therefore a series of filters are imposed to provide a more realistic estimation of the power and thus energy available throughout the year.

The filters imposed on lower potential sites (<100 MW) are as follows:

- Filter 1 removes outliers (floods) from the dataset.
- Filter 2 ensures that the power in the maximum month does not grossly exceed the adjacent months.
- Filter 3 ensures that the maximum month, before Filter 2 is applied, is maintained.

Filter 1 calculates the average volume and standard deviation of the imported matrix, excluding entries marked as ‘#’. The upper limit is then calculated as in Equation 3.1 and values that exceed the upper limit are set to the average. This step removes outliers, with 99.7% certainty, that are representative of floods, to better represent the potential of the site under normal conditions.

UL = Average + 3*Standard Deviations (Equation 3.1)

Where:

UL = Upper limit

Filter 2 calculates the upper limit in the same manner as Filter 1, however instead of calculating the values for the entire imported matrix, the average and standard deviation of the months adjacent to the month with the maximum average volume are calculated. The midpoint of these values is then used to calculate the upper limit using Equation 3.1 and values that exceed the upper limit, are set to the average. This is done to limit the difference in estimated flow between subsequent months, in order to generate a more realistic expectation of the power available throughout the year.

Filter 3 ensures that the month with the maximum average volume, before filter 2 was applied, remains the month with the maximum average volume afterwards. This is done by setting any months with an average volume that exceed the upper limit found during Filter 2 to that upper limit.

Finally, a second round of power calculations is done for both high potential sites, without filters, and lower potential sites, that have been filtered, that now considers the average water level for each month and applies it as a percentage of the height of the dam wall.

The procedure results in an estimated power potential for each month that is used to calculate the monthly energy output by multiplying the estimated monthly power by the annual load factor and the hours in that month. The theoretical hydropower potential of the site is taken as the maximum estimated monthly power and the theoretical annual energy is calculated as the sum of the monthly energy outputs.

Additionally, the number of turbines required is estimated, based on comparison to previous installations that suggests one turbine per 100 m^3/s of flow. The flow through each turbine and the head, for the month with the maximum potential, are used to select a turbine based on the criteria presented in Figure 3-5. However, it may be beneficial to utilise more than one turbine in parallel to allow for continued operation during maintenance. In the case of sites with highly variable power a single turbine may be sufficient as maintenance can be conducted during periods of low potential.

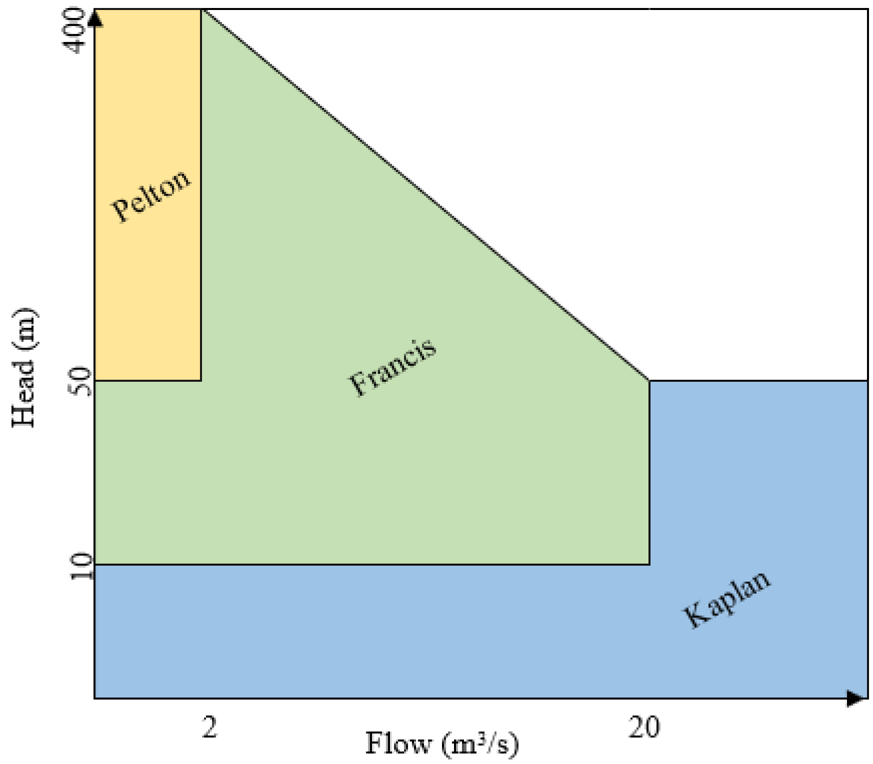


Figure 3-5: Turbine selection.

Note that only Pelton, Francis and Kaplan turbines are recommended by the tool, to match the requirements of the costing functions used in the LCCA tool. However, the turbines should only be taken as an indication of general turbine type and similar turbines can be substituted for those recommended.

3.6 SCENARIO ASSESSMENT TOOL

3.6.1 Introduction

The scenario assessment tool is used to evaluate the theoretical energy output for a given hydropower installation scenario. The tool estimates the amount of energy recoverable for an inputted combination of turbines, by generating a power duration curve for the site and evaluating how often each turbine combination can run.

The tool generates a daily power duration curve, wherein the flow is taken as the daily average flow of the abstraction/release point of the dam and the head is calculated as the daily average height between the water level in the dam and the centreline of the turbine. This assumes the retrofit turbine is installed above the TWL and thus discharges to atmospheric pressure.

The daily average height is calculated using the primary data of the spillway component of the dam. This expresses the water level relative to the crest of the spillway, which can be used to estimate an available head for each day when added to the height between the water level in the dam and the centreline of the turbine.

During the calculations the tool assumes the density, gravitational acceleration and efficiency as presented in Table 3-1. Additionally, the tool allows for the input or calculation of the headloss in the system. By default, this is set to zero, however, the tool can calculate the headloss using Equation 2.5, from Darcy-Weisbach with von Kármán & Prandtl, shown in Table 2-12.

3.6.2 Calculation Procedure

The tool begins by importing the daily average dataset and the primary dataset from the specified directory and storing the values to two distinct matrices. The value, imported as a string, is converted to a float (rational number), however, should the value contain no data or any non-numeric characters, such as ‘#’ or ‘+’, that indicate approximated or missing values the value is set to ‘#’, and is excluded in further calculations.

A daily power matrix is generated using the primary dataset of the dam, which contains water levels relative to the crest of the spillway, recorded several times each day. The average of these is calculated and stored to a new matrix which is further populated with the average flows, from the gauging station of the abstraction/release point, by cycling through each dataset until the corresponding dates are found.

The average water levels, as well as the headloss, are added to the height between the spillway crest and the turbine centreline, to obtain the available head for each day in the record. The available head, average flow and assumptions are used to calculate the power for each day using Equation 2.4, which is stored in the daily power matrix. Finally, a power duration curve, in tabular format, is generated by ranking the daily power in descending order.

The exceedance probability for the powers in power duration curve is calculated as the quotient of the power’s position and the total number of entries in the curve. It represents the amount of time, according to the historic record, an estimated power is available. For example, the 100% exceedance probability represents the minimum power estimated, however this power is available 100% of the time, whereas the 0% exceedance probability represents the maximum power estimated which only occurred once in the historic record, equivalent to being available 0% of the time.

Thus, an energy curve is generated by multiplying the power, on the power duration curve, by its exceedance probability and the number of hours in a year (8760). This allows the annual energy output for a given power to be read off the energy curve. Additionally, the energy curve allows for the determination of the optimal point, wherein maximum energy output is achieved for a fixed power rating, as shown in Figure 3-6.

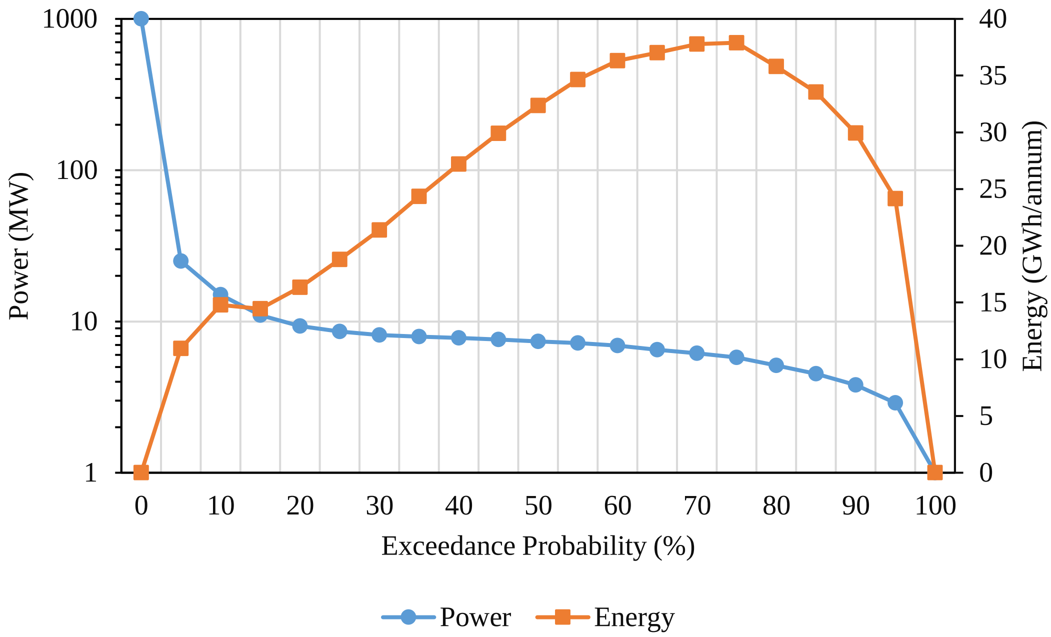


Figure 3-6: Power duration curve with corresponding energy curve.

However, the optimal point on the energy curve only represents the maximum theoretical energy of the hydropower installation scenario if a single turbine was used. Combinations of turbines are able to operate at multiple power ratings, for example an installation scenario of three 1 MW turbines could operate at 1, 2 and 3 MW respectively.

The scenario assessment tool accounts for this by estimating the annual energy output of the installation as the sum of the energy outputs for each turbine combination. This is done by finding the closest power value to that of the current turbine combination, within the power duration curve, and storing its respective energy output from the energy curve. The stored energies are then summed to yield the total annual energy output.

Additionally, turbines much like pumps, can operate within a narrow range around their respective duty points. As such, the user may specify an operating allowance, which is the percentage of the turbine's rated power that it may deviate below its rated power. The tool then calculates the energy output for each power value for each turbine combination's operating range. However, in this case the energy, for power ratings below that of the rated power, is calculated using an exceedance probability that is the difference between the subsequent exceedance probabilities. For example, in the case of rated power of 1 MW having an exceedance probability of 20%, energies for the turbine operating at 0.9 MW are calculated as its exceedance probability, say 21%, minus the previous exceedance probability to yield a value of 1%.

Finally, the tool does not allow operating ranges, for different turbine combinations, to overlap by requiring that the number of turbines be greater than the inverse of the operating allowance.

Multi-turbine operation allows the installation to operate across a wider range of the power duration curve albeit operating at higher power ratings less frequently, as shown in Figure 3-7. However, this should be constrained against the costs of the installation as, while it may be possible to install a multi-turbine installation that is capable of operating across the entire power duration curve, this would be costly and suboptimal. For this reason, the scenario assessment tool should be used in tandem with the LCCA tool to determine the most cost-effective installation scenario.

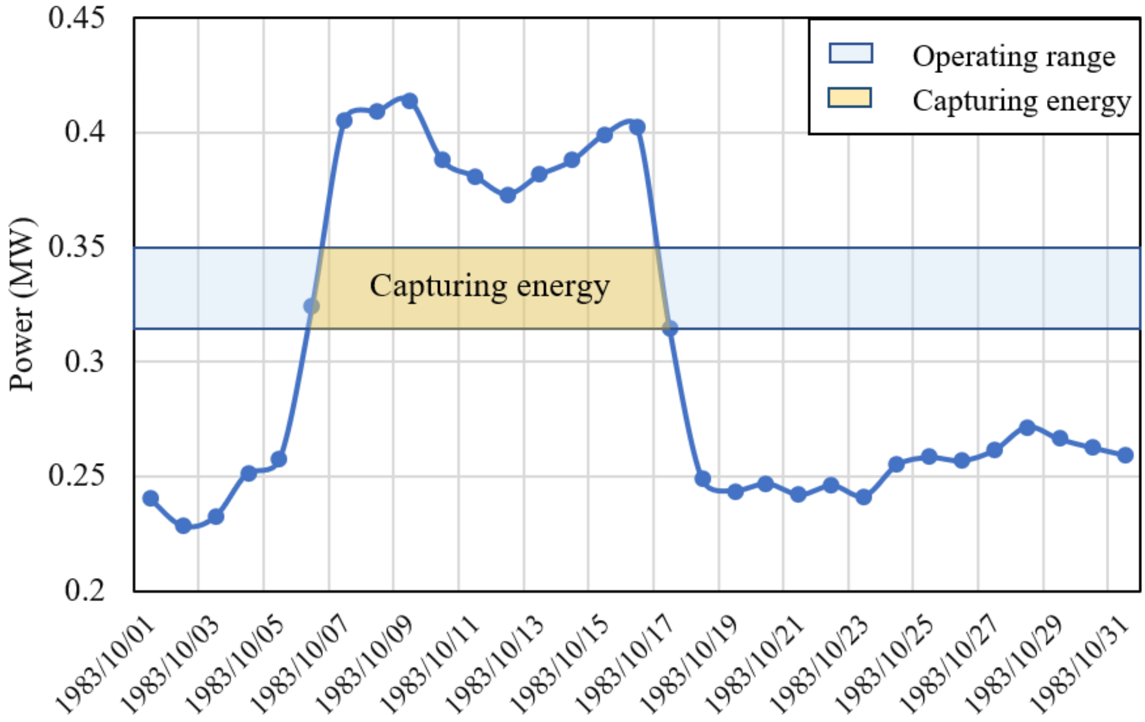


Figure 3-7: Daily power variations over a month.

3.7 LIFE CYCLE COST ANALYSIS TOOL

3.7.1 Introduction

The final tool in the UP-RHES is the Life Cycle Cost Analysis (LCCA) tool. The tool performs a financial assessment and determines, as a first-order assessment, the financial feasibility of the site. This is done by estimating the life cycle costs and benefits and, by using those values, calculating the Net Present Value (NPV), Benefit Cost (B/C) ratio, Levelized Cost of Energy (LCOE) and Internal Rate of Return (IRR) of the proposed project.

Financial analysis and prediction at pre-feasibility level is often inaccurate. This is due to the use of generalised costing functions and by assuming that economic drivers, such as the inflation rate, are constant throughout the duration of the project. However, accurately estimating the final costs and benefits of a project is not the point of a pre-feasibility analysis, rather a general estimation of the magnitude and proportions of the costs and benefits is desired. This allows for feasible sites to proceed to feasibility and detailed levels of analysis, wherein an accurate estimation of the costs and benefits will be developed.

The UP-RHES is a pre-feasibility analysis tool. Therefore, the LCCA tool was developed by calibrating the estimated costs using real values of retrofit hydropower projects undertaken in South Africa, as presented in Chapter 2.10, namely Sol Plaatjie and the estimated costs of retrofitting the Vaal dam according to the Vaal hydro report. The values of these projects were brought forward using an inflation rate of 6%, and the costs generated by the tool were calibrated such that they underestimate the costs compared to the "real" values, with minimal errors, while reporting similar project feasibilities based on the IRR.

By underestimating the costs of the project, the tool is more likely to suggest that the site is feasible. This was done to avoid a false negative error, where a feasible site is deemed unfeasible and does not proceed to more detailed levels of analysis. Furthermore, retrofit hydropower is a relevantly new field of interest, especially in South Africa, with very few publications available on estimating costs and benefits, thus the calibration was applied to the broad costs of construction, planning and operation and maintenance.

3.7.2 Construction Costs

The LCCA tool calculates construction costs as the sum of the electromechanical and civil works costs. The electromechanical cost for each turbine is estimated according to Equation 2.9 proposed by Cavazzini *et al.* (2016) and brought forward 5 years with an inflation rate of 6% and converted to South African Rands (ZAR) using the inputted ZAR/Euro conversion rate, which by default is set to 17 ZAR/€.

It was assumed that in retrofit hydropower installations the civil works cost will be less than the cost of the electromechanical equipment. Thus, the civil works were estimated at 77% of the electromechanical costs, using the cost breakdown illustrated by Ogayar & Vidal (2009).

During calibration it was found that this severely underestimated the total construction costs, thus an adjustment factor was introduced, such that the total construction costs estimated by the tool matched those of the calibration sites. The adjustment that resulted in an underestimation of the costs with minimal errors was found to be a factor of 4, as shown in Equation 3.3. The underestimation was likely due to the costing functions not considering the import, installation and escalation costs of the electromechanical equipment.

$$C_{Construction} = C_{em} + C_{Civil} + Adjustment \quad \text{(Equation 3.3)}$$

And:

$$C_{em} = aH^b + cQ^d + eP^f + g \quad \text{(Equation 3.4)}$$

$$C_{Civil} = 0.77C_{em} \quad \text{(Equation 3.5)}$$

$$Adjustment = 4(C_{em}+C_{Civil}) \quad \text{(Equation 3.6)}$$

Where:

C = Costs (ZAR, 2021)

H = Net head (m)

Q = Design flow rate (l/s)

P = Design power (kW)

a, b, c, d, e, f and g = Coefficients

Table 3-2: Coefficients brought forward and converted.

	Pelton	Francis	Kaplan
a	30909686.02	4330.885137	3169464.479
b	0.014	1.27963	0.02156
c	193142.6442	32796395.17	1.449619168
d	0.515	0.03064	1.45636
e	76942.20004	218.9448189	3531396.279
f	0.416	1.28487	0.11053
g	-33650652.88	-36890470.95	-6871319.296

The calibrated costing function was then compared to real values of electromechanical equipment used in international projects, by using a combination of the datasets presented by Cavazzini *et al.* (2016) and Filho *et al.* (2017). A conversion rate of 1.3 USD to Euro was applied to the Italian costs presented by Cavazzini *et al.* (2016).

The flow, head and power presented in the datasets were used to select a turbine, according to Figure 3-5, for which the costs were estimated including the adjustment factor of 4. The real costs as well as the costs estimated by the UP-RHES were plotted, as shown in Figure 3-8, and compared.

This showed that electromechanical costs can vary greatly between countries, with the Brazilian costs being particularly expensive and the Italian costs being relatively inexpensive. This better explained the initial underestimation found by the UP-RHES as the costing functions used were derived from the Italian datasets and by applying the adjustment factor the estimated costs begin to follow the trend of the Indian costs and the few available South African costs.

However, there is still uncertainty whether South African hydropower costs will follow any international trends, owing to the small sample size. Therefore, the costing functions used in the UP-RHES are sufficient and should allow for the identification of feasible sites, which if constructed, can be used to re-calibrate the tool accordingly.

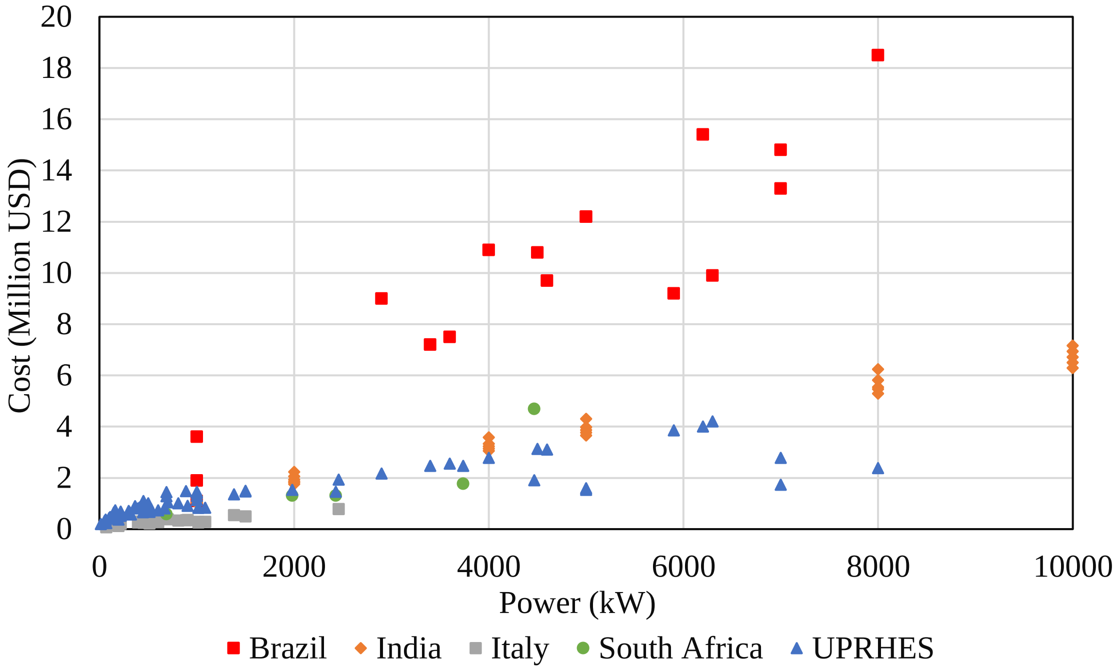


Figure 3-8: International cost comparison.

3.7.3 Planning Costs

The planning costs in the LCCA tool are calculated as the sum of the design fees, NERSA licence fee and the cost of preparation of documents as well as a BAR/EIA. Design fees were initially set to 15% of the construction costs according to the rates proposed by Bonthuys (2016). However, this underestimated the fees compared to the calibration sites. Instead, it was found that a rate of 45% better estimated the design fees.

The preparation of documents for application for a NERSA licence is a cost in the LCCA tool that is triggered under the following scenarios:

- The rated power of the site exceeds, 100 MW, or
- The site is not for own use.

The LCCA tool assumes that a BAR will be required for all sites, while only sites with a theoretical available power greater than 20 MW will be subject to an EIA. The costs for the NERSA licence application and environmental assessment used by the UP-RHES are the values presented by Van Vuuren *et al.* (2011), brought forward 10 years using a 6% inflation rate, as shown in Table 3-3. However, it was found that both the BAR and EIA were underestimated, thus a factor of 1.8 was applied to each.

Finally, the tool assumes no water use licence will be required as a retrofit hydropower station would be an extension of a current operation that should already be in the possession of a licence, or should only require general authorisation.

Table 3-3: Planning fees.

Item	Cost in 2011 (ZAR)	Cost used in UP-RHES (ZAR)
NERSA licence	20 000	36 000
BAR	200 000	650 000
EIA	1 000 000	3 200 000

3.7.4 Operation and Maintenance Costs

Annual operation and maintenance are calculated by the tool as the sum of the civil maintenance, electromechanical maintenance, operating costs, insurance and water use tariffs. The civil and electromechanical maintenance costs were set to 0.25% and 4% of their respective totals, including the adjustments applied during the estimation of the construction costs. This still underestimated the costs and as such a calibration factor of 1.955 was introduced.

However, insurance and water use tariffs received no calibration factor as they estimated costs similar to the calibration sites, using a value of 0.3% of the construction costs and the values presented in Table 2-26 respectively.

Operating costs, including staff expenses, are set to the values presented in Table 3-4 and Table 3-5 by default, however they can be changed by the user. The default values were assumed to be similar to that of a pump station, due to the similarity of equipment, thus the values were adapted from Van Vuuren & Van Dijk, (2006).

Table 3-4: Staff expenses.

Staff	Annual package (ZAR)	Amount of time (%)	Number of staff
Manager	2 756 040	10	1
Engineer	1 378 020	15	1
Technologist	826 810	20	1
Technician	689 010	20	2
Foreman	277 040	30	1
Labourers	137 800	25	15
Admin	251 640	10	2
Financial	419 400	10	2

Table 3-5: Operational expenses.

Expense	Annual amount (ZAR)
Transport	55 120
Fuel	29 960
Training	16 775
Housing	55 120

3.7.5 Revenue

The analyses conducted by Van Vuuren *et al.* (2011) and Ottermann & Barta (2012) both estimated the revenue of retrofit hydropower projects using the standard Eskom Ruraflex rate at the time, 51.7 c/kWh and 90c/kWh respectively. Thus, the default unit sale price in the LCCA tool is 1.2 ZAR/kWh, based on Eskom's current Ruraflex rate (Eskom, 2021). The annual revenue is then calculated as the unit sale price multiplied by the annual energy output of the site.

3.7.6 Financial Analysis

The analysis conducted begins by first estimating the NPV of costs and benefits respectively. This is done by assuming the construction costs to take place in year 1 and operation and maintenance fees as well as revenue to begin in year 2. The estimates of the costs occurring in year 0 are inflated using the inputted inflation rate, while the annual revenue is increased using a separate energy escalation rate. The estimated costs and benefits for each year in the expected life of the project are brought back to a present value using a geometric annuity, as shown in Equation 3.7 and 3.8, for a distinct discount rate.

Once the NPV of costs and benefits are known, the NPV, B/C, LCOE and payback period are calculated using the formulas presented in Table 2-19 and stored. The IRR is then calculated by repeating the calculation using an increasing discount rate, until the NPV reaches a value of 0, with that discount rate being the IRR and the initial estimates are then restored alongside the calculated IRR.

$$PV = A \cdot \frac{1-(1+i)^{n}*(1+r)^{-n}}{r-i} \qquad \text{(Equation 3.7)}$$

In the case where r = g:

$$PV = A \cdot \frac{n}{1+r} \qquad \text{(Equation 3.8)}$$

Where:

PV = Present value of the annuity (ZAR)

A = Annuity ($\frac{\text{ZAR}}{\text{annum}}$)

i = Growth rate of annuity (%)

r = Discount rate (%)

n = Years

3.8 VALIDATION OF PROCEDURE

3.8.1 Introduction

The UP-RHES uses two methods of hydropower evaluation: monthly power computations and power duration curve generation and analysis. Thus, it is prudent to ensure both methods produce accurate results. However, power duration curves were only used by the scenario assessment tool, which does not estimate the power available, rather, it finds the theoretical available energy for a given power rating. Therefore, only the results generated by the rapid assessment tool were compared to those of real storage hydropower sites in South Africa.

According to findings of the literature review, as shown in Table 2-6, there are 7 storage hydropower sites in South Africa. However only three sites could be found with useable datasets, with First and Second falls not having records available through the DWS and while Collywobbles and Sol Plaatjie had datasets available, they were entirely blank.

Furthermore, Ncora had missing values from 1982 to 1999, thus values from 2000 to 2021 were used as a representation of the full dataset.

To supplement this, two additional sites that do not have hydropower installations but have been previously estimated by reputable researchers (Van Vuuren *et al.*, 2011; Ottermann & Barta, 2012), were used in the comparison, as shown in Table 3-6. However, an estimation of the annual energy output could only be found for three of the sites, with two of the sites, Gariep and Vanderkloof being used for peak clipping power and thus are not well suited for comparison, and as such energy output comparisons were excluded.

Table 3-6: Validation dams.

Dam name	Reservoir station number	Downstream station number	Record length	Height (m)	Rated Capacity (MW)
Gariep	D3R002	D3H013	1973-2021	88	360
Vanderkloof	D3R003	D3H012	1981-2021	108	240
Ncora	S5R001	S5H004	1999-2021	44	2
Vaal	C1R001	C2H122	1980-2020	63	5.83 Van Vuuren *et al.* (2011)
Hartbeespoort	A2R001	A2H083	1979-2021	59	5.7 Ottermann & Barta (2012)

3.8.2 Height of Dam Walls

The height of the dam wall is a requirement of the rapid assessment tool, however the heights presented vary between the SANCOLD and DWS registers and are significantly different from those observable using satellite imagery. This is likely due to the depth of the foundation being included in the measurement of wall height. However, the foundation values cannot be easily determined or estimated through a desktop study.

To account for this, the average monthly water levels for each dam were taken from the expected percent of storage, available from the DWS website, under very-low conditions. This will reduce the effective height of the dam wall with a complete list of the expected percent of storage under very-low conditions available in Appendix B.

However, for the peak clipping sites of Gariep and Vanderkloof, the monthly level of the month with maximum estimated power was assumed to be 100%. This was done in order to maximise the available power in accordance with their operation. Figure 3-9 provides an example of the expected percent of storage of the Vanderkloof dam.

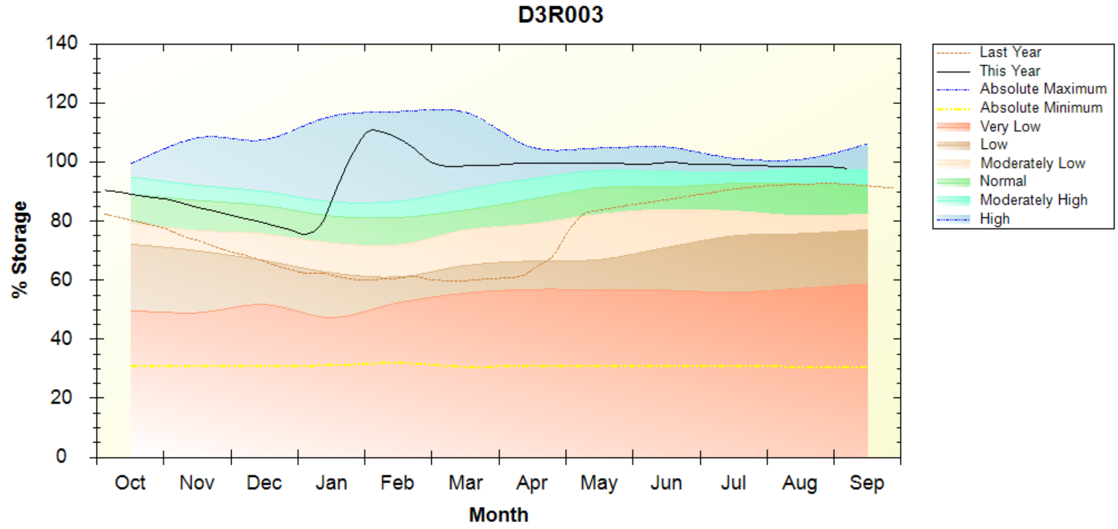


Figure 3-9: Percent of storage of Vanderkloof dam (DWS, 2021).

3.8.3 Abstraction Points

Another point of consideration was which abstraction/release point of the dam should be used during the comparison. This point is clearly illustrated by observing the gauges around the Hartbeespoort dam wall, shown in Figure 3-10, with the gauges as follows:

- A2H081: The left abstraction canal of the Hartbeespoort dam.
- A2H082: The right abstraction canal of the Hartbeespoort dam.
- A2H083: The Downstream gauge/W-component of the Hartbeespoort dam.
- A2H117: Return flow canal from A2H083.
- A2H120: A diversion from the right abstraction canal to the crocodile river.

However, the installation sites proposed by Ottermann & Barta (2012), would both discharge into the stream that ultimately flows through the Downstream/W-component (A2H083) of the dam. This is also true for the current installations at Gariep and Vanderkloof. Finally, in the case of Ncora dam the only gauge available was the W-component and as such it was decided to use the W-Component gauges for the comparison

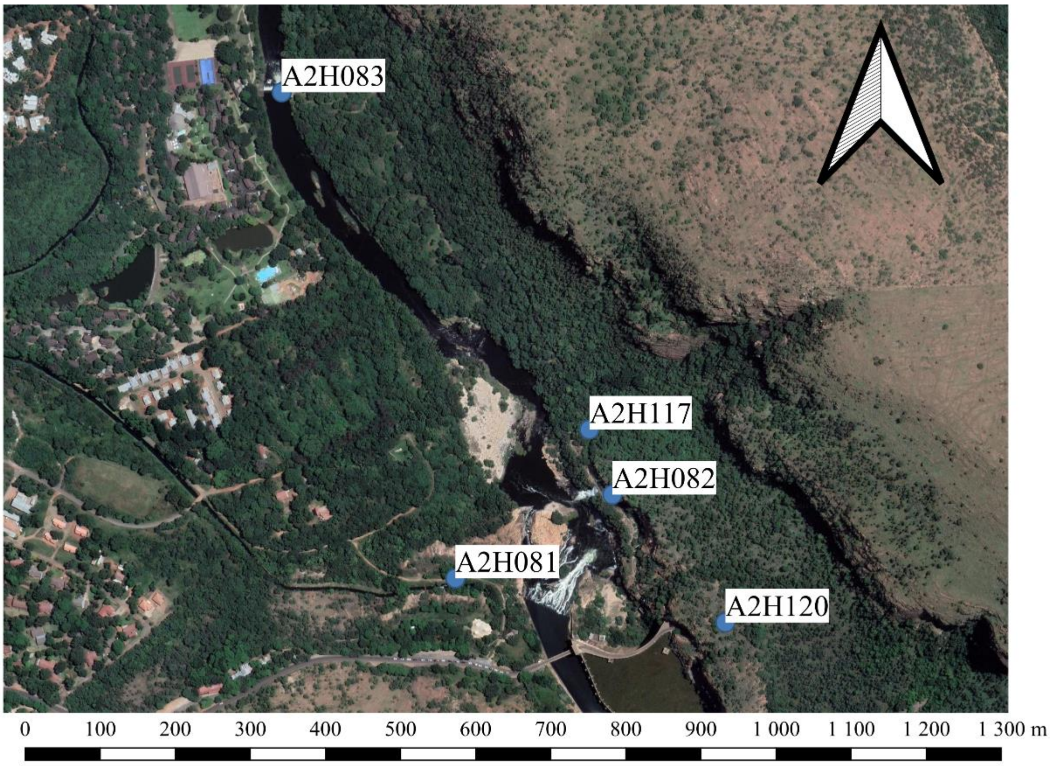


Figure 3-10: Hartbeespoort dam abstractions.

3.8.4 Comparison Results

The rapid assessment tool performed well with a mean error for power estimation of 24%, as shown in the breakdown in Table 3-7. The larger error produced by the rapid assessment tool at the Hartbeespoort dam was due to the estimation done by Ottermann & Barta (2012) containing seasonal power generation using flow over the spillway. The rapid assessment tool filters high flows that would result in spillway flow, thus not accounting for that potential power. Adjusting the rated power of the Hartbeespoort dam to not include the spillway potential, yielded significantly better results with a mean error of 12.5%. The adjusted results are displayed within brackets in the tables below.

Table 3-7: Rapid assessment tool validation.

Dam name	Rated power (MW)	Estimated power (MW)	Error (%)
Gariep	360	284.5	-20.9
Vanderkloof	240	247.8	+3.3
Ncora	2	2.31	+15.5
Vaal	5.83	6.02	+3.26
Hartbeespoort	5.7 (1.5)	1.21	+78.77 (-19.3)

Bracketed values represent the estimates without seasonal spillway generation for Hartbeespoort dam.

4 UNIVERSITY OF PRETORIA RETROFIT HYDROPOWER EVALUATION SOFTWARE

4.1 INTRODUCTION

This chapter details how to obtain and use the UP-RHES. Specific detail is given for each of the five tools that comprise the UP-RHES, and a general introduction covers how to download and install Python, which is required to run the UP-RHES. This chapter does not cover the methodology used to develop the tools, as this was presented in Chapter 3.

The UP-RHES is a set of five Python programs that, when used together, are capable of rapidly and accurately estimating the retrofit hydropower potential and viability of South African dams. The programs that comprise the UP-RHES are as follows:

- Initial screening tool,
- Dataset downloader,
- Rapid assessment tool,
- Scenario assessment tool, and
- Life cycle cost analysis tool,

The tools are available from a Google drive accessible from the following link: https://tinyurl.com/UPRHES

Alternatively, the source code, presented in Appendix A, can be run using a Python compiler. Once the tools have been obtained, they can be run by double clicking on the respective '.pyw' programs. This action requires Python 3, the latest version of the language, to be installed on the user's Windows, Linux or macOS device. This can be done by simply downloading the installer from the Python website, available at: https://www.Python.org/downloads/

4.2 INITIAL SCREENING TOOL

The initial screening tool is a basic tool and the first of the tools in UP-RHES. The initial screening tool is a series of questions that rapidly evaluate whether a site warrants further investigation.

The questions include general questions about the site, including the proposed use of electricity, and environmental and social considerations that may jeopardise the feasibility of the site.

The tool begins with simple yes and no questions as shown in Figure 4-1, and proceeds to checklists wherein the user should select all options that apply to the given site, an example of which is given in Figure 4-2.

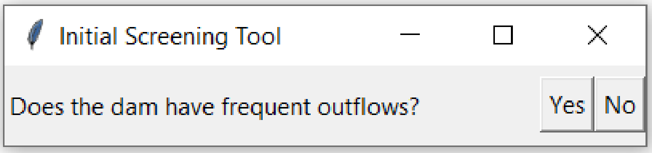


Figure 4-1: Initial screening tool (Yes/No Example).

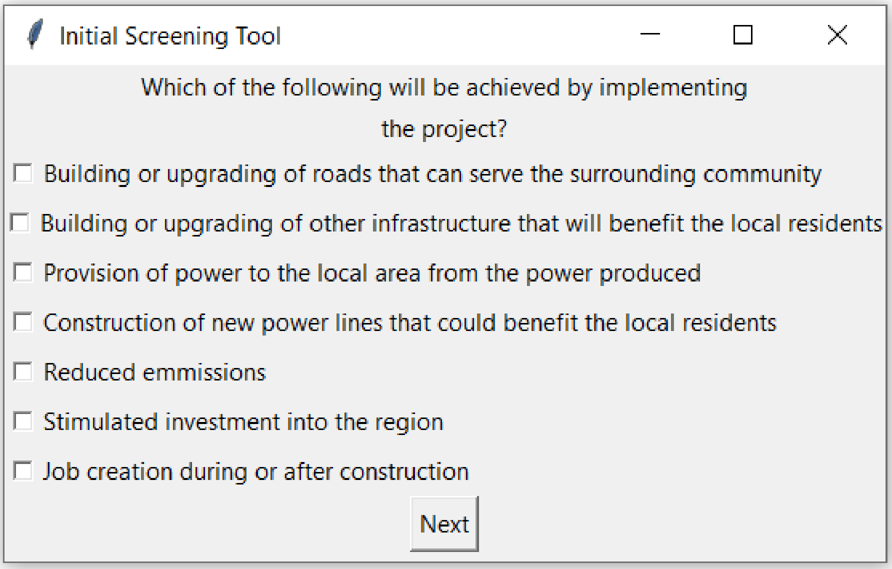


Figure 4-2: Initial screening tool (Checkbox Example).

Should the initial screening be successful the user will be greeted with the message "Proceed to analysis", however upon failure the message, "Abandon project", will be displayed, as shown in Figures 4-3 and 4-4 respectively.

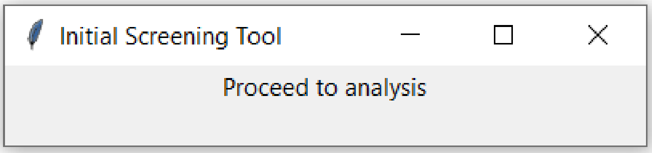


Figure 4-3: Initial screening tool (Success).

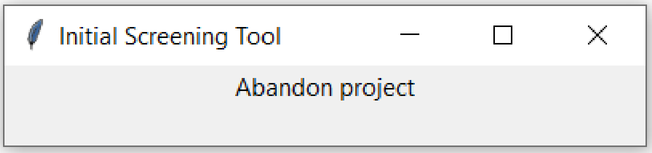


Figure 4-4: Initial screening tool (Failure).

4.3 DATASET DOWNLOADER

The UP-RHES relies upon data available from the DWS, however acquiring the data can be a tedious task. As such, a dataset downloader was developed that automates the process of downloading verified data from the DWS website. A layout of the dataset downloader's user interface is provided in Figure 4-5.

The tool generates a .txt file in the specified file directory that contains the dataset for the specified inputs. The dataset generated does not include headings, as such the user should familiarise themselves with the layout of DWS datasets to avoid errors.

In most cases the dataset downloader functions as intended. However, the DWS website is often offline and during that time the downloader will not be able to retrieve the data required and the user will receive an error. A second error type can occur while downloading primary data. This occurs when there is a gap in the data that results in no data being available for the requested period, or a specific sub-period of the request period. This will cause the downloader to complete its request, however the dataset generated will end where the data gap occurred.

To remedy this, simply update the start date in the user interface to a date after the gap. The downloader functions by appending the data to specified file name and directory, therefore the downloader will simply continue the dataset in the file beginning with the new start date. To estimate when a data gap will occur or end, the monthly data for the station in question clearly illustrates missing data using a '#'.

The downloader requires the following inputs:

- Gauge station number: The number of the measuring station whose dataset is required.

  Example: A2R001

- Station type: Whether the station is a reservoir or weir, this can be seen from the second letter in the station number.

  Example: R = Reservoir/Dam   H = Downstream Weir/W-component

- Start date: The date at which the dataset should begin.

  The inception starting date can be selected by pressing the "Default" button.

- End date: The date at which the dataset should end.

  The end date of the available dataset can be selected by pressing the "Default" button.

- Data type: Whether primary, daily, or monthly datasets should be downloaded. Note that primary datasets can be large and therefore may take some time to download.

- File directory: The location where the user would like the dataset to be saved. Note that the file directory must be an existing file and must be entered as shown in Figure 4-5, without spaces.

- File name: The name that the dataset will be saved as. Note that the file name must include the .txt extension as shown in Figure 4-5, without spaces.

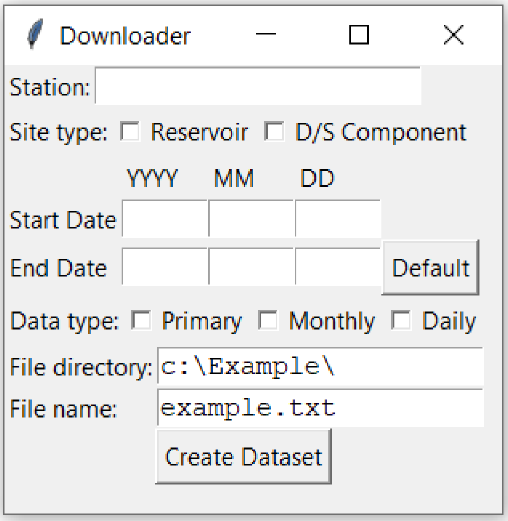


Figure 4-5: Dataset downloader UI.

4.4 IMPORTING NON DWS DATASETS

The UP-RHES was designed to function according to the formats of DWS datasets, however any dataset from any country can be used as an input for both the rapid assessment tool and the scenario assessment tool.

This is done by formatting the desired dataset to a '.txt' file with a layout that matches those of the applicable DWS dataset. In all cases the UP-RHES requires the dataset to exclude any headers.

4.4.1 Rapid Assessment Tool

The rapid assessment tool was designed for DWS monthly datasets, with a layout as shown in Figure 4-6, with the following points:

- 14 columns separated by a series of spaces. Note that Figure 4-6 omits the final 5 columns to fit the page.
- Each column represents the average monthly volume in Mm^3 according to the hydrological year,
- Except the first column which contains the years of which the hydrological year spanned,
- The last column contains the total volume for that row,
- The first column must have length of 9 characters,
- The readings must be limited to 2 decimal places,
- Incomplete or missing data is marked by a '#'.

1982/1983	299	454	821 #	427	224	238	238	255
1983/1984	655	696	356	656	371	420	356	539
1984/1985	414	387	404	377	518	619	609	268
1985/1986	314	287	672	923	889	551	283	316
1986/1987	413	1089	823	436	407	119	87.6	317
1987/1988	1976	1191	677	736	2140	6017	1435	848
1988/1989	963	904	829	1458	1564	1622	816	689
1989/1990	61.6	221	865	157	344	107	481	321
1990/1991	110	65.5	57.1	336	1532	1209	615	301
1991/1992	172	781	899	374	163	48.9	101	185
1992/1993	270	233	359	96.2	71	206	140	111

Figure 4-6: Layout of DWS monthly dataset.

4.4.2 Scenario Assessment Tool

The scenario assessment tool was designed for DWS daily average and primary datasets, with layouts as shown in Figure 4-7 and Figure 4-8 respectively.

The following are important points to consider with regards to the daily average datasets:

- 3 columns separated by a series of spaces,
- The first column represents the date using a YYYYMMDD format and is always 8 characters long,
- The second column contains the average flow in m^3/s,
- The third column contains quality codes, expressed as numerical values.

19731201	99.891	1
19731202	59.925	1
19731203	131.687	1
19731204	117.878	1
19731205	119.477	1
19731206	112.107	1
19731207	113.472	1
19731208	101.983	1
19731209	63.762	1
19731210	108.447	1
19731211	112.397	1
19731212	116.195	1
19731213	109.754	1
19731214	112.358	1

Figure 4-7: Layout of DWS daily average dataset.

The following are important points to consider with regards to the primary datasets:

- 6 columns separated by a series of spaces,
- The first column represents the date using a YYYYMMDD format and is always 8 characters long,
- The second column represents the time the reading was recorded in HHMMSS format and is always 6 characters long,
- The third column contains the level above the gauge in metres,
- The fourth column contains a quality code for the third column, expressed as a numerical value,
- The fifth column contains the flow over the gauge in m^3/s,
- The sixth column contains a quality code for fifth column, expressed as numerical values.

19720313	235900	-0.01	26	0	26
19720314	60000	-0.01	26	0	26
19720314	120000	0.01	26	0.4	26
19720314	180000	0.02	26	1.13	26
19720314	235900	0.03	26	2.07	26
19720315	60000	0.04	26	3.19	26
19720315	120000	0.025	26	1.577	26
19720315	180000	0.015	26	0.734	26
19720315	235900	-0.005	26	0	26
19720316	60000	-0.02	26	0	26
19720316	120000	-0.037	26	0	26
19720316	180000	-0.046	26	0	26
19720316	235900	-0.054	26	0	26
19720317	60000	-0.067	26	0	26

Figure 4-8: Layout of DWS primary dataset.

4.5 RAPID ASSESSMENT TOOL

The rapid assessment tool is the initial hydraulic assessment tool of the UP-RHES and can quickly and accurately estimate the hydropower potential of a dam. The rapid assessment tool performs monthly power computations, as proposed by Chadderton & Niece (1983). The rapid assessment tool requires the inputs as shown in Figure 4-9 and as listed below:

- Site name: Name of the site being analysed.
- Date: Date on which the analysis occurred.
- Station number: Station number of the flow record used in the analysis
- Height of the dam wall: Obtainable from the DWS database or the SANCOLD register, for registered and large dams respectively, or from as-built drawings.
- Average water levels: The expected average water levels, as a percentage of the height of the dam wall, for each month.
- File directory: The file location where the required flow record is stored. Note that the file directory must be an existing directory and must be entered as shown in Figure 4-9, without spaces.
- Import file name: The name of the file containing the monthly volumetric historic dataset of the abstraction point, that will be used in the analysis.
- Save file name: The name that the results file will be saved as.

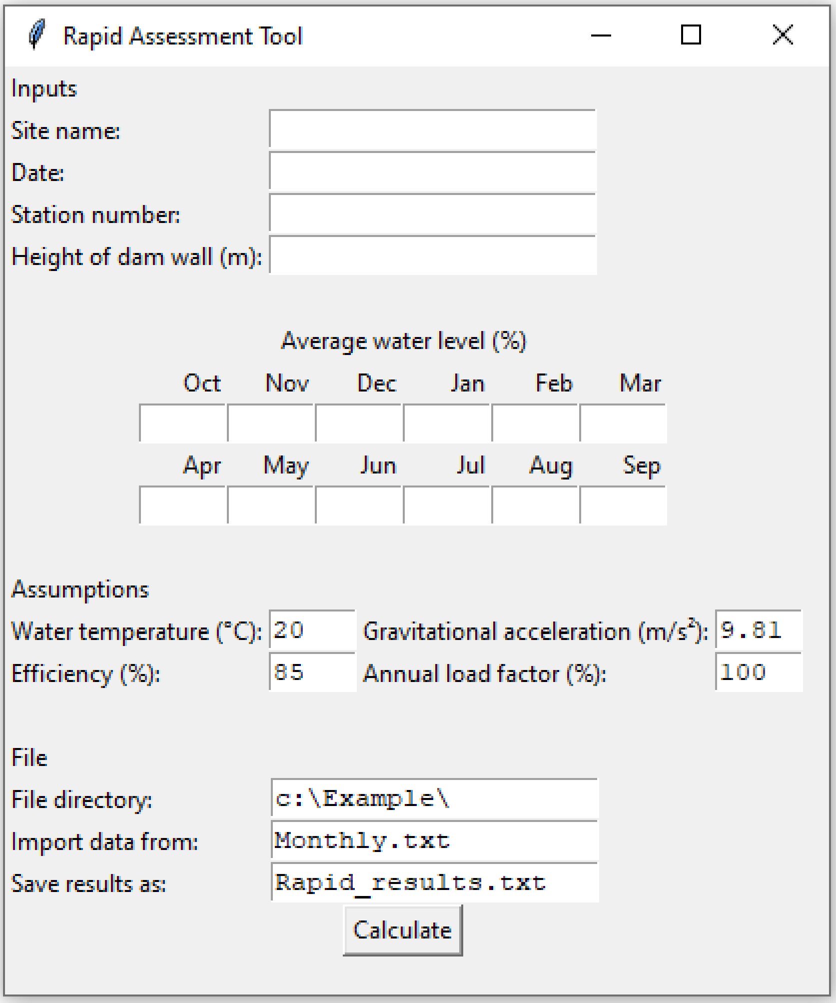


Figure 4-9: Rapid assessment tool UI.

Furthermore, the rapid assessment tool assumes the values of the water temperature, gravitational acceleration, general efficiency, and annual load factor to values as shown in Figure 4-9 by default. However, these can be changed by the user if desired.

The rapid assessment tool is a simple tool that can be executed by following the description of the inputs. Should an input be missing, the tool will generate a warning, stating that the inputs are incomplete. Once all inputs have been made the computations will be made and the results of the analysis will be saved to the specified file directory.

An example of a results page generated by the rapid assessment tool is shown in Figure 4-10. The results page contains the inputs used in the generation of the results as well as the calculated flow, power and energy for each month. The units that results are saved as, are dependent on the magnitudes of the results themselves, with larger values being saved as MW and smaller values in kW while the energy is always displayed in GWh. The units are displayed in all cases.

Finally, the results given by the rapid assessment tool are as follows:

- Maximum available power,
- Potential annual energy,
- Suggested flow,
- Suggested head,
- Suggested turbine type and
- The number of turbines.

Site name:	Vaal			
Date:	11/11/2021			
Station number:	C1R001			
Height of dam wall(m):	63			
Assumptions				
Water temperature (°C):	20			
Density (kg/m³):	998.21			
Gravitational acceleration (m/s²):	9.81			
Efficiency (%):	85			
Annual load factor (%):	100			
Month	Flow (m³/s)	Water level (%)	Power (MW)	Energy (GWh)
October	20.91	25	2.74	2.04
November	24.27	20	2.55	1.83
December	28.72	25	3.77	2.8
January	28.72	30	4.52	3.36
February	27.6	40	5.79	3.89
March	28.72	40	6.02	4.48
April	25.5	40	5.35	3.85
May	22.41	35	4.11	3.06
June	18.43	35	3.38	2.43
July	15.86	35	2.91	2.17
August	17.6	30	2.77	2.06
September	21.43	30	3.37	2.43
Results				
Maximum available power (MW):	6.02			
Potential annual energy (GWh):	34.4			
Suggested flow (m³/s):	28.72			
Suggested head (m):	63			
Suggested turbine type:	Francis			
Number of turbines:	1			

Figure 4-10: Rapid assessment tool results page.

Additionally, the power and energy for each month can be plotted using spreadsheet software, to illustrate the expected variation of power and energy throughout the year. This can be achieved by plotting the estimated power and energy for each month, as shown in Figure 4-11.

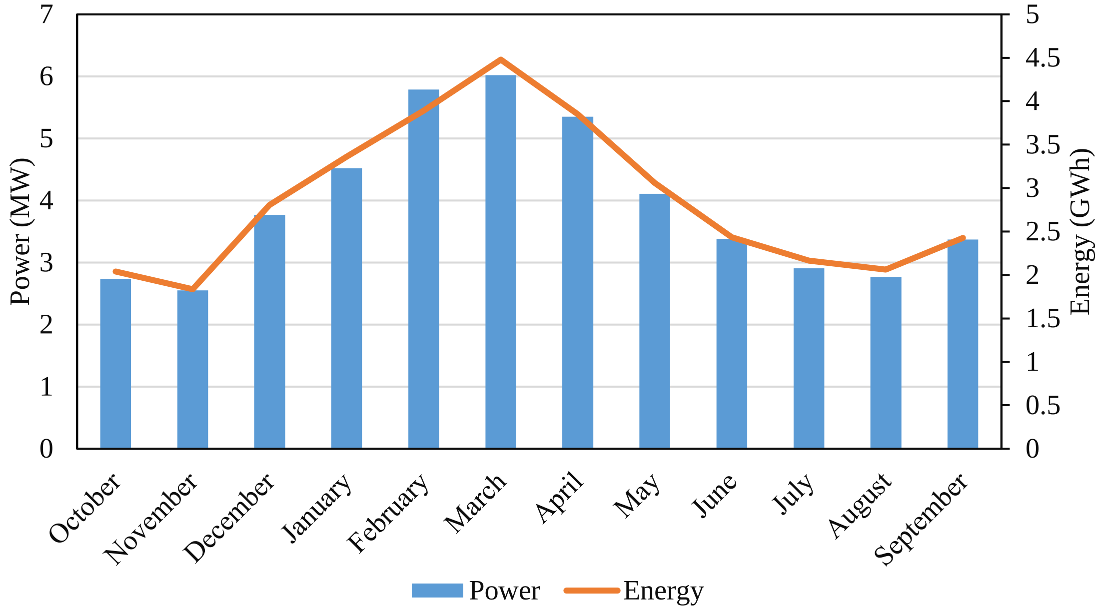


Figure 4-11: Example of monthly power and energy variations.

4.6 SCENARIO ASSESSMENT TOOL

The scenario assessment tool is the second of the hydraulic assessment tools in the UP-RHES, it generates a power duration curve, a modification of the conventional flow duration curves used in hydropower evaluation. The scenario assessment tool estimates the annual energy output available at a site for a given installation scenario, based on the historic power available. The tool should be used in conjunction with both the rapid assessment tool and the LCCA tool to estimate the maximum energy output of a dam. The scenario assessment tool requires the inputs as shown in Figure 4-12 and as listed below:

- Site name: Name of the site being analysed.
- Date: Date on which the analysis occurred.
- Station number: Station number of the spillway used in the analysis.
- Height between spillway crest and turbine: Obtainable from as-built drawings or assumed to be the height of the dam wall.
- Headloss: The expected headloss between the inlet and turbine. This can be calculated using Darcy-Weisbach with von Kármán & Prandtl, by selecting the calculate button, which will open a separate user interface, as shown in Figure 4-13.

- Rated power per turbine: The rated power of a single turbine that will be used in the installation.
- Operating allowance: The percentage of the rated power the turbine may deviate below its rated power.
- Turbine type: The type of turbine to be installed. Either Pelton, Francis or Kaplan turbines can be selected.
- Number of turbines: The number of turbines to be installed.
- File directory: The file location where the required data sets are stored. Note that the file directory must be an existing directory and must be entered as shown in Figure 4-12, without spaces.
- Import primary file name: The name of the file containing primary dataset of the spillway of the dam that will be used in the analysis.
- Import daily average file name: The name of the file containing the daily average dataset of the abstraction point, that will be used in the analysis.
- Save file name: The name that the results file will be saved as.

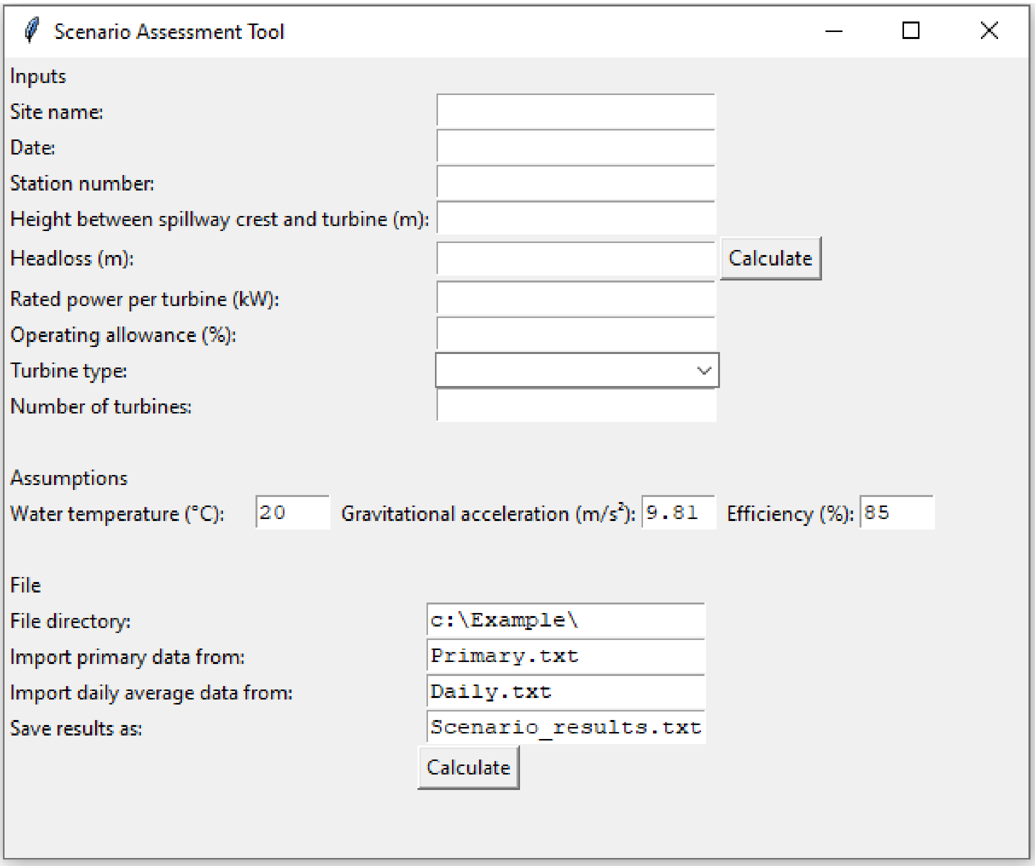


Figure 4-12: Scenario assessment tool UI.

The expected headloss can either be entered directly or it can be calculated by the programme using Darcy-Weisbach with von Kármán & Prandtl, by selecting the calculate button shown in Figure 4-12. This will open a separate user interface, shown in Figure 4-13, that requires the following inputs:

- Absolute roughness: The absolute roughness of the material of the penstock.
- Length: The length of the penstock.
- Assumed Diameter: The assumed diameter of the penstock.
- Required flow: The expected flow through the penstock. This can be estimated by performing an initial estimation without including the headloss and using the design flow generated by the tool.
- Sum of local loss coefficients: The sum of each local loss coefficient resulting from entry and exit losses and losses from changes in pipe geometry such as bends, and valves. As an initial estimate a value of 1.5 can be used.

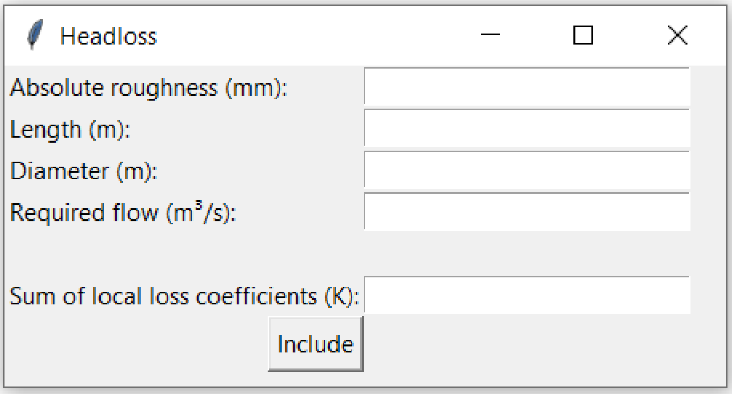


Figure 4-13: Headloss calculation UI.

Furthermore, the scenario assessment tool assumes the values of the water temperature, gravitational acceleration and general efficiency to values as shown in Figure 4-12 by default. However, these can be changed by the user if desired.

The scenario assessment tool requires two datasets to be downloaded: a) the primary data of the spillway gauge of the dam and b) the daily average data of the abstraction/release point of the dam. The primary data of the spillway gauge is used as this contains the recorded levels of the dam, while the daily average data does not.

Once the inputs have been loaded the computations will be performed by the tool, unless an input is missing, in which case an error will be displayed stating that the inputs are incomplete.

The results of the analysis will be saved to the file and directory as specified in the inputs, an example of which is shown in Figure 4-15. The results file contains the inputs used in the generation of the results as well as a table containing the power duration curve and energy curve for 5% exceedance probability intervals. The units that the results are saved as, is dependent on the magnitude of the results themselves, with larger values being saved as MW and smaller values in kW while the energy is always displayed in GWh. The units are displayed in all cases.

Finally, the results given by the scenario assessment tool are as follows:

- Potential annual energy for the input scenario,
- Total rated power of the input scenario,
- Potential annual energy for the optimal point on the power duration curve,
- Power rating for this point, and
- The load factor/exceedance probability of the optimal point.
- Additionally, a table containing the head, flow and daily power for each day in the record used is generated in the same directory as the results file itself.

However, the main benefit of the scenario assessment tool is the power duration curve, that illustrates variability of the estimated power potential based on the historic characteristics of the site. An example can be found in Figure 4-14.

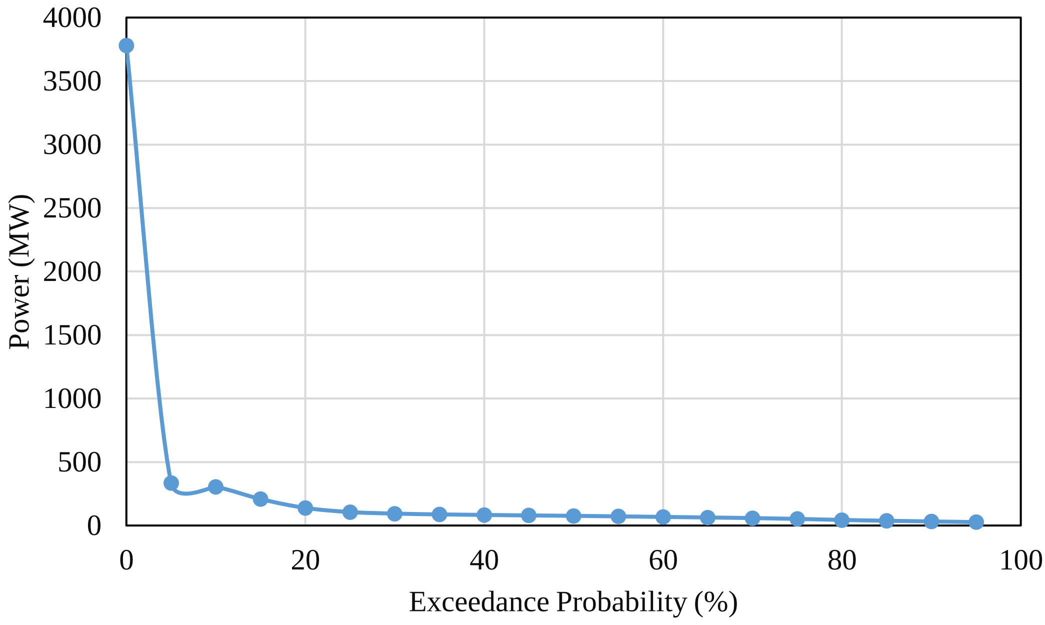


Figure 4-14: Power duration curve.

Site name:	Vaal	
Date:	11/11/2021	
Station number:	C1R001	
Height between spillway crest and turbine (m):	63	
Headloss (m):		
Rated power per turbine (kW):	6000	
Operating allowance (%):	0	
Turbine type:	Francis	
Number of turbines:	1	
Assumptions		
Water temperature (°C):	20	
Density (kg/m³):	998.21	
Gravitational acceleration (m/s²):	9.81	
Efficiency (%):	85	
Exceedance probability (%)	Power (MW)	Energy (GWh/a)
0	1228.72	0
5	59.89	26.23
10	16.87	14.78
15	10.99	14.44
20	9.33	16.35
25	8.57	18.78
30	8.14	21.39
35	7.94	24.34
40	7.77	27.21
45	7.59	29.92
50	7.39	32.35
55	7.19	34.64
60	6.91	36.31
65	6.5	37.02
70	6.16	37.79
75	5.77	37.9
80	5.11	35.79
85	4.51	33.56
90	3.8	29.94
95	2.9	24.15
100	0	0
Scenario results		
Potential annual energy (GWh):	38.12	
Total rated power (MW):	6	
Optimal point on curve		
Annual energy (GWh):	38.44	
Power rating (MW):	5.92	
Load factor (%):	74.18	

Figure 4-15: Power duration curve results page.

4.7 LIFE CYCLE COST ANALYSIS TOOL

The Life Cycle Cost Analysis (LCCA) tool determines the feasibility of the project based on a financial analysis using the results generated by either the rapid or scenario assessment tools. Although specific focus should be given to analyse the results of the scenario assessment and adjusting accordingly, until an optimal solution is reached.

The LCCA tool estimates the costs and benefits expected from the project over its design life, from which the financial feasibility of the project can be determined. Although this tool requires inputs that can be determined using the UP-RHES, a hydraulic analysis is not required to run the tool, should the values be known.

The LCCA tool requires the inputs as shown in Figure 4-16 and as listed below. Furthermore, several assumptions are made by the tool regarding the economic rates and design life used in the analysis. By default, these assumptions are set to values as shown in Figure 4-16, however they can be changed by the user.

The inputs required by the LCCA tool are as follows:

- <u>Rated power:</u> The power that the site will be designed to produce.
- <u>Annual energy output:</u> The expected annual energy generation of the site.
- <u>Design flow:</u> The flow at which the turbines are designed to operate at.
- <u>Design head:</u> The head at which the turbines are designed to operate at.
- <u>Turbine type:</u> The type of turbine to be installed. Either Pelton, Francis or Kaplan turbines can be selected.
- <u>Number of turbines:</u> The number of turbines to be installed.
- <u>File directory:</u> The location where the user would like the results file to be saved. Note that the file directory must be an existing directory and must be entered as shown in Figure 4-16.
- <u>File name:</u> The name that the results file will be saved as. Note that the file name must include the .txt extension as shown in Figure 4-16.

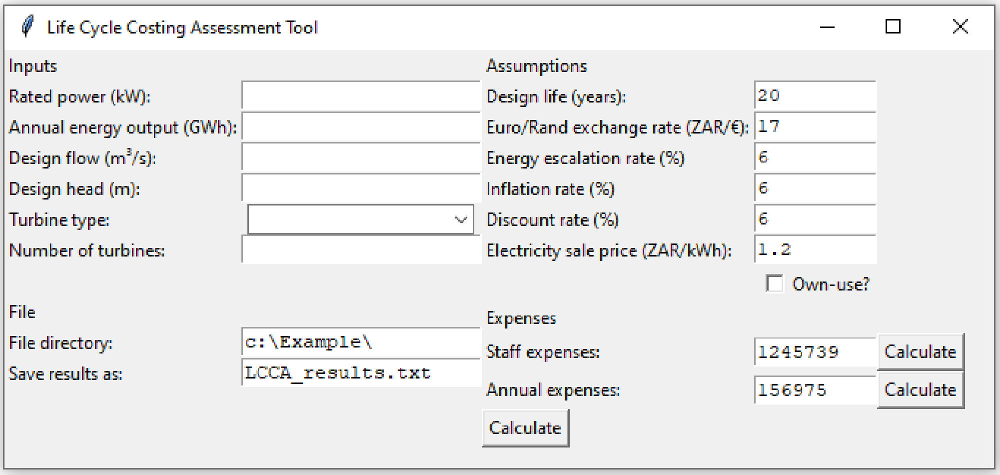


Figure 4-16: LCCA tool UI.

Additionally, the LCCA tool assumes the values for the staff and operating expenses. These can be changed directly. Alternatively, by pressing their respective calculate button, a separate user interface will be launched allowing for modification of the specific components, as shown in Figure 4-17 and Figure 4-18.

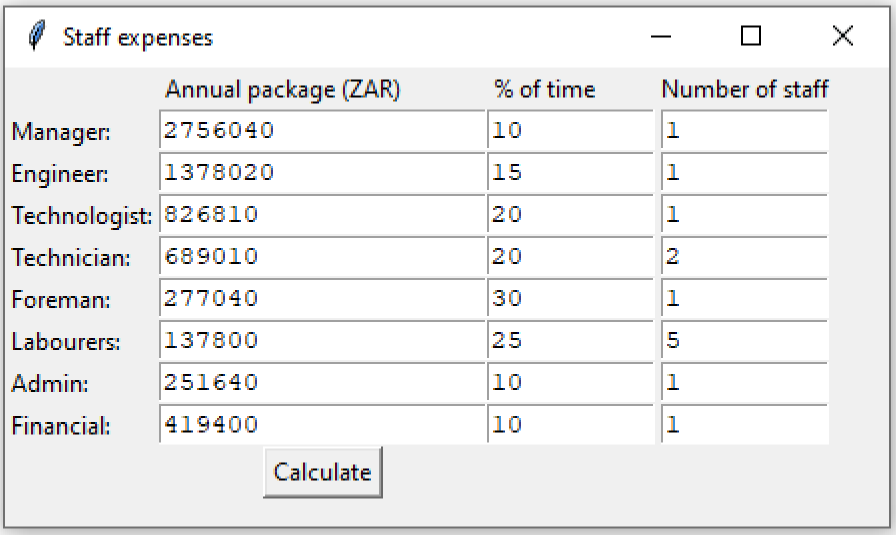


Figure 4-17: Staff expenses UI.

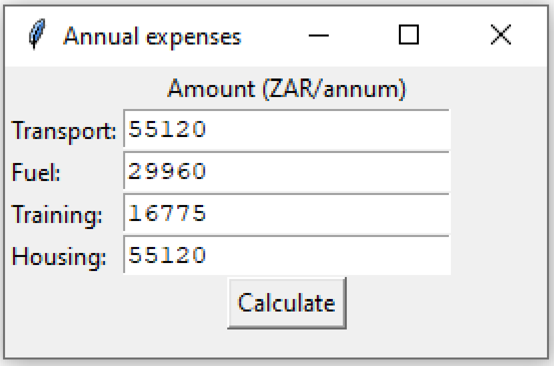


Figure 4-18: Annual expenses UI.

The results of the analysis will be saved to the file and directory as specified in the inputs, an example of which is shown in Figure 4-19. The results file contains the inputs and assumptions used in the LCCA and the estimated costs, in year 0, for planning, construction as well as annual operation and maintenance costs. The estimated yearly revenue is also shown, which is followed by the results of the financial analysis, as listed below:

- NPV (Costs): The NPV of the costs over the life of the project.
- NPV (Revenue): The NPV of the revenue generated of the life of the project.
- NPV: The NPV of the value of the project, equal to the difference of the NPV of costs and revenue.
- B/C: The benefit cost ratio of the project, equal to the quotient of the NPV of revenue and costs.
- IRR: The internal rate of return of the project, that represents the discount rate at which the project will no longer be viable.
- LCOE: The levelized cost of energy of the project, or the cost of generating a single unit of electricity (ZAR/kWh).
- Payback period: The amount of time it takes for the capital expenditure to be returned.

For the project to be deemed financially feasible the NPV should be positive, the B/C ratio should exceed 1 and the IRR should exceed the expected inflation rate over the life of the project. The payback period should not be used in determining feasibility. Instead, it could be used in negotiations to illustrate the expected fiscal timeline of the project.

Inputs		
Rated power	(kW):	5920
Annual energy output	(GWh):	38.44
Design flow	(m^3/s):	20
Design head	(m):	63
Turbine type	:	Francis
Number of turbines	:	1
Assumptions		
Design life	(years):	20
Euro/Rand exchange rate	:	17
Energy escalation rate	(%):	6
Inflation rate	(%):	6
Discount rate	(%):	6
Electricity sale price	(ZAR/kWh):	1.2
Planning		
Design fees	(ZAR):	18951000
NERSA License	(ZAR):	0
Environmental assessment	(ZAR):	645000
Total	(ZAR):	19596000
Construction		
Electromechanical costs	(ZAR):	23793000
Civil works	(ZAR):	18321000
Adjustment	(ZAR):	168456000
Total	(ZAR):	210570000
Operation and maintenance		
Civil works	(ZAR/annum):	448000
Electromechanical	(ZAR/annum):	9303000
Operational expenses	(ZAR/annum):	1426000
Insurance	(ZAR/annum):	632000
Water use tariffs	(ZAR/annum):	444000
Total	(ZAR/annum):	12252000
Revenue		
Revenue	(ZAR/annum):	46128000
Results		
NPV(Costs)	(ZAR):	449934000
NPV(Revenue)	(ZAR):	876432000
NPV	(ZAR):	426498000
B/C	:	1.9
IRR	(%):	21.4
LCOE	(ZAR/kWh):	0.59
Payback period	(years):	5

Figure 4-19: LCCA results page.

5 ESTIMATION OF SOUTH AFRICA'S HYDROPOWER POTENTIAL AT EXISTING DAMS

5.1 INTRODUCTION

The development of the UP-RHES achieves the first of the objectives of the dissertation, however, to achieve the remainder of the objectives a comprehensive and methodical approach is required.

This chapter shares the details of the first-order estimate conducted to estimate the hydropower potential at existing South African dams. An overview of the methodology and approach used is given, followed by an analysis of the results, with specific detail given to high potential sites including the 14 shortlisted sites specified in the NWRS, as listed in Table 5-1.

Table 5-1: DoE shortlisted sites (DWA, 2013).

Dams (A - J)	Dams (K - Z)
Albert falls dam	Kwena dam
Bergriver dam	Little Fish River canal+
Bloemhof dam	Ncora dam*
Blyderivierpoort dam	Pongolapoort dam
De Hoop dam#	Skoenmakers chute+
Elandsdrift dam	Vaal dam
Goedertrouw dam	Vygeboom dam

*Since the publication, Ncora dam has been fitted with a hydropower station, as illustrated in Chapter 3 and therefore was excluded from the analysis

#De Hoop was excluded due to a poor dataset.

+Little Fish River canal and Skoenmakers chute were excluded from the analysis as neither are a dam and therefore are outside of the scope of this study.

5.2 METHODOLGY OF ANALYSIS

5.2.1 Approach

The approach followed in the analysis was designed to estimate the total retrofit hydropower potential at South African dams, identify high potential dams, quantify the potential for each DWS water management area and estimate the financial feasibility of retrofitting South African dams with hydropower installations.

The approach was as follows:

- Rapid assessment, using the rapid assessment tool,
- Energy assessment, using the scenario assessment tool,
- Feasibility assessment, using the LCCA tool, followed by an,
- Analysis of the results.

The approach began by using the rapid assessment tool of the UP-RHES to estimate the total latent hydropower at South African dams. This was done by downloading the monthly volume datasets for each dam operated by the DWS, as the datasets for privately owned dams were not available. This amounted to over 130 dams with available data. However, several dam's datasets were of poor condition and therefore were excluded from the analysis. This left 118 dams with full datasets to be used in the analysis, which are spread throughout the country, as shown in Figure 5-1.

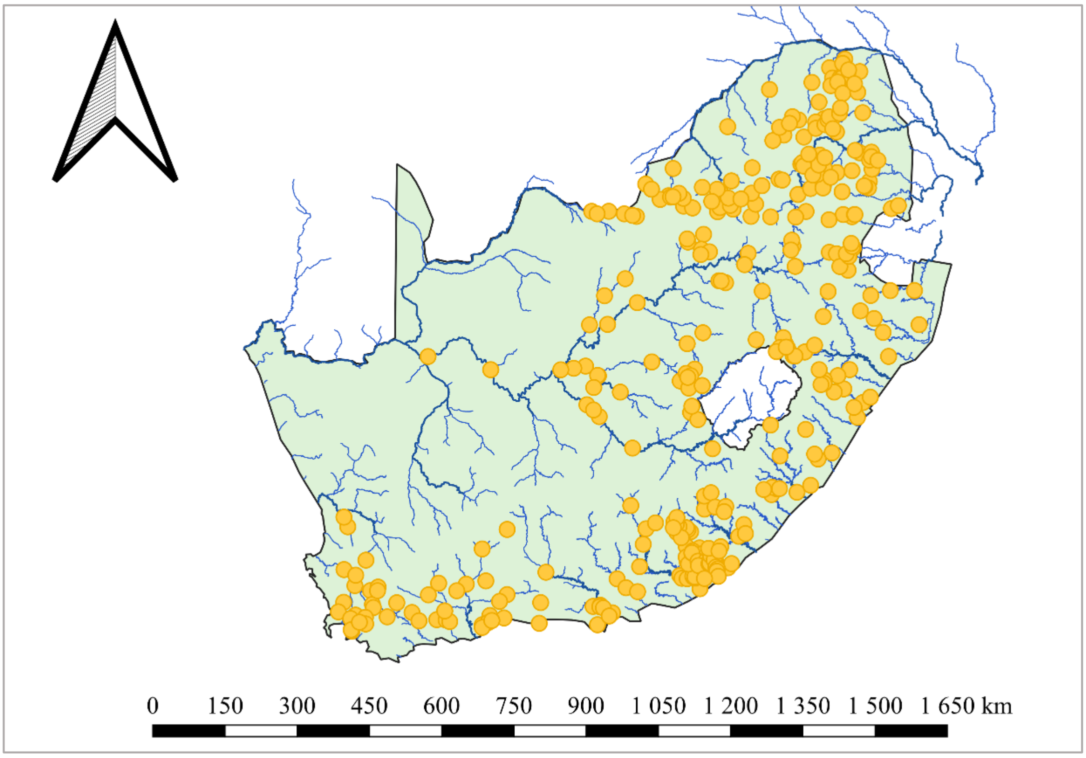


Figure 5-1: Location of dams used.

From the rapid assessment, the ten dams with the greatest potential were identified and included with the dams shortlisted by the DWS. These dams contain the majority of the hydropower estimated and as such were subject to a second round of analysis using the rapid assessment tool on each of their gauged abstraction/release points.

Next, the high potential dams were analysed using the scenario assessment tool to estimate the optimal annual energy available at South African dams. This was done as the scenario assessment tool is data intensive and as the high potential dams account for the majority of retrofit hydropower, while being a minority of the total dams.

Finally, the results of the scenario assessment tool were used to perform a LCCA on each of the high potential dams, to estimate the financial feasibility of retrofit hydropower at South African dams. This was done by calculating an average LCOE and comparing it to that of alternative energy sources such as wind, solar and coal.

The results of the analysis were then separated into their respective water management areas, as shown in Figure 5-2, and clustered/cascaded dams were identified, as these locations may significantly benefit from retrofit hydropower.

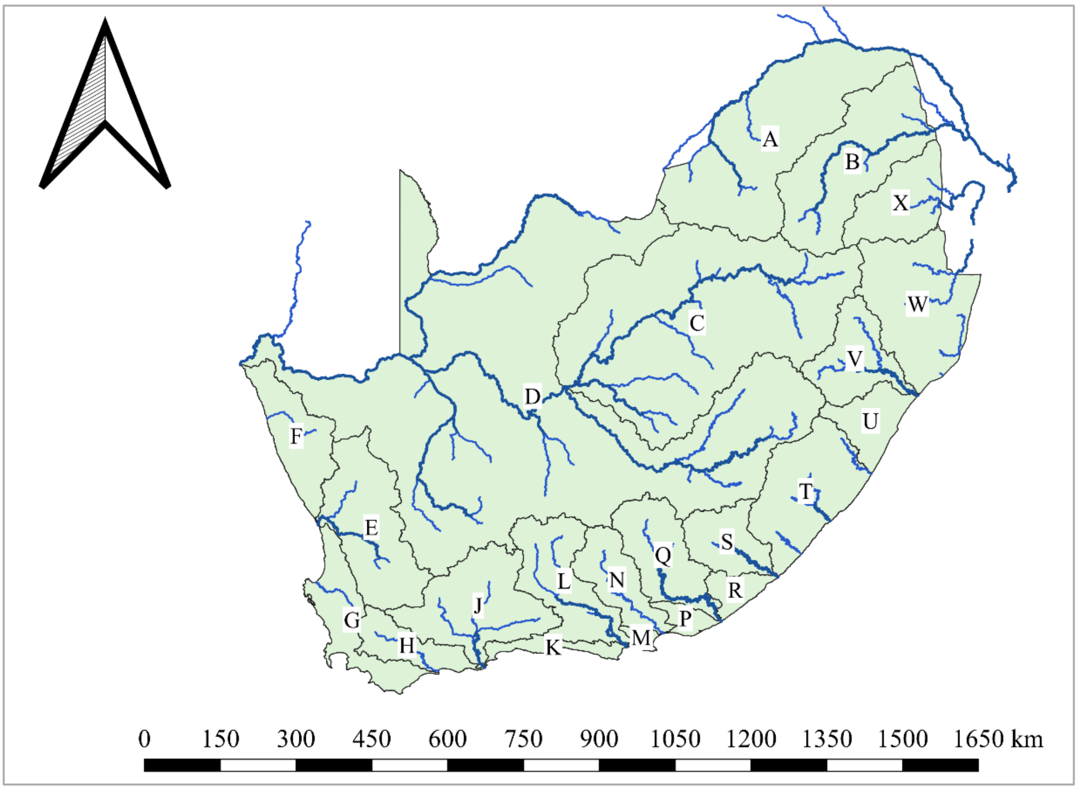


Figure 5-2: Primary catchment areas of South Africa.

5.2.2 Assumptions

As outlined in Chapter 3, the height of the dam wall is a requirement of the rapid assessment tool, however the heights presented vary between the SANCOLD and DWS registers and are significantly different from those observable using satellite imagery. This was likely due to the depth of the foundation not being known. To account for this, the average monthly water levels for each dam were taken from the expected percent of storage, available from the DWS website, under very-low conditions, while the height of dam walls was taken from the SANCOLD register.

Another point raised in Chapter 3 was which abstraction/release point of the dam should be used during the analysis. During the assessment of the total potential only the datasets for the downstream/W-component were used, as the flows over the W-component represent the outflows leaving the dam through either the spillway or environmental releases, which if passed through a turbine could generate hydropower and were assumed to account for the majority of the outflow. However additional abstraction points were investigated for high potential sites.

Finally, the efficiency was initially set to 100% to provide an estimation of the magnitude of power at a site, which was then used to select a general efficiency for each site as per the ranges shown in Table 2-9, with additional assumptions listed in Table 5-2. These assumptions were also used in the evaluation of hydropower potential at alternative abstraction points for high potential dams.

Table 5-2: Assumptions used during the analysis.

Parameter	Assumed value
Water temperature	20 °C
Gravitational acceleration	9.81
Efficiency	Site dependant
Annual load factor	100%

During the scenario assessment it was assumed that the height between the spillway crest and turbine centreline would be equal to the height of the dam and that no headloss would occur with additional assumptions as per Table 5-2. Finally, the following assumptions were made during the financial assessment:

- A design life of 20 years,
- Exchange rate of 17 Rands/Euro,
- Energy escalation, inflation and discount rates of 6%, and
- An electricity sale price of 1.2 ZAR/kWh.

5.3 ANALYSIS

5.3.1 Rapid Assessment

The initial analysis, assuming an efficiency of 100% estimated the retrofit hydropower potential of South African dams to be 128 MW with a gross annual energy output of 567 GWh. Once the efficiencies relevant to each site were applied, the retrofit hydropower potential of South Africa reduced to 108 MW with a gross annual energy output of 478 GWh, with the results for each dam being available in Appendix C.

One of the main benefits of storage hydropower is its ability to provide peak clipping during periods of fluctuating demand. In the analysis no dams evaluated showed a hydropower potential greater than 100 MW and only two dams showed a potential greater than 10 MW. This suggests that there are no dams that do not currently have hydropower installations that can stabilise the county's power supply directly, based on the assumption that sites exceeding 100 MW of capable of supplying peaking power.

Furthermore, 23 dams (19.5% of total dams) had a potential greater than 1 MW and accounted for 88% of the total estimated retrofit hydropower potential, this is illustrated in Table 5-3, and supports the decision to focus the energy and feasibility assessments on the top performing sites alone.

Table 5-3: Results tallied in terms of hydropower size.

Size	Efficiency range (%)	Count	Efficiency applied (%)
Pico (< 20 kW)	60	33	60
Micro (20 kW – 100 kW)	60 - 70	26	70
Mini (100 kW – 500 kW)	70 - 80	25	80
Mini (500 kW – 1 MW)	80 - 85	11	85
Small (1 MW – 10 MW)	85	21	85
Large (> 10 MW)	85	2	85

The 14 dams shortlisted by the DoE performed well, however did not constitute the top 14 dams in the analysis, with results ranging from 3rd to 26th position in terms of estimated power output. Using the top ten sites in regards to both power and energy output, as well as the dams shortlisted by the DoE, a list of high potential sites was developed as presented in Table 5-4.

Table 5-4: High potential sites.

Dam Name	Height of dam wall (m)	Power (MW)	Annual Energy (GWh)
Boegoeberg Dam	12	29.7	131.7
Spioenkop Dam	53	10.9	35.7
Blyderivierpoort Dam	71	6.1	29.3
Vaal Dam	63	6.0	34.4
Pongolapoort Dam	89	4.7	27.9
Wagendrift Dam	41	4.5	15.2
Driel Barrage	23	4.5	16.5
Vaalharts Weir	11	3.3	17.3
Welbedacht Dam	32	2.7	11.4
Inanda Dam	65	2.6	13.0
Vygeboom Dam	48	2.4	8.3
Bloemhof Dam	33	1.6	6.6
Bergriver Dam	60	1.1	4.7
Goedertrouw Dam	88	1.0	5.4
Albert falls Dam	33	0.79	3.4
Elandsdrift dam	26	0.77	3.7

The high potential of Boegoeberg dam was noted by Aurecon (2013) in a scoping study. The proposed project would operate as a run-of-river type installation with a rated power of 10.05 MW and a design flow of 120 m^3/s through two to three Kaplan turbines.

This is significantly less than the power estimated by the UP-RHES, of 29.7 MW, however as the project proposed by Aurecon (2013) would operate as a run-of-river installation, the rated power would be less than the total power available as only a portion of the flow would be diverted for hydropower generation and for this reason was excluded from the comparison conducted in Chapter 3.

5.3.2 Abstraction Point Assessment

Once high potential sites were identified using the rapid assessment tool, any additional abstraction/release points from the dam were also identified and assessed using the rapid assessment tool. This added an additional 15 sites, with 13.96 MW and 92.35 GWh/annum of additional hydropower potential, for a total retrofit hydropower potential at South African dams of 122 MW and 570 GWh/annum.

In general these sites underperformed compared to the W-component of the dam, due to significantly lower outflow volumes. However, the additional sites at the Vaal dam, Vaalharts weir and Inanda dam had hydropower potential comparable to those of the W-component, as shown in Table 5-5. This suggests that hydropower potential could be available within South Africa's current water infrastructure and that sites with large flow volumes could be suited for retrofit hydropower.

Table 5-5: Additional abstraction points of high potential dams.

Dam Name	Abstraction point	Power (MW)	Annual Energy (GWh)
Boegoeberg Dam	Left Canal	1.15	7.2
Spioenkop Dam	Pipe to Ladysmith	0.29	0.99
Vaal Dam	Treatment Works	0.007	0.04
	Pipe to Grootvl	0.05	0.35
	Pipe from Vaal D Grt	4.56	31.15
	Pipe from Vaal D Ltl	1.44	9.73
	Pipe to Randwater	3.53	23.39
Pongolapoort Dam	Right Canal	0.4	3.34
Wagendrift Dam	Pipe to Estcour	0.03	0.21
Vaalharts Weir	Right Canal	1.08	6.08
Inanda Dam	Treatment Works	1.04	7.655
Vygeboom Dam	Schoeman's Canal	0.07	0.41
Goedertrouw Dam	Left Canal	0.05	0.27
	Right Canal	0.25	1.42
	Pipe to Eshowe	0.02	0.11

5.3.3 Energy Assessment

After the rapid assessment had identified high potential dams, an energy assessment was conducted on them, using the scenario assessment tool. The scenario generated by the rapid assessment tool was analysed, which gave a more realistic evaluation of the theoretical annual energy available under the conditions recommended by the rapid assessment. Additionally, the tool generates an optimal condition for a single turbine configuration that would result in maximum energy generation.

Unfortunately, due to the required datasets being unavailable at the time, an energy assessment could not be conducted on the additional abstraction points nor on 5 of the high potential sites which did not have the required datasets. These sites were:

- Boegoeberg,
- Driel barrage,
- Welbedacht,
- Bloemhof, and
- Elandsdrift.

In 8 of the 11 sites analysed the scenario assessment tool drastically reduced the theoretical annual energy available and at sites where an increase was found, it was slight. On average the energy reduced by a factor of 0.69, which would suggest that the total annual energy output of South African dams would be between 393 and 429 GWh. However, under optimal conditions the range rises to be between 456 and 479 GWh, with a reduction factor of 0.8.

The revised theoretical energy available for the high potential dams as well as the optimum single turbine configuration are listed in Table 5-6. It should be noted that the optimal point is not the optimal energy available at the site, as this can only be achieved through multi-turbine installations and as such the optimal point is the optimum for single turbine configurations or configurations operating solely at their maximum power capacity.

Table 5-6: Energy assessment results.

Dam Name	Rapid assessment		Scenario assessment	Optimal point		
	Power (MW)	Annual Energy (GWh)	Annual Energy (GWh)	Annual Energy (GWh)	Power (MW)	% of time used
Spioenkop Dam	10.9	35.7	16.06	19.08	25.63	8.5
Blyderivierpoort Dam	6.1	29.3	15.09	19.08	4.94	44
Vaal Dam	6	34.4	38.12	38.44	5.92	74.2
Pongolapoort Dam	4.7	27.9	19.42	22.7	4.2	61.6
Wagendrift Dam	4.5	15.2	5.57	5.81	3.65	18.2
Vaalharts Weir	3.3	17.3	4.72	8.89	20.2	5
Inanda Dam	2.6	13	5.58	7.01	7.9	10.1
Vygeboom Dam	2.4	8.3	5.67	7.17	5.2	15.7
Bergriver Dam	1.1	4.7	2.42	2.93	1.9	16.9
Goedertrouw Dam	1	5.4	5.91	6.72	1.4	53.7
Albert falls Dam	0.79	3.7	4.83	4.96	0.94	60.2

5.3.4 Feasibility Assessment

While South Africa's dams may theoretically be able to provide small-scale hydropower, the feasibility of such projects is not known. Thus, a LCCA was conducted using the UP-RHES to estimate the financial feasibility of retrofit hydropower in South Africa.

The analysis was conducted on each of the high potential sites for two alternatives, the first using the results of the rapid assessment with the adjusted energy output suggested by the scenario assessment tool and secondly, using the optimal single turbine scenario. However, in the case where a dam was not analysed by the scenario assessment tool, the energy used was predicted by the rapid assessment and this was also applied to the additional abstraction/release points.

The first alternative resulted in 7 of the 31 sites being financially feasible with IRRs ranging from 9.2 to 21.5%. In all cases, except for the Vaal dam, the additional abstraction points were not financially feasible, with the Vaal dam accounting for 4 of the sites deemed feasible.

The second alternative, for optimal single turbine installations, resulted in 3 of the 11 sites being financially feasible with a similar range of IRR. The optimal condition did result in one dam, Blyderivierpoort, which was unfeasible using the results of the rapid assessment, to become feasible and in no case did a previously feasible site become unfeasible. Instead, the remaining dams did not have the datasets required for the scenario assessment tool and thus were not analysed under the optimal alternative.

Interestingly, all sites found feasible under the optimal scenario had their optimal power ratings occur for a significantly larger percentage of time compared to the unfeasible sites. However, two sites that were able to utilise their optimal power for a large percentage of time were not found feasible: Goedertrouw (53.7%) and Albert falls (60.18%), which are well above the average of 33%. Instead, their optimal energy output was significantly less than that of the sites found feasible.

This suggests that the main contributor to the financial feasibility of a retrofit hydropower project is its annual energy output. However, this should be coupled with a power rating that can be utilised consistently throughout the year, thereby resulting in a good ratio between performance (energy) and cost (power rating).

The feasible sites, with their corresponding IRR and LCOE, are presented in Table 5-7.

Table 5-7: Financially feasible sites.

Dam Name	Abstraction point	Rapid assessment		Optimal point	
		IRR (%)	LCOE (ZAR/kWh)	IRR (%)	LCOE (ZAR/kWh)
Boegoeberg Dam	W-component	14.9	0.75	-	
Blyderivierpoort Dam	W-component	Unfeasible		9	1
Vaal Dam	W-component	21.5	0.58	21.4	0.59
	Pipe from Vaal D Grt	20.9	0.6	-	
	Pipe from Vaal D Ltl	9.2	1.0	-	
	Pipe to Randwater	18.3	0.67	-	
Pongolapoort Dam	W-component	9.6	0.97	14.6	0.78
Driel Barrage	W-component	21.2	0.61	-	

5.4 RESULTS AND DISCUSSION

5.4.1 High Potential Locations

To achieve the second sub-objective of identifying any locations that may benefit greatly from retrofit hydropower, the results of the rapid assessment were broken down into each primary catchment, as listed in Table 5-8, which showed the following:

- The highest potential was in Catchment D, along the Orange River.
- This was supported by a high potential in the upstream Catchment C.
- The Tugela River in Catchment V also showed high potential, as well as,
- The Olifants River in Catchment B.

To simplify the results and put into perspective the magnitude of the energy available, a general household demand was used, which should be sufficient for lighting, cooking and cleaning. The general demand per household was taken as the government defined Free Basic Electricity (FBE) of 50 kWh/month (Ye *et al*. 2018). However, due to the variations of hydropower potential throughout the year, the households supplied will fluctuate. Therefore, it should be emphasised that the reported households supplied served only as an indication of the magnitude of electrification, that could be gained through retrofitting existing dams.

Thus, the estimated gross annual energy output of between 393 and 479 GWh could supply 655 000 to 798 000 households with basic electricity, without accounting for transmission losses.

Table 5-8: Retrofit hydropower potential in South African catchments.

Primary catchment	Power (MW)	Energy (GWh/a)	Households supplied
A	4.2	19.1	31 769
B	10.5	47.4	79 022
C	13.4	68.5	114 086
D	32.5	143.1	238 564
E	2.2	8.7	14 457
G	1.9	9.1	15 203
H	1.9	8.7	14 494
J	0.0	0.1	239
K	0.2	1.1	1 802
L	0.1	0.8	1 318
Q	1.0	5.5	9 087
R	0.7	4.7	7 857

Primary catchment	Power (MW)	Energy (GWh/a)	Households supplied
S	1.4	5.9	9 869
U	4.9	22.9	38 197
V	20.6	70.2	117 020
W	8.7	43.9	73 124
X	4.4	18.5	30 914

Plotting the location of each of the high potential sites yielded Figure 5-3, in which three river systems were found to have high potential sites that were upstream of each other. This implies that the hydropower potential of these sites may be dependent on the performance and demands of the upstream and downstream sites respectively. Thus, further investigation is required to accurately predict the potential of the sites, which is outside the scope of this study. The three river systems were as follows:

- The Orange River,
- The Tugela River, and
- The Umgeni River.

The Orange River consists of four high potential cascaded dams, beginning with the Vaal dam and then followed by Bloemhof dam and Vaalharts weir before ending at Boegoeberg, which is indirectly supplied by Welbedacht dam.

The Tugela River consists of two cascaded dams starting with Driel barrage and ending at Spioenkop Dam, with Wagendrift being situated close to both along a tributary of the Tugela. However this system is itself downstream of the Drakensberg pumped storage scheme. An additional dam, Sterkfontein, within the system had a potential of 126 kW or 0.56 GWh/a

The Umgeni River contains three cascaded high potential sites. Beginning with Albert falls dam and ending at Inanda, however Midmar Dam, upstream of Albert falls also showed significant potential of 1 MW and 3 GWh per year, and thus was also included in the high potential sites.

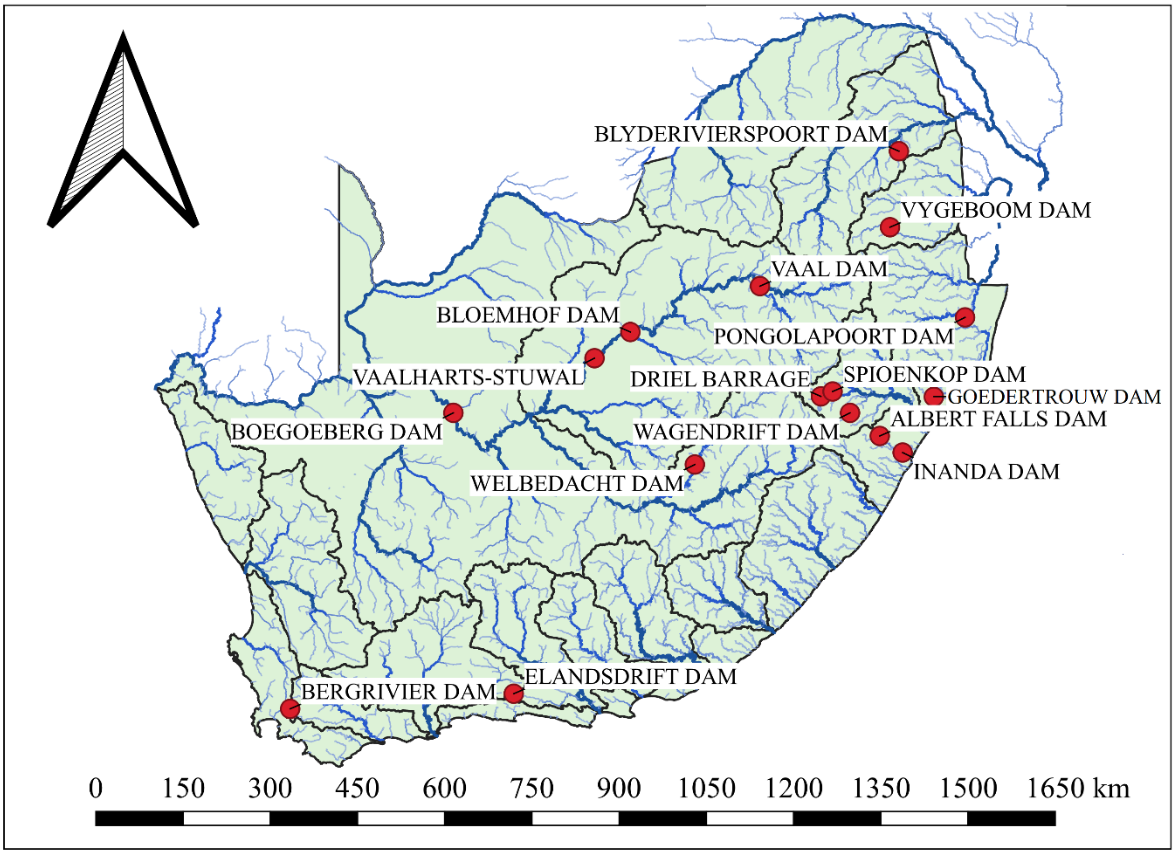


Figure 5-3: High potential sites.

5.4.2 Comparison to Alternative Energy Sources

While there is indeed latent hydropower potential at South Africa dams, the economic feasibility of retrofitting is questionable. Only a few sites were found to be feasible, with an average LCOE of 0.91 ZAR/kWh which, according to Table 2-21, is below the global average for hydropower of 1.05 to 1.64 ZAR/kWh, as well as for the average cost of wind, solar and coal in South Africa of 1.28, 1.2 and 0.8 ZAR/kWh, respectively. However, when the unfeasible sites are included the average LCOE raises to 3.56 ZAR/kWh which is substantially more expensive than alternative sources of renewable energy, suggesting that retrofit hydropower at South African dams may not be cost effective.

Yet, during the assessment the economic rates of energy escalation, inflation and discount rates were all set to 6% as this assumes that the benefits will increase with the costs. However as outlined in Chapter 2-1, the cost of energy in South Africa has drastically increased compared to the general inflation rate, with energy escalations rates averaging 15%.

While it may not be likely to expect a 15% yearly increase in revenue from a hydropower project, the benefits would include not being reliant on electricity supplied by Eskom, thus benefitting by avoiding an increasing energy cost of 15% per year. This is a complexity of

LCCA that was outside the scope of this investigation and could affect the feasibility of retrofit hydropower at South African dams. Therefore, it is recommended that the high potential sites identified during the assessment should be analysed in greater detail, with specific regard to the financial assessment.

5.4.3 Conclusions

The assessment showed that South African dams have a significant latent hydropower potential with a total estimated potential of 122 MW and between 393 and 479 GWh/annum, although the majority of this potential comes from a minority of its dams.

In comparison to alternative forms of renewable energy, retrofit hydropower seems to be prohibitively expensive, with only the Vaal, Blyderivierpoort and Pongolapoort Dam being found to be feasible and this was due their consistent high outflows.

However, the feasibility assessment did not consider benefits, such as savings, incurred from not being subject to a 15% energy escalation rate on Eskom’s grid, which may affect the overall feasibility of a retrofit hydropower installation, as this requires a more detailed analysis of the financial parameters of the project and thus was outside the scope of the study.

Nevertheless, cascaded systems may be more cost effective due to their close proximity or could be retrofitted to act as pumped storage schemes, which would allow for greater control over the timing and magnitude of the flows released.

Three river systems with high potential cascaded sites were identified as follows:

- The Orange River,
- The Tugela River, and
- The Umgeni River.

The high potential sites along these rivers, as well as the sites deemed feasible, should be subject to detailed investigations with regards to pumped storage retrofitting and conventional storage retrofitting respectively.

In conclusion, the DoE’s focus on solar and wind power is warranted for large scale generation. However, hydropower may still play a role in South Africa’s energy mix, with the 3 dams found to be financially feasible, being able to supply 80.22 GWh/annum or enough energy to supply 133 000 households with basic electricity, a substantial contribution to a country in dire need of additional generation capacity.

6 CONCLUSIONS AND RECOMMENDATIONS

South Africa is in a critical power situation and is in dire need of additional generation capacity. Thus, renewable energy sources such as wind, solar and hydropower should be evaluated to identify high potential and cost-effective sites. South Africa, being a water-scarce country, is already heavily dammed, meaning there are no more suitable new sites for conventional hydropower generation. Instead, novel solutions such as retrofitting hydropower installations to existing infrastructure, such as at existing dams, are required.

The study focussed on the latter and found that there is indeed retrofit hydropower potential at South African dams. This was achieved by developing a procedure and tool, known as the UP-RHES, that is capable of evaluating hydropower potential at South African dams, thereby achieving the first objective of the study.

The tool evaluates hydropower in a 4-stage approach:

- Firstly, an initial screening determines whether a site warrants further investigation,
- Secondly a rapid assessment of the site's hydropower potential is conducted using monthly computations,
- Thirdly the estimate of the annual energy available at a site is refined, based on a power duration curve derived from historic daily records,
- Finally, the annual energy output is optimised, with regards to cost, through an iterative procedure by adjusting the installation scenario according to the results of the LCCA tool.

The second objective, to estimate the total hydropower potential available at South African dams, was accomplished by applying this procedure to 118 DWS operated dams, it was found that the majority of South Africa's retrofit hydropower potential comes from a minority of its dams. The total estimated hydropower potential was estimated at 122 MW with an annual energy output of between 393 and 479 GWh.

Of the 118 dams assessed 16 high potential sites were identified. These were a combination of high potential sites found during the rapid assessment and sites previously shortlisted by the DWS. Unfortunately, no dams were found that were large enough to provide instantaneous load demand sufficient to stabilise the national grid. By plotting the 16 high potential sites it was found that the hydropower available is clustered into three main river systems: the Orange, Tugela and Umgeni rivers and as such these locations may benefit from retrofit hydropower installations.

To estimate the feasibility of retrofitting South African dams with hydropower installations a LCCA was conducted on the high potential sites. It was found that retrofit hydropower is financially feasible at 3 of the sites, with an average LCOE of 0.91 ZAR/kWh. These sites were the Vaal, Blyderivierpoort and Pongolapoort Dams with a combined capacity of 80.22 GWh/annum or enough energy to supply 133 000 households with FBE.

However, in the majority of cases retrofit hydropower was found to be unfeasible when compared to alternative renewable energy sources such as wind and solar, with an average LCOE of 3.56 ZAR/kWh compared to wind and solar's LCOE of 1.28 and 1.2 ZAR/kWh, respectively. Thus, the DoE's focus on solar and wind power for large scale generation is warranted.

Further studies are recommended, as several limitations were encountered during the study. Specifically, the study does not fully account for the timing and magnitude of dam releases, which will affect the estimated rated power of a site as well as the frequency with which it can supply demand. This will directly affect whether a site is suitable for retrofit hydropower. Furthermore, the study makes use of costing functions to estimate the financial feasibility of a site. This should be refined by acquiring quotes from suppliers and contractors, for similar installations and care should be taken when using international costs for comparison as these costs and fees can vary greatly between countries.

Recommendations for further studies are as follows:

- Further investigation of retrofit hydropower at the Vaal, Blyderivierpoort and Pongolapoort Dams is required and warranted.
- This could be accomplished by adjusting the UP-RHES for stochastic inputs to estimate a firm yield for hydropower abstraction.
- The cascaded dams along the Orange, Tugela and Umgeni rivers could be a feasible source of retrofit hydropower due to their proximities and cascaded natures, however this was not accounted for during the study and thus should be evaluated.
- Finally, the analysis could be refined by making use of daily or primary data to calculate the monthly average hydropower using smaller time steps. This negates the necessity for assuming the flow to be constant over a month, which may be able to account for the timing of the releases from the dam.

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APPENDIX A

A.1 INTRODUCTION

Appendix A contains the source code of the UP-RHES, please take care to copy the code exactly with careful consideration of the indentations. Note that no formatting has been done on the code, this should allow for direct copying.

A.2 INITIAL SCREENING TOOL

```
from tkinter import *

#first set of questions
uf1=Tk()#initialises GUI for first round of question
uf1.title('Initial Screening Tool')
uf1.geometry('400x50')
t1=Label(uf1,text='Does the dam have frequent outflows?')
t1.pack(side= LEFT)

def abandon():#defines buttons
    b1.destroy()
    b2.destroy()

pos=0
def click_yes():
    global pos
    if pos==0:
        t1.configure(text='Is there a demand for electricity at the site?')
        pos=1
    elif pos==1 or pos==2:
        t1.configure(text='Is your organisation the owner?')
        pos=3
    elif pos==3 or pos==4:
        uf1.destroy()
        pos=5
def click_no():
    global pos
    if pos==0 or pos==2 or pos==4:
        t1.configure(text='Abandon project')
        abandon()
    elif pos==1:
        t1.configure(text='Will the site feed into the grid')
        pos=2
    elif pos==3:
        t1.configure(text='Can an agreement be made?')
        pos=4

b2=Button(uf1,text='No',command=click_no)
b2.pack(side=RIGHT)
b1=Button(uf1,text='Yes',command=click_yes)
b1.pack(side=RIGHT)
uf1.mainloop()

if pos==5:#second set of questions
    uf2=Tk()
    v1=IntVar()
    v2=IntVar()
    v3=IntVar()
    v4=IntVar()
    v5=IntVar()
    v6=IntVar()
    v7=IntVar()
```

```
    cnt1=0
    def Next1():
        global cnt1
        cnt1=v1.get()+v2.get()+v3.get()+v4.get()+v5.get()+v6.get()+v7.get()
        uf2.destroy()

    uf2.title('Initial Screening Tool')
    uf2.geometry('550x310')
    t2=Label(uf2,text='Which of the following will be achieved by implementing')
    t3=Label(uf2,text='the project?')
    t2.pack()
    t3.pack()
    cb1=Checkbutton(uf2,text='Building or upgrading of roads that can serve the
surrounding community', variable=v1)
    cb2=Checkbutton(uf2,text='Building or upgrading of other infrastructure that
will benefit the local residents',variable=v2)
    cb3=Checkbutton(uf2,text='Provision of power to the local area from the power
produced',variable=v3)
    cb4=Checkbutton(uf2,text='Construction of new power lines that could benefit
the local residents',variable=v4)
    cb5=Checkbutton(uf2,text='Reduced emmissions',variable=v5)
    cb6=Checkbutton(uf2,text='Stimulated investment into the region',variable=v6)
    cb7=Checkbutton(uf2,text='Job creation during or after
construction',variable=v7)
    cb8=Button(uf2,text='Next',command=Next1)
    cb1.pack(anchor=W)
    cb2.pack(anchor=W)
    cb3.pack(anchor=W)
    cb4.pack(anchor=W)
    cb5.pack(anchor=W)
    cb6.pack(anchor=W)
    cb7.pack(anchor=W)
    cb8.pack()
    uf2.mainloop()

    if cnt1>=1:#third set of questions
        uf3=Tk()
        v21=IntVar()
        v22=IntVar()
        v23=IntVar()
        v24=IntVar()
        v25=IntVar()
        cnt2=0
        def Next2():
            global cnt2
            cnt2=v21.get()+v22.get()+v23.get()+v24.get()+v25.get()
            uf3.destroy()

        uf3.title('Initial Screening Tool')
        uf3.geometry('550x225')
        t4=Label(uf3,text='Which of the following impacts are expected to have a
HIGH severity?')
        t4.pack()
        cb21=Checkbutton(uf3,text='Slope stability from excavation and
earthmoving', variable=v21)
        cb22=Checkbutton(uf3,text='Modification of the natural habitat from
dredging of the watercourse',variable=v22)
        cb23=Checkbutton(uf3,text='Noise during construction and/or
operation',variable=v23)
        cb24=Checkbutton(uf3,text='Loss of cultural and historic sites during and
after construction',variable=v24)
        cb25=Checkbutton(uf3,text='Negative visual impact from structures in and
around the riverbed',variable=v25)
        b9=Button(uf3,text='Next',command=Next2)
        cb21.pack(anchor=W)
        cb22.pack(anchor=W)
        cb23.pack(anchor=W)
        cb24.pack(anchor=W)
```

```
        cb25.pack(anchor=W)
        b9.pack()
        uf3.mainloop()

        if cnt2<3:#fourth set of questions
            uf4=Tk()
            v31=IntVar()
            v32=IntVar()
            v33=IntVar()
            v34=IntVar()
            v35=IntVar()
            v36=IntVar()
            v37=IntVar()
            cnt3=0
            def Next3():
                global cnt3

cnt3=v31.get()+v32.get()+v33.get()+v34.get()+v35.get()+v36.get()+v37.get()
                uf4.destroy()

            uf4.title('Initial Screening Tool')
            uf4.geometry('550x290')
            t5=Label(uf4,text='Which of the following impacts are expected to have
a VERY HIGH severity?')
            t5.pack()
            cb31=Checkbutton(uf4,text='Modification of the natural habitat from
road upgrading/expansion', variable=v31)
            cb32=Checkbutton(uf4,text='Modification of the natural habitat from
construction in and around the riverbed',variable=v32)
            cb33=Checkbutton(uf4,text='Modifying groundwater movement through
excavation and earthmoving',variable=v33)
            cb34=Checkbutton(uf4,text='Change in available flow',variable=v34)
            cb35=Checkbutton(uf4,text='Loss of cultural and historic sites during
and after construction',variable=v35)
            cb36=Checkbutton(uf4,text='Influx of workers from other
areas',variable=v36)
            cb37=Checkbutton(uf4,text='Water quality changes during and after
construction',variable=v37)
            b10=Button(uf4,text='Next',command=Next3)
            cb31.pack(anchor=W)
            cb32.pack(anchor=W)
            cb33.pack(anchor=W)
            cb34.pack(anchor=W)
            cb35.pack(anchor=W)
            cb36.pack(anchor=W)
            cb37.pack(anchor=W)
            b10.pack()
            uf4.mainloop()

            if cnt3<1:
                uf_p=Tk()
                uf_p.title('Initial Screening Tool')
                uf_p.geometry('400x50')
                tp=Label(uf_p,text='Proceed to analysis')
                tp.pack()
                uf_p.mainloop()
            else:
                uf_a=Tk()
                uf_a.title('Initial Screening Tool')
                uf_a.geometry('400x50')
                ta=Label(uf_a,text='Abandon project')
                ta.pack()
                uf_a.mainloop()

        else:
            uf_a=Tk()
            uf_a.title('Initial Screening Tool')
            uf_a.geometry('400x50')
```

```
            ta=Label(uf_a,text='Abandon project')
            ta.pack()
            uf_a.mainloop()
    else:
        uf_a=Tk()
        uf_a.title('Initial Screening Tool')
        uf_a.geometry('400x50')
        ta=Label(uf_a,text='Abandon project')
        ta.pack()
        uf_a.mainloop()
```

A.3 DATASET DOWNLOADER

```
from tkinter import *
from urllib.request import urlopen

def is_leap(lyyyy):#next day functions
    if lyyyy%400==0:
        leap=1
    elif lyyyy%100==0:
        leap=0
    elif lyyyy%4==0:
        leap=1
    else:
        leap=0
    return leap

def days_in_month(lyyyy,lmm):
    if lmm==1 or lmm==3 or lmm==5 or lmm==7 or lmm==8 or lmm==10 or lmm==12:
        return 31
    elif lmm==4 or lmm==6 or lmm==9 or lmm==11:
        return 30
    else:
        if is_leap(lyyyy)==1:
            return 29
        else:
            return 28

def next_day(lyyyy,lmm,ldd):
    try:
        lyyyy=int(lyyyy)
        lmm=int(lmm)
        ldd=int(ldd)
    except:
        return -5

    if days_in_month(lyyyy,lmm)==31 and ldd==31:#end of month
        nyyyy=str(lyyyy)
        nmm=str(lmm+1)
        ndd='01'
    elif days_in_month(lyyyy,lmm)==30 and ldd==30:
        nyyyy=str(lyyyy)
        nmm=str(lmm+1)
        ndd='01'
    elif days_in_month(lyyyy,lmm)==28 and ldd==28:
        nyyyy=str(lyyyy)
        nmm=str(lmm+1)
        ndd='01'
    elif days_in_month(lyyyy,lmm)==29 and ldd==29:
        nyyyy=str(lyyyy)
        nmm=str(lmm+1)
        ndd='01'
    else:#other days
        nyyyy=str(lyyyy)
        nmm=str(lmm)
        ndd=str(ldd+1
if lmm==12 and ldd==31:#end of year
        nyyyy=str(lyyyy+1)
        nmm='01'
        ndd='01'

    if len(nmm)==1:#adds a 0 for <10 entries
        nmm='0'+nmm
    if len(ndd)==1:
        ndd='0'+ndd

    combo=nyyyy+'-'+nmm+'-'+ndd
    return combo

```

```
def single_request(url1,initial_date,url2,datatype,file_name,sitetype):#request function
    url=url1+initial_date+url2
    page=urlopen(url)
    html_bytes=page.read()
    html=html_bytes.decode("utf-8")#downloads and converts the entire html document to one long string

    check_data=html[0:29]#checks for 'No data for requested period.'
    if check_data=='No data for requested period.':
        return -5
    else:
        if datatype==1:
            header=940
            footer=11
            last_date_spacing=0
            if sitetype=="DC":
                header=header-11
        elif datatype==2:
            header=303
            footer=13
            last_date_spacing=25
            if sitetype=="DC":
                header=header-11
        elif datatype==3:
            header=455
            footer=0
            last_date_spacing=64
            if sitetype=="DC":
                header=header-38

        pre_from=html.find("<pre>")+header#postitions to cut the string
        pre_to=html.find("</pre>")-footer
        data=html[pre_from:pre_to]
        file=open(file_name,"a")#saves to file
        file.write(data)
        file.close()

        if datatype==2 or datatype==3:#gets and returns the next day
            last_date_pos=pre_to-last_date_spacing#gets last date
            last_date=html[last_date_pos:last_date_pos+8]
            lyyyy=last_date[0:4]
            lmm=last_date[4:6]
            ldd=last_date[6:8]
            return next_day(lyyyy,lmm,ldd)

uf1=Tk()#functions for the buttons
val1=IntVar()
val2=IntVar()
val3=IntVar()
val4=IntVar()
val5=IntVar()
def proceed():
    #error checking
    if (val1.get()==0 and val2.get()==0) or (val3.get()==0 and val4.get()==0 and val5.get()==0) or tb1.get("1.0","end-1c")=="" or tb1.get("1.0","end-1c")=="" or tb2.get("1.0","end-1c")=="" or tb3.get("1.0","end-1c")=="" or tb4.get("1.0","end-1c")=="" or tb5.get("1.0","end-1c")=="" or tb6.get("1.0","end-1c")==""or tb7.get("1.0","end-1c")=="":
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Please complete the form')
        terr.pack()
        uf2.mainloop()

    try:
        direc=tb8.get("1.0","end-1c")#checks if direct is real
```

```
        fil=tb9.get("1.0","end-1c")
        file_name=direc+fil
        file=open(file_name,"a")
        file.close()
    except:
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='File directory not found')
        terr.pack()
        uf2.mainloop()

    else:
        station=tb1.get("1.0","end-1c").upper()#station number
        if val1.get()==1:# site tpye
            sitetype="RES"
        elif val2.get()==1:
            sitetype="DC"

        syyyy=tb2.get("1.0","end-1c")#dates
        smm=tb3.get("1.0","end-1c")
        sdd=tb4.get("1.0","end-1c")
        eyyyy=tb5.get("1.0","end-1c")
        emm=tb6.get("1.0","end-1c")
        edd=tb7.get("1.0","end-1c")

        old=""
        if val3.get()==1 :# data type
            datatype='Point&StartDT='
        elif val4.get()==1:
            datatype='Monthly&StartDT='
            old="&Format=Old"
        elif val5.get()==1:
            datatype='Daily&StartDT='


url1="https://www.dws.gov.za/Hydrology/Verified/HyData.aspx?Station="+station+"100.
00&DataType="+datatype
        initial_date=syyyy+"-"+smm+"-"+sdd
        url2="&EndDT="+eyyyy+"-"+emm+"-"+edd+"&SiteType="+sitetype+old

        if val3.get()==1 :# data type
            datatypes=3
        elif val4.get()==1:
            datatypes=1
        elif val5.get()==1:
            datatypes=2

        direc=tb8.get("1.0","end-1c")#save location
        fil=tb9.get("1.0","end-1c")
        file_name=direc+fil

        x=0
        while x<1:#loops through multiple request until error occurs
            if datatypes==1:
                single_request(url1,initial_date,url2,datatypes,file_name,sitetype)
                break
            else:

check=single_request(url1,initial_date,url2,datatypes,file_name,sitetype)
                if check==-5:
                    break
                else:
                    initial_date=check

def default():
    if len(tb1.get("1.0","end-1c"))<6:
        uf3=Tk()
```

```
        uf3.title('Error')
        uf3.geometry('310x50')
        terr1=Label(uf3,text='Please insert a valid station number')
        terr1.pack()
        uf3.mainloop()
    else:
        station=tb1.get("1.0","end-1c").upper()

url='https://www.dws.gov.za/Hydrology/Verified/HyDataSets.aspx?Station='+station
        page=urlopen(url)
        html_bytes=page.read()
        html=html_bytes.decode("utf-8")#downloads and converts the entire html 
document to one long string

        li=[]
        arr=range(0,17)
        stt=1
        for i in arr:#gets the postition of all the <td> tags in the string
                pos=html.find("<td>",stt)
                li.append(pos)
                stt=pos+1

        start_from=li[15]+43#postitions to cut the string
        start_to=start_from+10
        start_date=html[start_from:start_to]
        end_from=li[16]+45#postitions to cut the string
        end_to=end_from+10
        end_date=html[end_from:end_to]
        syyyy=start_date[0:4]#splits dates into components
        smm=start_date[5:7]
        sdd=start_date[8:10]
        eyyyy=end_date[0:4]
        emm=end_date[5:7]
        edd=end_date[8:10]

        tb2.delete(1.0,END)#clears the existing text
        tb3.delete(1.0,END)
        tb4.delete(1.0,END)
        tb5.delete(1.0,END)
        tb6.delete(1.0,END)
        tb7.delete(1.0,END)
        tb2.insert(END,syyyy)#writes to the textbox
        tb3.insert(END,smm)
        tb4.insert(END,sdd)
        tb5.insert(END,eyyyy)
        tb6.insert(END,emm)
        tb7.insert(END,edd)

def swap1():
    if val2.get()==1:
        ob2.deselect()
def swap2():
    if val1.get()==1:
        ob1.deselect()
def swap3():
    if val4.get()==1:
        ob4.deselect()
    if val5.get()==1:
        ob5.deselect()
def swap4():
    if val3.get()==1:
        ob3.deselect()
    if val5.get()==1:
        ob5.deselect()
def swap5():
    if val3.get()==1:
        ob3.deselect()
    if val4.get()==1:
```

```
        ob4.deselect()

uf1.title('Downloader')#componenets
uf1.geometry('310x280')

f1=Frame(uf1)#station only
t1=Label(f1,text='Station:')
tb1=Text(f1,height=1,width=20)
f1.grid(column=0,row=0,sticky=W)
t1.grid(column=0,row=0)
tb1.grid(column=1,row=0)

f2=Frame(uf1)#site type
t2=Label(f2,text='Site type:')
ob1=Checkbutton(f2,text='Reservoir',variable=val1,command=swap1)
ob2=Checkbutton(f2,text='D/S Component',variable=val2,command=swap2)
f2.grid(column=0,row=1,sticky=W)
t2.grid(column=0,row=1)
ob1.grid(column=1,row=1)
ob2.grid(column=2,row=1)

f3=Frame(uf1)#dates
t3=Label(f3,text='YYYY')
t4=Label(f3,text='MM')
t5=Label(f3,text='DD')
t6=Label(f3,text='Start Date')
t7=Label(f3,text='End Date')
b1=Button(f3,text='Default',command=default)
tb2=Text(f3,height=1,width=5)
tb3=Text(f3,height=1,width=5)
tb4=Text(f3,height=1,width=5)
tb5=Text(f3,height=1,width=5)
tb6=Text(f3,height=1,width=5)
tb7=Text(f3,height=1,width=5)
f3.grid(column=0,row=2,sticky=W)
t3.grid(column=1,row=0,sticky=W)
t4.grid(column=2,row=0,sticky=W)
t5.grid(column=3,row=0,sticky=W)
t6.grid(column=0,row=1,sticky=W)
t7.grid(column=0,row=2,sticky=W)
tb2.grid(column=1,row=1)
tb3.grid(column=2,row=1)
tb4.grid(column=3,row=1)
tb5.grid(column=1,row=2)
tb6.grid(column=2,row=2)
tb7.grid(column=3,row=2)
b1.grid(column=4,row=2)

f4=Frame(uf1)#data type
t8=Label(f4,text='Data type:')
ob3=Checkbutton(f4,text='Primary',command=swap3,variable=val3)
ob4=Checkbutton(f4,text='Monthly',command=swap4,variable=val4)
ob5=Checkbutton(f4,text='Daily',command=swap5,variable=val5)
f4.grid(column=0,row=3,sticky=W)
t8.grid(column=0,row=0)
ob3.grid(column=1,row=0)
ob4.grid(column=2,row=0)
ob5.grid(column=3,row=0)

f5=Frame(uf1)#saving
t9=Label(f5,text='File directory:')
t10=Label(f5,text='File name:')
tb8=Text(f5,height=1,width=20)
tb9=Text(f5,height=1,width=20)
tb8.insert(END,'c:\Example'+'\\')
tb9.insert(END,'example.txt')
f5.grid(column=0,row=4,sticky=W)
t9.grid(column=0,row=0,sticky=W)
```

```
t10.grid(column=0,row=1,sticky=W)
tb8.grid(column=1,row=0)
tb9.grid(column=1,row=1)

f6=Frame(uf1)#just the button
b2=Button(f6,text='Create Dataset',command=proceed)
f6.grid(column=0,row=5)
b2.grid(column=0,row=1)

uf1.mainloop()
```

A.4 RAPID ASSESSMENT TOOL

```
from tkinter import *

def import_monthly(file_directory):#writes data from file_directory to the matrix
mat
    monthly_file=open(file_directory,"r")
    monthly_data=monthly_file.readlines()
    monthly_file.close()
    mat=[]
    cnt=0
    for line in monthly_data:
        row=[]
        try:
            row.append(float(monthly_data[cnt][11:18]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][20:27]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][29:36]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][38:45]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][47:54]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][56:63]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][65:72]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][74:81]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][83:90]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][92:99]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][101:108]))
        except:
            row.append('#')
        try:
            row.append(float(monthly_data[cnt][110:117]))
        except:
            row.append('#')
        mat.append(row)
        cnt=cnt+1
    return mat, cnt

def average_volume(mat,cnt):#calculates average volume for each month (Oct-Sept)
    volume=[]
    for i in range(12):
```

```
        add=0
        n=0
        for k in range(cnt):
            if mat[k][i]=='#':
                x=0
            else:
                add=mat[k][i]*1000000+add
                n=n+1
                average=add/n
        volume.append(average)
    return volume

def power_calc(volume,h,p,g,eff,lf):#calculates the flow, power and energy for each
month for a given volume list with inputs
    flow_list=[0,0,0,0,0,0,0,0,0,0,0,0]
    power_list=[0,0,0,0,0,0,0,0,0,0,0,0]
    energy_list=[0,0,0,0,0,0,0,0,0,0,0,0]
    for i in range(12):
        if i==0 or i==2 or i==3 or i==5 or i==7 or i==9 or i==10:
            day=31
        elif i==4:
            day=28
        else:
            day=30
        flow_list[i]=volume[i]/(day*24*3600)
        power_list[i]=p*g*flow_list[i]*h*eff/1000
        energy_list[i]=power_list[i]*24*day*lf
    return flow_list,power_list,energy_list

def upper_limit_1(mat,cnt):#calculates the upper_limit for the given matrix and
sets the values that exceed the ul to the average
    volume=average_volume(mat,cnt)
    add=0
    n=0
    for i in range(12):#calculates the average of the entire set
        for k in range(cnt):
            if mat[k][i]=='#':
                x=0
            else:
                add=mat[k][i]*1000000+add
                n=n+1
    average=add/n
    add=0
    n=0

    for i in range(12):#calculates the standard deviation of the entire set
        for k in range(cnt):
            if mat[k][i]=='#':
                x=0
            else:
                add=(mat[k][i]*1000000-average)**2+add
                n=n+1
    standard=(add/n)**0.5
    ul=average+3*standard#upperlimit

    for i in range(12):#sets values that exceed the ul to the average
        for k in range(cnt):
            try:
                if mat[k][i]*1000000>ul:
                    mat[k][i]=average/1000000
            except:
                x=0
    return mat

def upper_limit_2(mat,cnt):#calculates the midpoint upper_limit for months adjacent
to maximum month
    volume=average_volume(mat,cnt)
    max_position=volume.index(max(volume,key=float))
```

```
        max_minor=max_position-1
        max_major=max_position+1
        if max_minor==-1:
            max_minor=11
        if max_major==12:
            max_major=0
        average=(volume[max_minor]+volume[max_major])/2
        standard_dev=[]

        if max_minor==11:
            for i in range(2):
                add=0
                n=0
                for k in range(cnt):
                    if mat[k][max_minor]=='#' or mat[k][1]=='#':
                        x=0
                    else:
                        if i==0:
                            add=(mat[k][max_minor]*1000000-average)**2+add
                            n=n+1
                        else:
                            add=(mat[k][1]*1000000-average)**2+add
                            n=n+1
                standard=(add/n)**0.5
                standard_dev.append(standard)

        elif max_minor==10:
            for i in range(2):
                add=0
                n=0
                for k in range(cnt):
                    if mat[k][max_minor]=='#' or mat[k][0]=='#':
                        x=0
                    else:
                        if i==0:
                            add=(mat[k][max_minor]*1000000-average)**2+add
                            n=n+1
                        else:
                            add=(mat[k][0]*1000000-average)**2+add
                            n=n+1
                standard=(add/n)**0.5
                standard_dev.append(standard)

        else:
            for i in range(0,3,2):
                add=0
                n=0
                for k in range(cnt):#standard dev of adjacent months
                    if mat[k][max_minor+i]=='#':
                        x=0
                    else:
                        add=(mat[k][max_minor+i]*1000000-average)**2+add
                        n=n+1
                standard=(add/n)**0.5
                standard_dev.append(standard)

        average_standard_dev=sum(standard_dev)/2
        ul=average+3*average_standard_dev#upperlimit

        for i in range(12):#sets values that exceed the ul to the average
            for k in range(cnt):
                try:
                    if mat[k][i]*1000000>ul:
                        mat[k][i]=average/1000000
                except:
                    x=0
        return mat,max_position
```

```
def upper_limit_3(mat,cnt,max_position):#sets volumes values that exceed the maximum for the month before the ul2 to the new maximum
    volume=average_volume(mat,cnt)
    ul=volume[max_position]
    for i in range(12):
        try:
            if volume[i]>ul:
                volume[i]=ul
        except:
            x=0

    return volume

uf1=Tk()
def proceed():#calculate procedure
    #error checking
    if tb1.get("1.0","end-1c")==""  or tb2.get("1.0","end-1c")=="" or tb3.get("1.0","end-1c")=="" or tb4.get("1.0","end-1c")=="" or tb5.get("1.0","end-1c")=="" or tb6.get("1.0","end-1c")==""or tb7.get("1.0","end-1c")==""or tb8.get("1.0","end-1c")=="":
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Please complete the form')
        terr.pack()
        uf2.mainloop()
    try:
        monthly_loc=tb9.get("1.0","end-1c")+tb10.get("1.0","end-1c")
        file=open(monthly_loc,"r")
        file.close()
    except:
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Monthly data not found')
        terr.pack()
        uf2.mainloop()
    else:
        h=float(tb4.get("1.0","end-1c"))#gets values
        t=float(tb5.get("1.0","end-1c"))
        p=1000.14+0.0094*t-0.0053*t**2
        g=float(tb6.get("1.0","end-1c"))
        eff=float(tb7.get("1.0","end-1c"))/100
        lf=float(tb8.get("1.0","end-1c"))/100
        levels=[float(tb100.get("1.0","end-1c"))/100,float(tb101.get("1.0","end-1c"))/100,float(tb102.get("1.0","end-1c"))/100,float(tb103.get("1.0","end-1c"))/100,float(tb104.get("1.0","end-1c"))/100,float(tb105.get("1.0","end-1c"))/100,float(tb106.get("1.0","end-1c"))/100,float(tb107.get("1.0","end-1c"))/100,float(tb108.get("1.0","end-1c"))/100,float(tb109.get("1.0","end-1c"))/100,float(tb110.get("1.0","end-1c"))/100,float(tb111.get("1.0","end-1c"))/100,]

        file_directory=tb9.get("1.0","end-1c")+tb10.get("1.0","end-1c")#imports monthly data
        results=import_monthly(file_directory)
        mat=results[0]
        cnt=results[1]

        volume=average_volume(mat,cnt)#initial calculation
        results=power_calc(volume,h,p,g,eff,lf)
        flow_list=results[0]
        power_list=results[1]
        energy_list=results[2]

        if max(power_list,key=float)<100000:#checks for sites smaller 100MW
            mat=upper_limit_1(mat,cnt)
            results=upper_limit_2(mat,cnt)
            mat=results[0]
```

```
            max_position=results[1]
            volume=upper_limit_3(mat,cnt,max_position)
            results=power_calc(volume,h,p,g,eff,lf)
            flow_list=results[0]
            power_list=results[1]
            energy_list=results[2]

        if max(power_list,key=float)>1000:
            for i in range(12):#rounds final values (MW)
                flow_list[i]=round(flow_list[i],2)
                power_list[i]=round(levels[i]*power_list[i]/1000,2)
                energy_list[i]=round(levels[i]*energy_list[i]/1000000,2)
                levels[i]=round(levels[i]*100,2)
            unit='M'
        else:
            for i in range(12):#rounds final values (KW)
                flow_list[i]=round(flow_list[i],2)
                power_list[i]=round(levels[i]*power_list[i],2)
                energy_list[i]=round(levels[i]*energy_list[i]/1000000,2)
                levels[i]=round(levels[i]*100,2)
            unit='k'

        results_loc=tb9.get("1.0","end-1c")+tb11.get("1.0","end-1c")bsaves results
        results_file=open(results_loc,"w")
        results_file.write('Site name:
'+'\t'+tb1.get("1.0","end-1c")+'\n')
        results_file.write('Date:
'+'\t'+tb2.get("1.0","end-1c")+'\n')
        results_file.write('Station number:
'+'\t'+tb3.get("1.0","end-1c")+'\n')
        results_file.write('Height of dam wall(m):
'+'\t'+tb4.get("1.0","end-1c")+'\n')
        results_file.write('\n')
        results_file.write('Assumptions\n')
        results_file.write('Water temperature (°C):
'+'\t'+tb5.get("1.0","end-1c")+'\n')
        results_file.write('Density (kg/m³):
'+'\t'+str(round(p,2))+'\n')
        results_file.write('Gravitational acceleration
(m/s²):'+'\t'+tb6.get("1.0","end-1c")+'\n')
        results_file.write('Efficiency (%):
'+'\t'+tb7.get("1.0","end-1c")+'\n')
        results_file.write('Annual load factor (%):
'+'\t'+tb8.get("1.0","end-1c")+'\n')
        results_file.write('\n')
        results_file.write('Month                             '+'\t')
        results_file.write('Flow (m³/s)'+'\t'+'\t')
        results_file.write('Water level (%)'+'\t'+'\t')
        power_string='({}W):'.format(unit)
        results_file.write('Power '+power_string+'\t'+'\t')
        results_file.write('Energy (GWh)'+'\n')

        months=['October                     ','November
','December                     ','January                     ','February
','March                     ','April                     ','May
','June                     ','July                     ','August
','September                     ']
        for i in range(12):
            while len(str(flow_list[i]))<11:
                flow_list[i]=str(flow_list[i])+' '
            while len(str(power_list[i]))<11:
                power_list[i]=str(power_list[i])+' '
            while len(str(levels[i]))<11:
                levels[i]=str(levels[i])+' '
            results_file.write(months[i]+'\t'+'\t')
            results_file.write(str(flow_list[i])+'\t'+'\t')
            results_file.write(str(levels[i])+'\t'+'\t')
            results_file.write(str(power_list[i])+'\t'+'\t')
```

```
            results_file.write(str(energy_list[i])+'\n')

        q_int=float(max(flow_list,key=float))#calculates number of turbines
        if q_int>110:
            nturbines=round(q_int/100)
            q_des=round(q_int/nturbines,2)
        else:
            nturbines=1
            q_des=q_int

        results_file.write('\n')
        results_file.write('Results\n')
        results_file.write('Maximum available power '+power_string+'\t'+'\t')
        mm=round(float(max(power_list,key=float)),2)
        results_file.write(str(mm)+'\n')
        results_file.write('Potential annual energy (GWh):   \t')
        results_file.write(str(round(sum(energy_list),2))+'\n')
        results_file.write('Suggested flow (m³/s):              \t')
        results_file.write(str(q_des)+'\n')
        results_file.write('Suggested head (m):                 \t')
        results_file.write(str(h)+'\n')
        results_file.write('Suggested turbine type:          \t')

        if h>50 and q_des<2:
            turbine='Pelton'
        else:
            if (h>10 and q_des<=20) or h>=50:
                turbine='Francis'
            else:
                turbine='Kaplan'

        results_file.write(turbine+'\n')
        results_file.write('Number of turbines:              \t')
        results_file.write(str(nturbines)+'\n')
        results_file.close()

#componenets
uf1.title('Rapid Assessment Tool')
uf1.geometry('510x560')

f1=Frame(uf1)#inputs
t0=Label(f1,text='Inputs')
t1=Label(f1,text='Site name:')
t2=Label(f1,text='Date:')
t3=Label(f1,text='Station number:')
t4=Label(f1,text='Height of dam wall (m):')
tb1=Text(f1,height=1,width=20)
tb2=Text(f1,height=1,width=20)
tb3=Text(f1,height=1,width=20)
tb4=Text(f1,height=1,width=20)
f1.grid(column=0,row=0,sticky=W)
t0.grid(column=0,row=0,sticky=W)
t1.grid(column=0,row=1,sticky=W)
t2.grid(column=0,row=2,sticky=W)
t3.grid(column=0,row=3,sticky=W)
t4.grid(column=0,row=4,sticky=W)
tb1.grid(column=1,row=1)
tb2.grid(column=1,row=2)
tb3.grid(column=1,row=3)
tb4.grid(column=1,row=4)

f5=Frame(uf1)#Assumptions
t5=Label(f5,text='Water temperature (°C):')
t6=Label(f5,text='Gravitational acceleration (m/s²):')
t7=Label(f5,text='Efficiency (%):')
t8=Label(f5,text='Annual load factor (%):')
t87=Label(f5,text='')
t88=Label(f5,text='Assumptions')
```

```
tb5=Text(f5,height=1,width=5)
tb6=Text(f5,height=1,width=5)
tb7=Text(f5,height=1,width=5)
tb8=Text(f5,height=1,width=5)
tb5.insert(END,'20')
tb6.insert(END,'9.81')
tb7.insert(END,'85')
tb8.insert(END,'100')
f5.grid(column=0,row=6,sticky=W)
t87.grid(column=0,row=0,sticky=W)
t88.grid(column=0,row=1,sticky=W)
t5.grid(column=0,row=2,sticky=W)
t6.grid(column=2,row=2)
t7.grid(column=0,row=3,sticky=W)
t8.grid(column=2,row=3,sticky=W)
tb5.grid(column=1,row=2)
tb6.grid(column=3,row=2)
tb7.grid(column=1,row=3)
tb8.grid(column=3,row=3)

f88=Frame(uf1)#water levels
f89=Frame(uf1)
t98=Label(f88,text='')
t99=Label(f88,text='Average water level (%)')
t100=Label(f89,text='Oct')
t101=Label(f89,text='Nov')
t102=Label(f89,text='Dec')
t103=Label(f89,text='Jan')
t104=Label(f89,text='Feb')
t105=Label(f89,text='Mar')
t106=Label(f89,text='Apr')
t107=Label(f89,text='May')
t108=Label(f89,text='Jun')
t109=Label(f89,text='Jul')
t110=Label(f89,text='Aug')
t111=Label(f89,text='Sep')
tb100=Text(f89,height=1,width=5)
tb101=Text(f89,height=1,width=5)
tb102=Text(f89,height=1,width=5)
tb103=Text(f89,height=1,width=5)
tb104=Text(f89,height=1,width=5)
tb105=Text(f89,height=1,width=5)
tb106=Text(f89,height=1,width=5)
tb107=Text(f89,height=1,width=5)
tb108=Text(f89,height=1,width=5)
tb109=Text(f89,height=1,width=5)
tb110=Text(f89,height=1,width=5)
tb111=Text(f89,height=1,width=5)
f88.grid(column=0,row=4)
t98.grid(column=0,row=0,sticky=W)
t99.grid(column=0,row=1,sticky=W)
f89.grid(column=0,row=5)
t100.grid(column=0,row=2,sticky=E)
t101.grid(column=1,row=2,sticky=E)
t102.grid(column=2,row=2,sticky=E)
t103.grid(column=3,row=2,sticky=E)
t104.grid(column=4,row=2,sticky=E)
t105.grid(column=5,row=2,sticky=E)
t106.grid(column=0,row=4,sticky=E)
t107.grid(column=1,row=4,sticky=E)
t108.grid(column=2,row=4,sticky=E)
t109.grid(column=3,row=4,sticky=E)
t110.grid(column=4,row=4,sticky=E)
t111.grid(column=5,row=4,sticky=E)
tb100.grid(column=0,row=3,sticky=E)
tb101.grid(column=1,row=3,sticky=E)
tb102.grid(column=2,row=3,sticky=E)
tb103.grid(column=3,row=3,sticky=E)
```

```
tb104.grid(column=4,row=3,sticky=E)
tb105.grid(column=5,row=3,sticky=E)
tb106.grid(column=0,row=5,sticky=E)
tb107.grid(column=1,row=5,sticky=E)
tb108.grid(column=2,row=5,sticky=E)
tb109.grid(column=3,row=5,sticky=E)
tb110.grid(column=4,row=5,sticky=E)
tb111.grid(column=5,row=5,sticky=E)

f6=Frame(uf1)#Import & Save
t9=Label(f6,text='File directory:              ')
t10=Label(f6,text='Import data from:           ')
t11=Label(f6,text='Save results as:            ')
t98=Label(f6,text='')
t99=Label(f6,text='File')
tb9=Text(f6,height=1,width=20)
tb10=Text(f6,height=1,width=20)
tb11=Text(f6,height=1,width=20)
tb9.insert(END,'c:\Example'+'\\')
tb10.insert(END,'Monthly.txt')
tb11.insert(END,'Rapid_results.txt')
f6.grid(column=0,row=7,sticky=W)
t98.grid(column=0,row=0,sticky=W)
t99.grid(column=0,row=1,sticky=W)
t9.grid(column=0,row=2,sticky=W)
t10.grid(column=0,row=3,sticky=W)
t11.grid(column=0,row=4,sticky=W)
tb9.grid(column=1,row=2)
tb10.grid(column=1,row=3)
tb11.grid(column=1,row=4)

f7=Frame(uf1)#just the button
b2=Button(f7,text='Calculate',command=proceed)
f7.grid(column=0,row=8)
b2.grid(column=0,row=1)

uf1.mainloop()
```

A.5 SCENARIO ASSESSMENT TOOL

```
from tkinter import *
from tkinter import ttk
import math

def import_daily(file_directory):#writes data from file_directory to the matrix
    daily_file=open(file_directory,"r")
    daily_data=daily_file.readlines()
    daily_file.close()
    mat=[]
    cnt=0
    for line in daily_data:
        row=[]
        try:
            row.append(float(daily_data[cnt][0:8]))
        except:
            row.append('#')
        try:
            row.append(float(daily_data[cnt][10:18]))
        except:
            row.append('#')

        mat.append(row)
        cnt=cnt+1
    return mat,cnt

def import_primary(file_directory):#writes data from file_directory to the matrix
    primary_file=open(file_directory,"r")
    primary_data=primary_file.readlines()
    primary_file.close()
    mat=[]
    cnt=0
    for line in primary_data:
        row=[]
        try:
            row.append(float(primary_data[cnt][0:8]))
        except:
            row.append('#')
        try:
            row.append(float(primary_data[cnt][27:35]))
        except:
            row.append('#')

        mat.append(row)
        cnt=cnt+1
    return mat,cnt

def average_primary(mat,cnt):#calcutes the average level for each day for a given
matrix
    mat_average=[]
    i=0
    cnt5=0
    while i != cnt:
        row=[]
        initial_date=mat[i][0]
        row.append(initial_date)
        add=0
        n=0
        while mat[i][0]==initial_date:
            if mat[i][1]!='#':
                add=mat[i][1]+add
                n=n+1
            i=i+1
            if i==cnt:
                break
        if n==0:
            average=add
```

```
        else:
            average=add/n
        row.append(average)
        cnt5=cnt5+1
        mat_average.append(row)
    return mat_average,cnt5

def power_mat2(daily,primary,cntd,cntp):#generates power matrix
    mat=[]
    k_s=0
    cnt=0
    for i in range(cntp):
        row=[]
        k=k_s
        while k != cntd:
            if primary[i][0]==daily[k][0]:
                row.append(primary[i][0])
                row.append(primary[i][1])
                row.append(daily[k][1])
                mat.append(row)
                cnt=cnt+1
                k_s=k
                break
            k=k+1

    return mat,cnt

def power_calc(mat,p,g,h,eff,cnt):#calculates the power for each day
    ppp=[]
    for i in range(cnt):
        if mat[i][1]!='#' and mat[i][2]!='#':
            mat[i][1]=mat[i][1]+h
            H=mat[i][1]
            power=p*g*mat[i][2]*H*eff
        else:
            power='#'
        mat[i].append(power)
    return mat

def power_ranked(mat):#ranks the matrix in descending order
    ppp=[]
    for i in range(len(mat)):
        try:
            if mat[i][3]!='#':
                ppp.append(mat[i][3])
        except:
            x=0

    ppp.sort(reverse=True)
    maxi=ppp[0]
    cnt=len(ppp)-1
    intervals=[5,10,15,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90,95]
    interval_positions=[]
    for i in range(19):
        pos=round((intervals[i]/100)*cnt)
        interval_positions.append(pos)

    duration_curve=[maxi]
    for i in interval_positions:
        duration_curve.append(ppp[i])

    duration_curve.append(ppp[cnt])

    return duration_curve,ppp

uf1=Tk()
def show_headloss():#shows headloss userform
    uf3=Tk()
```

```
    def include():#button to include headloss
        ks=float(tb21.get("1.0","end-1c"))/1000
        L=float(tb22.get("1.0","end-1c"))
        D=float(tb23.get("1.0","end-1c"))
        Q=float(tb24.get("1.0","end-1c"))
        K=float(tb25.get("1.0","end-1c"))

        log=math.log((3.7*D)/(ks),10)
        lamda=(1/(2*log))**2
        A=math.pi*(D/2)**2
        V=Q/A
        hf=(lamda*L*V**2)/(2*9.81*D)
        hl=(K*V**2)/(2*9.81)
        delta_h=str(hf+hl)
        tb800.insert(END,delta_h)
        uf3.destroy()

    uf3.title('Headloss')
    uf3.geometry('450x200')
    t21=Label(uf3,text='Absolute roughness (mm):')
    t22=Label(uf3,text='Length (m):')
    t23=Label(uf3,text='Diameter (m):')
    t24=Label(uf3,text='Required flow (m³/s):')
    t26=Label(uf3,text=' ')
    t25=Label(uf3,text='Sum of local loss coefficients (K):')
    tb21=Text(uf3,height=1,width=20)
    tb22=Text(uf3,height=1,width=20)
    tb23=Text(uf3,height=1,width=20)
    tb24=Text(uf3,height=1,width=20)
    tb25=Text(uf3,height=1,width=20)
    t21.grid(column=0,row=1,sticky=W)
    t22.grid(column=0,row=2,sticky=W)
    t23.grid(column=0,row=3,sticky=W)
    t24.grid(column=0,row=4,sticky=W)
    t26.grid(column=0,row=5,sticky=W)
    t25.grid(column=0,row=6,sticky=W)
    tb21.grid(column=1,row=1)
    tb22.grid(column=1,row=2)
    tb23.grid(column=1,row=3)
    tb24.grid(column=1,row=4)
    tb25.grid(column=1,row=6)
    f33=Frame(uf3)
    b22=Button(f33,text='Include',command=include)
    f33.grid(column=0,row=7,sticky=E)
    b22.grid(column=1,row=0)
    uf3.mainloop

def closest(lst, K):#finds closest value in list
    return lst[min(range(len(lst)), key = lambda i: abs(lst[i]-K))]

def proceed():#calculate procedure
    #error checking
    if tb1.get("1.0","end-1c")==""  or tb2.get("1.0","end-1c")=="" or
tb3.get("1.0","end-1c")=="" or tb4.get("1.0","end-1c")=="" or tb5.get("1.0","end-
1c")=="" or tb6.get("1.0","end-1c")==""or tb7.get("1.0","end-1c")=="":
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Please complete the form')
        terr.pack()
        uf2.mainloop()
    try:
        primary_loc=tb9.get("1.0","end-1c")+tb10.get("1.0","end-1c")
        file=open(primary_loc,"r")
        file.close()
        daily_loc=tb9.get("1.0","end-1c")+tb100.get("1.0","end-1c")
        file=open(daily_loc,"r")
        file.close()
```

```
    except:
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Import data not found')
        terr.pack()
        uf2.mainloop()
    else:
        site=tb1.get("1.0","end-1c")#saves values
        date=tb2.get("1.0","end-1c")
        station=tb3.get("1.0","end-1c")
        h=float(tb4.get("1.0","end-1c"))
        try:
            delta_h=float(tb800.get("1.0","end-1c"))
        except:
            delta_h=0
        h=h-delta_h
        t=float(tb5.get("1.0","end-1c"))
        p=1000.14+0.0094*t-0.0053*t**2
        g=float(tb6.get("1.0","end-1c"))
        eff=float(tb7.get("1.0","end-1c"))/100
        lf=1#left over from previos versions to avoid errors

        try:#gets scenario
            turbine_power=float(tb600.get("1.0","end-1c"))*1000
        except:
            turbine_power=0
        try:
            turbine_type=tb601.get()
        except:
            turbine_type='Kaplan'
        try:
            num_turbines=int(tb602.get("1.0","end-1c"))
        except:
            num_turbines=1
        try:
            op_allow=float(tb603.get("1.0","end-1c"))/100
        except:
            op_allow=0

        if 1/num_turbines<=op_allow:
            uf25=Tk()
            uf25.title('Error')
            uf25.geometry('310x50')
            terr25=Label(uf25,text='Operating allowance to high')
            terr25.pack()
            uf25.mainloop()

        primary_directory=tb9.get("1.0","end-1c")+tb10.get("1.0","end-1c")
        daily_directory=tb9.get("1.0","end-1c")+tb100.get("1.0","end-1c")
        save_directory=tb9.get("1.0","end-1c")+tb11.get("1.0","end-1c")

        results=import_daily(daily_directory)#calls functions
        daily=results[0]
        cntd=results[1]
        results=import_primary(primary_directory)
        primary=results[0]
        cntp=results[1]
        results=average_primary(primary,cntp)
        primary=results[0]
        cntp=results[1]
        results=power_mat2(daily,primary,cntd,cntp)
        power_mat=results[0]
        power_cnt=results[1]
        power_mat=power_calc(power_mat,p,g,h,eff,power_cnt)
        results=power_ranked(power_mat)
        duration_curve=results[0]
        duration_curve_full=results[1]
```

```

        energy_curve=[]#generates energy curve
        for i in range(len(duration_curve_full)):
            energy_step=duration_curve_full[i]*8760*(i/len(duration_curve_full))
            energy_curve.append(energy_step)

        max_energy=max(energy_curve,key=float)#finds max energy on curve
        max_pos=energy_curve.index(max_energy)
        opt_power=duration_curve_full[max_pos]

        num_scenarios=num_turbines#calculates energy for each scenario (number of 
tubrines with
        target_energy=0
        turbine_energy=0
        single_turbine=turbine_power
        for i in range(num_scenarios):#loops through each turbine number
            pos_list=[]
            turbine_power=single_turbine*(i+1)
            for k in range(2):#loops through max and min power
                if k==0:
                    target_power=turbine_power
                else:
                    target_power=turbine_power-(turbine_power*op_allow)

                target_power_curve=closest(duration_curve_full, target_power)
                target_pos=duration_curve_full.index(target_power_curve)
                pos_list.append(target_pos)

            start_exc=pos_list[0]/len(duration_curve_full)
            turbine_energy=(duration_curve_full[pos_list[0]]*8760*start_exc)
            adj_exc=start_exc
            for qwe in range(pos_list[0]+1,pos_list[1]+1):
                energy_exc=(qwe/len(duration_curve_full))-adj_exc
                adj_exc=energy_exc+adj_exc

turbine_energy=(duration_curve_full[qwe]*8760*energy_exc)+turbine_energy

            target_energy=target_energy+turbine_energy

        energy_report=[]

probs_dec=[0,0.05,0.1,0.15,0.2,0.25,0.3,0.35,0.4,0.45,0.5,0.55,0.6,0.65,0.7,0.75,0.
8,0.85,0.9,0.95,1]
        max_power=duration_curve[3]
        if max_power>1000000:
            for i in range(21):#sets to MW
                duration_curve[i]=duration_curve[i]/1000000
                e_step=(duration_curve[i]*probs_dec[i]*24*365)/1000
                energy_report.append(e_step)
            opt_power=opt_power/1000000
            turbine_power=(turbine_power)/1000000
            unit='M'
        else:
            for i in range(21):#sets to kW
                duration_curve[i]=duration_curve[i]/1000
                e_step=(duration_curve[i]*probs_dec[i]*24*365)/1000000
                energy_report.append(e_step)
            opt_power=opt_power/1000
            turbine_power=(turbine_power)/1000
            unit='k'

        power_string='({}W)'.format(unit)
        results_file=open(save_directory,"w")
        results_file.write('Site name: 
'+'\t'+tb1.get("1.0","end-1c")+'\n')
        results_file.write('Date: 
'+'\t'+tb2.get("1.0","end-1c")+'\n')
```

```
        results_file.write('Station number:
'+'\t'+tb3.get("1.0","end-1c")+'\n')
        results_file.write('Height between spillway crest and turbine
(m):'+'\t'+tb4.get("1.0","end-1c")+'\n')
        results_file.write('Headloss (m):
'+'\t'+tb800.get("1.0","end-1c")+'\n')
        results_file.write('Rated power per turbine (kW):
'+'\t'+tb600.get("1.0","end-1c")+'\n')
        results_file.write('Operating allowance (%):
'+'\t'+tb603.get("1.0","end-1c")+'\n')
        results_file.write('Turbine type:
'+'\t'+tb601.get()+'\n')
        results_file.write('Number of turbines:
'+'\t'+tb602.get("1.0","end-1c")+'\n')
        results_file.write('\n')
        results_file.write('Assumptions\n')
        results_file.write('Water temperature (°C):
'+'\t'+tb5.get("1.0","end-1c")+'\n')
        results_file.write('Density (kg/m³):
'+'\t'+str(round(p,2))+'\n')
        results_file.write('Gravitational acceleration (m/s²):
'+'\t'+tb6.get("1.0","end-1c")+'\n')
        results_file.write('Efficiency (%):
'+'\t'+tb7.get("1.0","end-1c")+'\n')
        results_file.write('\n')
        results_file.write('Exceedance probability (%)                    '+'\t')
        results_file.write('Power '+power_string+'\t')
        results_file.write('Energy (GWh/a)')
        results_file.write('\n')

        probs=['0                             ','5
','10                             ','15                             ','20
','25                          ',
                   '30                          ','35
','40                             ','45                             ','50
','55                          ',
                   '60                          ','65
','70                             ','75                             ','80
','85                          ',
                   '90                          ','95
','100                            ']

        for i in range(21):
            results_file.write(probs[i]+'\t'+'\t'+'\t')
            results_file.write(str(round(duration_curve[i],2))+'\t'+'\t')
            results_file.write(str(round(energy_report[i],2))+'\t'+'\t')
            results_file.write('\n')

        results_file.write('\n')
        results_file.write('Scenario results\n')
        results_file.write('Potential annual energy (GWh):'+'\t'+'\t'+'\t')
        results_file.write(str(round(target_energy/1000000000,2))+'\n')
        results_file.write('Total rated power '+power_string+':
'+'\t'+'\t'+'\t')
        results_file.write(str(round(turbine_power,2))+'\n')
        results_file.write('\n')
        results_file.write('Optimal point on curve\n')
        results_file.write('Annual energy (GWh):'+'\t'+'\t'+'\t'+'\t')
        results_file.write(str(round(max_energy/1000000000,2))+'\n')
        results_file.write('Power rating '+power_string+':       '+'\t'+'\t'+'\t')
        results_file.write(str(round(opt_power,2))+'\n')
        results_file.write('Load factor (%):'+'\t'+'\t'+'\t'+'\t')

results_file.write(str(round((max_pos/len(duration_curve_full))*100,2))+'\n')
        results_file.close()

        save_directory_2=tb9.get("1.0","end-1c")+'Daily_power.txt'#Generates daily
power table document
```

```
        results_file_2=open(save_directory_2,"w")
        results_file_2.write('Date\t')
        results_file_2.write('Head(m)\t')
        results_file_2.write('Flow(m³/s)\t')
        results_file_2.write('Power(W)\t')
        eff_string='Efficiency of {}%\t'.format(round(eff*100,0))
        results_file_2.write(eff_string)
        results_file_2.write('\n')
        for i in range(len(power_mat)):
            line=power_mat[i]
            results_file_2.write(str(line[0])+'\t')
            results_file_2.write(str(line[1])+'\t')
            results_file_2.write(str(line[2])+'\t')
            results_file_2.write(str(line[3])+'\t')
            results_file_2.write('\n')
        results_file_2.close()


#componenets
uf1.title('Scenario Assessment Tool')
uf1.geometry('600x470')

f1=Frame(uf1)#inputs
t0=Label(f1,text='Inputs')
t1=Label(f1,text='Site name:')
t2=Label(f1,text='Date:')
t3=Label(f1,text='Station number:')
t4=Label(f1,text='Height between spillway crest and turbine (m):')
t500=Label(f1,text='Headloss (m):')
cb1=Button(f1,text='Calculate',command=show_headloss)
t600=Label(f1,text='Rated power per turbine (kW):')
t603=Label(f1,text='Operating allowance (%):')
t601=Label(f1,text='Turbine type:')
t602=Label(f1,text='Number of turbines:')
tb1=Text(f1,height=1,width=20)
tb2=Text(f1,height=1,width=20)
tb3=Text(f1,height=1,width=20)
tb4=Text(f1,height=1,width=20)
tb800=Text(f1,height=1,width=20)
tb600=Text(f1,height=1,width=20)
turbines_list=['Pelton','Francis','Kaplan']
tb601=ttk.Combobox(f1,height=1,width=24,state='readonly',values=turbines_list)
tb602=Text(f1,height=1,width=20)
tb603=Text(f1,height=1,width=20)
f1.grid(column=0,row=0,sticky=W)
t0.grid(column=0,row=0,sticky=W)
t1.grid(column=0,row=1,sticky=W)
t2.grid(column=0,row=2,sticky=W)
t3.grid(column=0,row=3,sticky=W)
t4.grid(column=0,row=4,sticky=W)
t500.grid(column=0,row=5,sticky=W)
t600.grid(column=0,row=6,sticky=W)
t601.grid(column=0,row=8,sticky=W)
t602.grid(column=0,row=9,sticky=W)
t603.grid(column=0,row=7,sticky=W)
tb1.grid(column=1,row=1)
tb2.grid(column=1,row=2)
tb3.grid(column=1,row=3)
tb4.grid(column=1,row=4)
tb800.grid(column=1,row=5)
tb600.grid(column=1,row=6)
tb601.grid(column=1,row=8)
tb602.grid(column=1,row=9)
tb603.grid(column=1,row=7)
cb1.grid(column=2,row=5,sticky=W)

f5=Frame(uf1)#Assumptions
t5=Label(f5,text='Water temperature (°C):     ')
```

```
t6=Label(f5,text=' Gravitational acceleration (m/s²):')
t7=Label(f5,text=' Efficiency (%):')
t8=Label(f5,text=' Target power (kW):')
t87=Label(f5,text='')
t88=Label(f5,text='Assumptions')
tb5=Text(f5,height=1,width=5)
tb6=Text(f5,height=1,width=5)
tb7=Text(f5,height=1,width=5)
tb5.insert(END,'20')
tb6.insert(END,'9.81')
tb7.insert(END,'85')
f5.grid(column=0,row=4,sticky=W)
t87.grid(column=0,row=0,sticky=W)
t88.grid(column=0,row=1,sticky=W)
t5.grid(column=0,row=2,sticky=W)
t6.grid(column=2,row=2)
t7.grid(column=4,row=2,sticky=W)
tb5.grid(column=1,row=2)
tb6.grid(column=3,row=2)
tb7.grid(column=5,row=2)

f6=Frame(uf1)#Import & Save
t9=Label(f6,text='File directory:                                           ')
t10=Label(f6,text='Import primary data from:                                ')
t100=Label(f6,text='Import daily average data from:                         ')
t11=Label(f6,text='Save results as:                                         ')
t98=Label(f6,text='')
t99=Label(f6,text='File')
tb9=Text(f6,height=1,width=20)
tb10=Text(f6,height=1,width=20)
tb100=Text(f6,height=1,width=20)
tb11=Text(f6,height=1,width=20)
tb9.insert(END,'c:\Example'+'\\')
tb10.insert(END,'Primary.txt')
tb100.insert(END,'Daily.txt')
tb11.insert(END,'Scenario_results.txt')
f6.grid(column=0,row=6,sticky=W)
t98.grid(column=0,row=0,sticky=W)
t99.grid(column=0,row=1,sticky=W)
t9.grid(column=0,row=2,sticky=W)
t10.grid(column=0,row=3,sticky=W)
t100.grid(column=0,row=4,sticky=W)
t11.grid(column=0,row=5,sticky=W)
tb9.grid(column=1,row=2)
tb10.grid(column=1,row=3)
tb100.grid(column=1,row=4)
tb11.grid(column=1,row=5)

f7=Frame(uf1)#just the button
b2=Button(f7,text='Calculate',command=proceed)
f7.grid(column=0,row=7)
b2.grid(column=0,row=1)

uf1.mainloop()
```

A.6 LIFE CYCLE COSTING ANALYSIS TOOL

```
from tkinter import *
from tkinter import ttk

def main_calc(h,q,p,n,energy,price,turbine,inf,disc,esc,exchange,life,own_use):
    if turbine=='Pelton':#turbine
            a=1358677.67
            b=0.014
            c=8489.85
            d=0.515
            e=3382.1
            f=0.416
            g=-1479160.63
    elif turbine=='Francis':
            a=190.37
            b=1.27963
            c=1441610.56
            d=0.03064
            e=9.62402
            f=1.28487
            g=-1621571.28
    elif turbine=='Kaplan':
            a=139318.161
            b=0.02156
            c=0.06372
            d=1.45636
            e=155227.37
            f=0.11053
            g=-302038.27
    turbine_cost=a*(h**b)+c*(q**d)+e*(p**f)+g#construction
    electro_mech=turbine_cost*n
    electro_mech=((1+0.06)**5)*exchange*electro_mech#calibration
    civil_works=0.77*electro_mech
    capital_works=(electro_mech+civil_works)*5

    design=0.15*(electro_mech+civil_works)*3#planning

    if p<100000 and own_use==1:#legislation
        nersa=0
    else:
        nersa=20000*((1+0.06)**10)
    if p>20000:
        EIA=1.8*1000000*((1+0.06)**10)
    elif 100<p<20000:
        EIA=1.8*200000*((1+0.06)**10)#1.8 is calibration
    else:
        EIA=0
    planning=design+nersa+EIA

    civil_maint=0.0025*civil_works*9.775#o&m (5*1.955= 5 from capital calibration
1.955 from maint calibration)
    em_maint=0.04*electro_mech*9.775
    operation=float(tb14.get("1.0","end-1c"))+float(tb15.get("1.0","end-1c"))*1.15
    insurance=0.003*capital_works

    if p<1000:#wateruse license
        water_use=0
    else:
        water_use=10*p+0.01*energy

    annual_expense=civil_maint+em_maint+operation+insurance+water_use#annuities
    annual_revenue=price*energy

    if inf != disc:#npv costs
        npv_costs=((annual_expense)*((1+inf)**2)*((1-(1+inf)**(life-1)*(1+disc)**-
(life-1))/(disc-inf)))/(1+disc)**1+(planning+capital_works)/(1+disc)**1
    else:
```

```
        npv_costs=annual_expense*(1+inf)**1*(life-
1)/(1+disc)+(planning+capital_works)/((1+disc)**1)
    if esc != disc:#npv income
        npv_revenue=((annual_revenue)*((1+esc)**2)*((1-(1+esc)**(life-
1)*(1+disc)**-(life-1))/(disc-esc)))/(1+disc)**1
    else:
        npv_revenue=annual_revenue*(1+esc)**1*(life-1)/(1+disc)

    npv=npv_revenue-npv_costs#economic results
    bc=npv_revenue/npv_costs
    payback=(capital_works+planning)/annual_revenue

    return
npv,bc,payback,design,nersa,EIA,planning,electro_mech,civil_works,capital_works,civ
il_maint,em_maint,operation,insurance,water_use,annual_expense,annual_revenue,npv_c
osts,npv_revenue

uf1=Tk()
def staff():
    uf3=Tk()
    def include_staff():
        try:
            v1=float(tb32.get("1.0","end-1c"))
        except:
            v1=0
        try:
            v2=float(tb33.get("1.0","end-1c"))
        except:
            v2=0
        try:
            v3=float(tb34.get("1.0","end-1c"))
        except:
            v3=0
        try:
            v4=float(tb35.get("1.0","end-1c"))
        except:
            v4=0
        try:
            v5=float(tb36.get("1.0","end-1c"))
        except:
            v5=0
        try:
            v6=float(tb37.get("1.0","end-1c"))
        except:
            v6=0
        try:
            v7=float(tb38.get("1.0","end-1c"))
        except:
            v7=0
        try:
            v8=float(tb39.get("1.0","end-1c"))
        except:
            v8=0
        try:
            p1=float(tb40.get("1.0","end-1c"))/100
        except:
            p1=0
        try:
            p2=float(tb41.get("1.0","end-1c"))/100
        except:
            p2=0
        try:
            p3=float(tb42.get("1.0","end-1c"))/100
        except:
            p3=0
        try:
            p4=float(tb43.get("1.0","end-1c"))/100
        except:
```

```
            p4=0
        try:
            p5=float(tb44.get("1.0","end-1c"))/100
        except:
            p5=0
        try:
            p6=float(tb45.get("1.0","end-1c"))/100
        except:
            p6=0
        try:
            p7=float(tb46.get("1.0","end-1c"))/100
        except:
            p7=0
        try:
            p8=float(tb47.get("1.0","end-1c"))/100
        except:
            p8=0
        try:
            n1=float(tb551.get("1.0","end-1c"))
        except:
            n1=0
        try:
            n2=float(tb552.get("1.0","end-1c"))
        except:
            n2=0
        try:
            n3=float(tb553.get("1.0","end-1c"))
        except:
            n3=0
        try:
            n4=float(tb554.get("1.0","end-1c"))
        except:
            n4=0
        try:
            n5=float(tb555.get("1.0","end-1c"))
        except:
            n5=0
        try:
            n6=float(tb556.get("1.0","end-1c"))
        except:
            n6=0
        try:
            n7=float(tb557.get("1.0","end-1c"))
        except:
            n7=0
        try:
            n8=float(tb558.get("1.0","end-1c"))
        except:
            n8=0

val=str(v1*p1*n1+v2*p2*n2+v3*p3*n3+v4*p4*n4+v5*p5*n5+v6*p6*n6+v7*p7*n7+v8*p8*n8)
        tb14.delete(1.0,END)
        tb14.insert(END,val)

    uf3.title('Staff expenses')
    uf3.geometry('420x280')
    t30=Label(uf3,text='Annual package (ZAR)')
    t31=Label(uf3,text='% of time')
    t333=Label(uf3,text='Number of staff')
    t32=Label(uf3,text='Manager:')#level13
    t33=Label(uf3,text='Engineer:')#level12
    t34=Label(uf3,text='Technologist:')#level 11
    t35=Label(uf3,text='Technician:')#level 11
    t36=Label(uf3,text='Foreman:')#values brought forward from 2006
    t37=Label(uf3,text='Labourers:')
    t38=Label(uf3,text='Admin:')
    t39=Label(uf3,text='Financial:')
    tb32=Text(uf3,height=1,width=20)
```

```
tb33=Text(uf3,height=1,width=20)
tb34=Text(uf3,height=1,width=20)
tb35=Text(uf3,height=1,width=20)
tb36=Text(uf3,height=1,width=20)
tb37=Text(uf3,height=1,width=20)
tb38=Text(uf3,height=1,width=20)
tb39=Text(uf3,height=1,width=20)
tb40=Text(uf3,height=1,width=10)
tb41=Text(uf3,height=1,width=10)
tb42=Text(uf3,height=1,width=10)
tb43=Text(uf3,height=1,width=10)
tb44=Text(uf3,height=1,width=10)
tb45=Text(uf3,height=1,width=10)
tb46=Text(uf3,height=1,width=10)
tb47=Text(uf3,height=1,width=10)
tb551=Text(uf3,height=1,width=10)
tb552=Text(uf3,height=1,width=10)
tb553=Text(uf3,height=1,width=10)
tb554=Text(uf3,height=1,width=10)
tb555=Text(uf3,height=1,width=10)
tb556=Text(uf3,height=1,width=10)
tb557=Text(uf3,height=1,width=10)
tb558=Text(uf3,height=1,width=10)
tb32.insert(END,'2756040')
tb33.insert(END,'1378020')
tb34.insert(END,'826810')
tb35.insert(END,'689010')
tb36.insert(END,'277040')
tb37.insert(END,'137800')
tb38.insert(END,'251640')
tb39.insert(END,'419400')
tb40.insert(END,'10')
tb41.insert(END,'15')
tb42.insert(END,'20')
tb43.insert(END,'20')
tb44.insert(END,'30')
tb45.insert(END,'25')
tb46.insert(END,'10')
tb47.insert(END,'10')
tb551.insert(END,'1')
tb552.insert(END,'1')
tb553.insert(END,'1')
tb554.insert(END,'2')
tb555.insert(END,'1')
tb556.insert(END,'5')
tb557.insert(END,'1')
tb558.insert(END,'1')
b4=Button(uf3,text='Calculate',command=include_staff)
t30.grid(column=1,row=0,sticky=W)
t31.grid(column=2,row=0,sticky=W)
t333.grid(column=3,row=0,sticky=W)
t32.grid(column=0,row=1,sticky=W)
t33.grid(column=0,row=2,sticky=W)
t34.grid(column=0,row=3,sticky=W)
t35.grid(column=0,row=4,sticky=W)
t36.grid(column=0,row=5,sticky=W)
t37.grid(column=0,row=6,sticky=W)
t38.grid(column=0,row=7,sticky=W)
t39.grid(column=0,row=8,sticky=W)
tb32.grid(column=1,row=1)
tb33.grid(column=1,row=2)
tb34.grid(column=1,row=3)
tb35.grid(column=1,row=4)
tb36.grid(column=1,row=5)
tb37.grid(column=1,row=6)
tb38.grid(column=1,row=7)
tb39.grid(column=1,row=8)
tb40.grid(column=2,row=1)
```

```
        tb41.grid(column=2,row=2)
        tb42.grid(column=2,row=3)
        tb43.grid(column=2,row=4)
        tb44.grid(column=2,row=5)
        tb45.grid(column=2,row=6)
        tb46.grid(column=2,row=7)
        tb47.grid(column=2,row=8)
        tb551.grid(column=3,row=1)
        tb552.grid(column=3,row=2)
        tb553.grid(column=3,row=3)
        tb554.grid(column=3,row=4)
        tb555.grid(column=3,row=5)
        tb556.grid(column=3,row=6)
        tb557.grid(column=3,row=7)
        tb558.grid(column=3,row=8)
        b4.grid(column=1,row=9)
        uf3.mainloop()

    def annual():
        uf4=Tk()
        def include_annual():
            try:
                v41=float(tb49.get("1.0","end-1c"))
            except:
                v41=0
            try:
                v42=float(tb50.get("1.0","end-1c"))
            except:
                v42=0
            try:
                v43=float(tb51.get("1.0","end-1c"))
            except:
                v43=0
            try:
                v44=float(tb52.get("1.0","end-1c"))
            except:
                v44=0
            val2=str(v41+v42+v43+v44)
            tb15.delete(1.0,END)
            tb15.insert(END,val2)

        uf4.title('Annual expenses')
        uf4.geometry('290x170')
        t48=Label(uf4,text='Amount (ZAR/annum)')
        t49=Label(uf4,text='Transport:')
        t50=Label(uf4,text='Fuel:')
        t51=Label(uf4,text='Training:')
        t52=Label(uf4,text='Housing:')
        tb49=Text(uf4,height=1,width=20)
        tb50=Text(uf4,height=1,width=20)
        tb51=Text(uf4,height=1,width=20)
        tb52=Text(uf4,height=1,width=20)
        tb49.insert(END,'55120')
        tb50.insert(END,'29960')
        tb51.insert(END,'16775')
        tb52.insert(END,'55120')
        b5=Button(uf4,text='Calculate',command=include_annual)
        t48.grid(column=1,row=0)
        t49.grid(column=0,row=1,sticky=W)
        t50.grid(column=0,row=2,sticky=W)
        t51.grid(column=0,row=3,sticky=W)
        t52.grid(column=0,row=4,sticky=W)
        tb49.grid(column=1,row=1)
        tb50.grid(column=1,row=2)
        tb51.grid(column=1,row=3)
        tb52.grid(column=1,row=4)
        b5.grid(column=1,row=5)
        uf4.mainloop()
```

```
def proceed():#calculate procedure
    #error checking
    if tb1.get("1.0","end-1c")=="" or tb2.get("1.0","end-1c")=="" or tb3.get("1.0","end-1c")=="" or tb4.get("1.0","end-1c")=="" or tb5.get("1.0","end-1c")=="" or tb6.get()=="" or tb8.get("1.0","end-1c")=="" or tb9.get("1.0","end-1c")=="" or tb10.get("1.0","end-1c")=="" or tb11.get("1.0","end-1c")=="" or tb12.get("1.0","end-1c")==""or tb13.get("1.0","end-1c")=="" or tb14.get("1.0","end-1c")=="" or tb15.get("1.0","end-1c")=="":
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Please complete the form')
        terr.pack()
        uf2.mainloop()
    try:
        save_loc=tb19.get("1.0","end-1c")+tb20.get("1.0","end-1c")
        file=open(save_loc,"w")
        file.close()
    except:
        uf2=Tk()
        uf2.title('Error')
        uf2.geometry('310x50')
        terr=Label(uf2,text='Directory not found')
        terr.pack()
        uf2.mainloop()
    else:
        h=float(tb4.get("1.0","end-1c"))
        q=float(tb3.get("1.0","end-1c"))*1000
        p=float(tb1.get("1.0","end-1c"))
        n=float(tb5.get("1.0","end-1c"))
        energy=float(tb2.get("1.0","end-1c"))*1000000
        price=float(tb13.get("1.0","end-1c"))
        turbine=tb6.get()
        inf=float(tb11.get("1.0","end-1c"))/100
        disc=float(tb12.get("1.0","end-1c"))/100
        esc=float(tb10.get("1.0","end-1c"))/100
        exchange=float(tb9.get("1.0","end-1c"))
        life=float(tb8.get("1.0","end-1c"))
        own_use=v1313.get()


results=main_calc(h,q,p,n,energy,price,turbine,inf,disc,esc,exchange,life,own_use)
        npv=results[0]
        bc=results[1]
        payback=results[2]
        design=results[3]
        nersa=results[4]
        enviro=results[5]
        planning=results[6]
        em=results[7]
        civ=results[8]
        cap=results[9]
        cmaint=results[10]
        emmaint=results[11]
        opera=results[12]
        insur=results[13]
        wut=results[14]
        costs=results[15]
        benefits=results[16]
        npv_costs=results[17]
        npv_benefits=results[18]

        npvi=npv
        irr=0.0
        while npvi > 0:

results2=main_calc(h,q,p,n,energy,price,turbine,inf,irr,esc,exchange,life,own_use)
```

```
            npvi=results2[0]
            irr=round(irr+0.001,3)
        irr=irr*100

        p=str(round(p,2))#rounds
        energy=str(round(energy/1000000,2))
        q=str(round(q/1000,2))
        h=str(round(h,2))
        n=str(round(n,2))

        life=str(round(life,2))
        exchange=str(round(exchange,2))
        esc=str(round(esc*100,2))
        inf=str(round(inf*100,2))
        disc=str(round(disc*100,2))
        price=str(round(price,2))

        design=str(round(design/1000,0)*1000)#round to R1000
        nersa=str(round(nersa/1000,0)*1000)
        enviro=str(round(enviro/1000,0)*1000)
        planning=str(round(planning/1000,0)*1000)

        em=str(round(em/1000,0)*1000)
        civ=str(round(civ/1000,0)*1000)
        cap=str(round(cap/1000,0)*1000)
        Misc_cap=str(round((float(cap)-float(em)-float(civ))/1000,0)*1000)

        cmaint=str(round(cmaint/1000,0)*1000)
        emmaint=str(round(emmaint/1000,0)*1000)
        opera=str(round(opera/1000,0)*1000)
        insur=str(round(insur/1000,0)*1000)
        wut=str(round(wut/1000,0)*1000)
        costs=str(round(costs/1000,0)*1000)

        benefits=str(round(benefits/1000,0)*1000)
        lcoe=(float(npv_costs))/(float(life)*float(energy)*1000000)
        npv_costs=str(round(npv_costs/1000,0)*1000)
        npv_benefits=str(round(npv_benefits/1000,0)*1000)
        npv=str(round(npv/1000,0)*1000)
        bc=str(round(bc,1))
        irr=str(round(irr,1))
        lcoe=str(round(lcoe,2))#ZAR/kwh
        payback=str(round(payback,1))

        save_loc=tb19.get("1.0","end-1c")+tb20.get("1.0","end-1c")#saves to file
        results_file=open(save_loc,"w")
        results_file.write('Inputs'+'\n')
        results_file.write('Rated power                 (kW):'+'\t'+p+'\n')
        results_file.write('Annual energy output       (GWh):'+'\t'+energy+'\n')
        results_file.write('Design flow               (m³/s):'+'\t'+q+'\n')
        results_file.write('Design head                  (m):'+'\t'+h+'\n')
        results_file.write('Turbine type                    :'+'\t'+turbine+'\n')
        results_file.write('Number of turbines              :'+'\t'+n+'\n')
        results_file.write('\n')
        results_file.write('Assumptions'+'\n')
        results_file.write('Design life              (years):'+'\t'+life+'\n')
        results_file.write('Euro/Rand exchange rate         :'+'\t'+exchange+'\n')
        results_file.write('Energy escalation rate       (%):'+'\t'+esc+'\n')
        results_file.write('Inflation rate               (%):'+'\t'+inf+'\n')
        results_file.write('Discount rate                (%):'+'\t'+disc+'\n')
        results_file.write('Electricity sale price (ZAR/kWh):'+'\t'+price+'\n')
        results_file.write('\n')
        results_file.write('Planning'+'\n')
        results_file.write('Design fees                (ZAR):'+'\t'+design+'\n')
        results_file.write('NERSA License              (ZAR):'+'\t'+nersa+'\n')
        results_file.write('Environmental assessment   (ZAR):'+'\t'+enviro+'\n')
        results_file.write('Total                      (ZAR):'+'\t'+planning+'\n')
        results_file.write('\n')
```

```
        results_file.write('Construction'+'\n')
        results_file.write('Electromechanical costs    (ZAR):'+'\t'+em+'\n')
        results_file.write('Civil works                (ZAR):'+'\t'+civ+'\n')
        results_file.write('Adjustment                 (ZAR):'+'\t'+Misc_cap+'\n')
        results_file.write('Total                      (ZAR):'+'\t'+cap+'\n')
        results_file.write('\n')
        results_file.write('Operation and maintenance'+'\n')
        results_file.write('Civil works          (ZAR/annum):'+'\t'+cmaint+'\n')
        results_file.write('Electromechanical    (ZAR/annum):'+'\t'+emmaint+'\n')
        results_file.write('Operational expenses (ZAR/annum):'+'\t'+opera+'\n')
        results_file.write('Insurance            (ZAR/annum):'+'\t'+insur+'\n')
        results_file.write('Water use tariffs    (ZAR/annum):'+'\t'+wut+'\n')
        results_file.write('Total                (ZAR/annum):'+'\t'+costs+'\n')
        results_file.write('\n')
        results_file.write('Revenue'+'\n')
        results_file.write('Revenue              (ZAR/annum):'+'\t'+benefits+'\n')
        results_file.write('\n')
        results_file.write('Results'+'\n')
        results_file.write('NPV(Costs)                      :'+'\t'+npv_costs+'\n')
        results_file.write('NPV(Revenue)
:'+'\t'+npv_benefits+'\n')
        results_file.write('NPV                             :'+'\t'+npv+'\n')
        results_file.write('B/C                             :'+'\t'+bc+'\n')
        results_file.write('IRR                          (%):'+'\t'+irr+'\n')
        results_file.write('LCOE                   (ZAR/kWh):'+'\t'+lcoe+'\n')
        results_file.write('Payback period           (years):'+'\t'+payback+'\n')
        results_file.close()


#componenets
uf1.title('Life Cycle Costing Assessment Tool')
uf1.geometry('820x350')

f1=Frame(uf1)#inputs
t0=Label(f1,text='Inputs')
t1=Label(f1,text='Rated power (kW):')
t2=Label(f1,text='Annual energy output (GWh):')
t3=Label(f1,text='Design flow (m³/s):')
t4=Label(f1,text='Design head (m):')
t5=Label(f1,text='Turbine type:')
t6=Label(f1,text='Number of turbines:')
tb1=Text(f1,height=1,width=20)
tb2=Text(f1,height=1,width=20)
tb3=Text(f1,height=1,width=20)
tb4=Text(f1,height=1,width=20)
tb5=Text(f1,height=1,width=20)
turbines=['Pelton','Francis','Kaplan']
tb6=ttk.Combobox(f1,height=1,width=22,state='readonly',values=turbines)
f1.grid(column=0,row=0,sticky=N)
t0.grid(column=0,row=0,sticky=W)
t1.grid(column=0,row=1,sticky=W)
t2.grid(column=0,row=2,sticky=W)
t3.grid(column=0,row=3,sticky=W)
t4.grid(column=0,row=4,sticky=W)
t5.grid(column=0,row=5,sticky=W)
t6.grid(column=0,row=6,sticky=W)
tb1.grid(column=1,row=1)
tb2.grid(column=1,row=2)
tb3.grid(column=1,row=3)
tb4.grid(column=1,row=4)
tb5.grid(column=1,row=6)
tb6.grid(column=1,row=5)

f5=Frame(uf1)#Assumptions
t7=Label(f5,text='Assumptions')
t8=Label(f5,text='Design life (years):')
t9=Label(f5,text='Euro/Rand exchange rate (ZAR/€):')
t10=Label(f5,text='Energy escalation rate (%)')
```

```
t11=Label(f5,text='Inflation rate (%)')
t12=Label(f5,text='Discount rate (%)')
t13=Label(f5,text='Electricity sale price (ZAR/kWh):')
v1313=IntVar()
cb1313=Checkbutton(f5,text='Own-use?', variable=v1313)
tb8=Text(f5,height=1,width=10)
tb9=Text(f5,height=1,width=10)
tb10=Text(f5,height=1,width=10)
tb11=Text(f5,height=1,width=10)
tb12=Text(f5,height=1,width=10)
tb13=Text(f5,height=1,width=10)
tb8.insert(END,'20')
tb9.insert(END,'17')
tb10.insert(END,'6')
tb11.insert(END,'6')
tb12.insert(END,'6')
tb13.insert(END,'1.2')
f5.grid(column=1,row=0,sticky=W)
t7.grid(column=0,row=0,sticky=W)
t8.grid(column=0,row=1,sticky=W)
t9.grid(column=0,row=2,sticky=W)
t10.grid(column=0,row=3,sticky=W)
t11.grid(column=0,row=4,sticky=W)
t12.grid(column=0,row=5,sticky=W)
t13.grid(column=0,row=6,sticky=W)
cb1313.grid(column=1,row=7,sticky=E)
tb8.grid(column=1,row=1)
tb9.grid(column=1,row=2)
tb10.grid(column=1,row=3)
tb11.grid(column=1,row=4)
tb12.grid(column=1,row=5)
tb13.grid(column=1,row=6)

t17=Label(f5,text='Expenses')#Expenses
t18=Label(f5,text=' ')
t14=Label(f5,text='Staff expenses:')
t15=Label(f5,text='Annual expenses:')
tb14=Text(f5,height=1,width=10)
tb15=Text(f5,height=1,width=10)
tb14.insert(END,'1245739')
tb15.insert(END,'156975')
b1=Button(f5,text='Calculate',command=staff)
b2=Button(f5,text='Calculate',command=annual)
t17.grid(column=0,row=8,sticky=W)
t18.grid(column=0,row=7,sticky=W)
t14.grid(column=0,row=9,sticky=W)
t15.grid(column=0,row=10,sticky=W)
tb14.grid(column=1,row=9,sticky=E)
tb15.grid(column=1,row=10,sticky=E)
b1.grid(column=2,row=9,sticky=E)
b2.grid(column=2,row=10,sticky=E)

t21=Label(f1,text='File')#import and save
t22=Label(f1,text=' ')
t19=Label(f1,text='File directory:')
t20=Label(f1,text='Save results as:')
tb19=Text(f1,height=1,width=20)
tb20=Text(f1,height=1,width=20)
tb19.insert(END,'c:\Example'+'\\')
tb20.insert(END,'LCCA_results.txt')
t22.grid(column=0,row=7,sticky=W)
t21.grid(column=0,row=8,sticky=W)
t19.grid(column=0,row=9,sticky=W)
t20.grid(column=0,row=10,sticky=W)
tb19.grid(column=1,row=9,sticky=E)
tb20.grid(column=1,row=10,sticky=E)

f7=Frame(uf1)#just the button
```

```
b3=Button(f7,text='Calculate',command=proceed)
f7.grid(column=1,row=7,sticky=W)
b3.grid(column=0,row=0,sticky=W)

uf1.mainloop()
```

APPENDIX B

B.1 INTRODUCTION

Appendix B contains a list of the expected percent of storage under very low conditions for South African dams.

B.2 PERCENT OF STORAGE UNDER VERY LOW CONDITIONS

Dam	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Albasini Dam	10	10	10	10	15	15	15	15	15	15	10	10
Albert Falls Dam	15	15	15	20	25	30	35	30	30	20	20	20
Allemanskraal Dam	10	15	15	10	15	15	15	15	15	15	15	15
Armenia Dam	25	25	20	20	25	40	35	35	30	30	30	30
Beervlei Dam	0	0	0	0	0	0	0	0	0	0	0	0
Bellair Dam	0	0	0	0	0	0	0	0	0	0	0	0
Berg River Dam	65	65	60	50	40	35	30	30	40	40	55	60
Binfield Dam	60	60	70	75	60	60	65	65	65	60	60	60
Bivane dam	20	15	15	40	25	60	55	50	50	35	30	25
Bloemhof Dam	5	5	5	10	10	10	10	5	5	5	5	5
Blyderivierpoort Dam	60	55	45	70	80	85	95	100	90	90	80	75
Boegoeberg Dam	90	90	90	100	95	95	80	80	50	10	80	80
Bon Accord Dam	55	55	95	90	90	85	80	80	70	80	70	65
Boskop Dam	80	75	70	70	70	60	65	65	70	80	65	85
Bospoort Dam	10	5	10	10	10	10	10	10	10	15	10	10
Brandvlei Dam	45	45	35	35	25	20	15	15	20	25	40	45
Bridle Drift Dam	40	40	40	40	40	40	40	40	40	40	40	40
Bronkhorstspruit Dam	45	40	40	40	60	60	60	40	55	50	50	45
Buffeljags Dam	100	95	90	65	65	90	90	95	100	100	100	100
Buffelskloof Dam	20	15	25	30	30	50	60	50	40	40	30	30
Buffelspoort Dam	15	15	15	20	20	20	20	25	20	20	20	15
Bulshoek Dam	65	55	40	40	40	30	20	30	20	20	30	35
Calitzdorp Dam	15	20	15	10	10	15	15	15	15	20	20	15
Clanwilliam Dam	95	90	70	50	30	20	10	10	20	40	80	95
Corana Dam	20	25	20	15	10	25	30	5	25	5	20	5
Craigie Burn Dam	55	55	55	55	60	70	75	75	75	70	65	65
Da Gama Dam	15	20	20	20	30	35	35	35	35	35	20	25
Dap Naude Dam	50	40	40	50	60	65	75	65	65	65	65	55
Darlington Dam	10	10	5	5	10	10	20	15	15	20	15	15
De Mistkraal Dam	55	60	60	60	65	65	65	70	25	60	60	60
Disaneng Dam	40	40	40	40	35	55	55	55	50	50	50	45
Doorndraai Dam	10	10	10	10	10	10	20	10	10	10	10	10
Doornrivier Dam	50	50	45	50	55	60	55	55	55	50	50	50
Douglas Weir	50	55	70	60	60	80	90	90	90	80	80	60
Driekoppies Dam	20	20	20	20	20	25	30	25	25	25	25	25
Driel Barrage	75	75	90	90	85	90	85	85	85	85	70	70

Dam	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Duiwenhoks Dam	65	75	60	55	50	40	50	45	55	55	55	65
Ebenezer Dam	15	15	15	15	20	25	30	25	25	25	15	15
Egmont Dam	20	20	15	15	20	25	30	25	30	25	25	25
Eikenhof Dam	100	90	85	70	60	50	40	40	50	60	80	100
Elands Drift Dam	30	30	30	25	30	30	40	56	0	10	30	30
Elandskloof Dam	85	85	80	50	40	30	20	20	20	40	40	60
Elandskuil Dam	10	20	20	20	15	10	15	20	20	40	20	15
Erfenis Dam	15	15	15	15	15	15	20	20	20	20	20	15
Ernest Robertson Dam	75	75	80	55	55	60	55	55	50	50	40	60
Fika-Patso Dam	10	15	10	15	15	30	30	45	40	40	40	15
Flag Boshielo Dam	20	20	20	20	40	40	40	35	40	30	25	25
Floriskraal Dam	0	0	0	0	0	0	0	0	0	0	5	5
Gamka Dam	0	0	0	0	0	5	5	0	0	0	0	0
Gamkapoort Dam	5	5	5	5	5	5	5	5	5	5	5	5
Garden Route Dam	65	65	70	70	75	75	75	70	75	70	65	65
Gariep Dam	45	45	45	40	55	55	55	55	50	45	50	50
Gcuwa Dam	45	45	60	55	80	75	65	60	40	40	35	30
Glen Alpine Dam	5	5	5	15	15	10	10	10	10	10	5	5
Glen Melville Dam	50	40	40	40	35	75	70	60	50	40	30	25
Goedertrouw Dam	30	30	30	30	30	45	35	35	35	35	35	35
Grassridge Dam	15	15	15	15	20	20	15	15	15	15	15	15
Groendal Dam	50	50	50	50	50	50	50	50	50	50	50	50
Grootdraai Dam	60	50	70	70	60	80	80	70	70	60	60	60
Groothoek Dam	10	10	5	5	5	5	5	5	5	5	5	5
Gubu Dam	35	35	50	40	40	50	45	45	45	40	40	35
Haarlem Dam	50	50	45	50	30	35	40	30	40	35	35	40
Hans Merensky Dam	45	40	65	80	80	100	95	90	90	90	70	60
Hartbeespoort Dam	10	10	15	15	20	30	30	25	25	25	20	15
Hartebeestkuil Dam	10	10	10	10	10	10	10	10	5	5	10	10
Hazelmere Dam	50	45	50	55	55	55	55	50	50	45	45	45
Heyshope Dam	65	65	65	65	65	75	75	75	75	70	70	70
Hluhluwe Dam	10	10	20	20	20	20	20	15	15	15	15	10
Houtrivier Dam	35	35	35	40	50	50	50	45	45	40	40	40
Impofu Dam	30	30	30	30	30	30	30	25	25	25	20	30
Inanda Dam	60	60	60	60	60	60	70	60	70	65	65	65
Inyaka Dam	45	45	45	45	45	55	55	55	45	45	50	45
Jericho Dam	40	40	40	40	40	40	45	45	40	40	40	40
Johan Neser Dam	0	0	0	5	10	5	10	10	5	5	10	5
Jozanashoek Dam	85	80	80	80	85	90	90	95	90	90	85	85
Kalkfontein Dam	10	10	10	10	10	10	10	10	10	10	10	10
Kammanassie Dam	5	5	5	5	5	5	5	5	5	5	5	5
Karee Dam	20	15	15	10	5	5	5	5	10	15	20	25
Katrivier Dam	35	35	35	35	35	40	35	40	45	45	40	40
Katse Dam	25	25	30	40	45	50	50	45	35	35	30	25
Keerom Dam	25	25	20	15	15	10	10	10	10	15	20	20

Dam	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Klaserie Dam	10	10	10	30	50	50	50	50	30	40	20	15
Klein-Maricopoort Da	5	5	5	5	10	10	10	15	10	10	10	5
Klerkskraal Dam	75	70	65	60	60	55	60	70	70	70	75	85
Klipberg Dam	5	5	5	5	5	5	5	5	5	5	5	5
Klipdrift Dam	25	25	20	35	40	45	40	35	30	30	30	25
Klipfontein Dam	30	35	40	45	45	60	60	55	55	50	45	45
Klipkopjes Dam	0	0	0	0	5	5	0	0	0	0	0	0
Klipvoor Dam	25	30	30	35	30	35	35	40	35	45	40	35
Knellpoort Dam	15	15	15	15	15	15	15	20	15	15	15	15
Kommandodrift Dam	0	0	0	0	5	5	5	5	5	5	5	0
Koppies Dam	20	20	20	30	40	50	40	40	40	40	40	30
Korentepoort Dam	50	55	60	55	55	55	55	55	50	50	45	55
Kosterrivier Dam	5	5	5	10	10	10	10	10	10	10	10	5
Kouga Dam	10	10	10	10	10	10	10	10	10	10	10	10
Kromellenboog Dam	5	5	5	10	20	20	20	15	15	20	15	10
Kromrivier Dam	45	45	45	40	40	40	40	35	35	35	40	45
Krugersdrift Dam	5	10	10	5	10	10	15	10	10	10	5	5
Kwaggaskloof Dam	45	40	40	30	30	25	15	15	15	20	35	40
Kwena Dam	20	15	15	20	25	35	40	35	35	35	30	25
Laing Dam	80	85	85	85	85	95	95	80	80	80	80	80
Lake Arthur Dam	0	0	0	0	0	0	0	0	0	0	0	0
Lakenvallei Dam	50	50	50	55	45	40	40	40	40	45	45	45
Leeugamka Dam	0	0	0	0	0	0	0	0	0	0	0	0
Lindleyspoort Dam	5	5	5	5	10	10	10	10	10	10	10	10
Loerie Dam	45	50	50	50	45	40	40	40	45	35	35	35
Longmere Dam	15	10	15	20	35	50	50	50	40	45	25	25
Loskop Dam	20	20	25	30	30	35	40	40	35	30	25	20
Lubisi Dam	35	35	35	30	30	30	45	45	45	40	40	40
Luphephe Dam	5	5	5	5	5	10	10	10	5	5	5	5
Madikwe Dam	0	0	0	0	10	25	10	25	25	10	20	5
Magoebaskloof Dam	45	40	60	65	70	85	95	85	80	80	70	60
Maguga Dam	55	50	45	40	40	80	75	75	70	70	65	65
Marico-Bosveld Dam	10	10	10	15	15	20	20	20	20	20	15	15
Mearns Dam	10	10	45	50	70	80	40	20	20	0	20	0
Metsi-Matsho Dam	70	65	65	65	65	85	80	80	80	75	75	75
Middelburg Dam	35	40	50	50	45	55	55	50	50	45	45	40
Middel-Letaba Dam	0	0	0	5	10	10	10	10	5	5	0	0
Midmar Dam	55	55	55	55	55	70	70	65	65	65	60	60
Miertjieskraal Dam	5	5	5	5	0	0	0	0	0	0	0	0
Misverstand Dam	100	100	100	100	100	100	100	100	100	100	100	100
Modjadji Dam	10	10	10	10	20	30	30	30	20	20	15	15
Mohale Dam	15	15	15	15	15	20	25	30	30	30	25	15
Mokolo Dam	35	35	35	40	40	45	50	50	45	45	45	40
Molatedi Dam	10	10	10	10	10	10	10	10	10	10	10	10
Morgenstond Dam	25	30	35	35	40	40	40	40	40	35	30	30

Dam	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Mutshedzi Dam	25	20	35	35	60	90	90	80	80	75	35	40
Nagle Dam	60	60	55	70	70	70	80	70	65	70	70	50
Nahoon Dam	40	40	35	40	40	35	50	45	45	40	45	40
Nandoni Dam	85	80	80	75	85	95	95	95	90	90	85	85
Ncora Dam	45	45	45	45	60	70	65	60	55	55	50	45
Ngotwane Dam	10	5	5	10	10	20	15	15	15	15	10	10
Nooitgedacht Dam	30	30	30	30	30	30	40	35	35	30	30	30
Nqweba Dam	0	0	0	0	0	0	0	0	0	0	0	0
Nsami Dam	5	5	5	10	10	10	10	10	5	5	10	10
Ntshingwayo Dam	60	55	55	55	60	60	70	70	65	65	60	60
Nuwejaars Dam	25	20	25	25	20	20	20	20	25	25	20	20
Nwanedzi Dam	20	15	20	20	30	35	40	30	20	20	15	15
Nzhelele Dam	10	10	10	10	15	10	10	20	10	10	10	10
Ohrigstad Dam	0	0	5	5	10	10	10	10	10	10	5	10
Olifantsnek Dam	0	0	0	10	15	10	10	5	5	5	5	5
Oukloof Dam	5	5	5	5	0	0	0	5	5	5	5	5
Oxkraal Dam	35	30	30	30	40	45	40	35	40	40	40	40
Pella Dam	25	25	25	35	35	35	35	30	30	30	30	25
Pietersfontein Dam	5	5	5	5	5	5	5	5	5	5	5	5
Pongolapoort Dam	40	40	40	40	40	40	40	40	40	40	40	40
Poortjieskloof Dam	5	5	5	5	5	0	0	0	0	5	5	5
Potchefstroom Dam	70	70	80	85	65	75	90	95	40	55	60	70
Primkop Dam	20	10	10	10	15	20	40	30	30	30	25	20
Prinsrivier Dam	10	10	10	0	0	0	0	10	10	10	15	10
Rhenosterkop Dam	0	0	0	0	0	0	0	0	0	0	0	0
Rietspruit Dam	45	35	45	45	35	35	30	50	55	60	65	55
Rietvlei Dam	45	45	45	50	55	55	55	60	55	55	50	50
Roode Els Berg Dam	60	65	65	20	10	10	10	10	10	20	40	45
Roodefontein Dam	40	45	45	45	45	45	40	40	40	35	35	40
Roodekopjes Dam	10	10	10	15	15	10	10	10	10	10	10	10
Roodeplaat Dam	35	35	30	40	40	40	40	40	40	40	35	35
Rooikrans Dam	45	55	55	55	55	70	60	55	50	50	40	40
Rust De Winter Dam	5	10	10	15	20	20	20	15	15	15	10	10
Rustfontein Dam	25	25	25	25	25	25	25	25	25	25	25	25
Sandile Dam	40	40	45	45	50	55	55	55	50	50	45	45
Saulspoort Dam	45	50	65	60	60	60	60	55	55	55	50	50
Sehujwane Dam	35	35	30	35	45	45	45	45	45	40	40	40
Setumo Dam	35	35	35	40	40	40	40	40	40	40	40	40
Spioenkop Dam	70	70	70	70	80	90	90	90	80	80	75	75
Spitskop Dam	10	10	10	10	20	30	25	25	20	20	20	15
Sterkfontein Dam	25	25	25	25	25	25	25	25	25	25	25	25
Stettynskloof Dam	100	95	95	65	50	35	30	30	40	60	95	100
Stompdrift Dam	5	5	5	5	5	5	5	5	5	5	5	5
Swartruggens Dam	0	0	0	0	0	0	0	0	0	0	0	0
Theewaterskloof Dam	30	25	25	20	20	15	15	15	20	25	25	30

Dam	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Tierpoort Dam	0	0	0	0	0	0	0	0	0	0	0	0
Tonteldoos Dam	30	30	70	90	80	80	80	65	65	70	50	50
Tours Dam	25	25	25	25	30	30	45	40	40	40	35	30
Tzaneen Dam	10	10	10	10	10	15	15	15	20	20	15	10
Umtata Dam	20	25	25	30	35	35	45	40	35	35	30	30
Vaal Dam	25	20	25	30	40	40	40	35	35	35	30	30
Vaalharts Weir	70	70	70	70	70	70	70	60	70	70	70	70
Vaalkop Dam	15	15	15	20	25	25	25	20	20	20	15	15
Vanderkloof Dam	50	50	50	45	50	50	50	50	50	50	50	50
Vergelegen Dam	75	75	80	80	80	80	80	85	80	80	80	80
Vlugkraal Dam	35	35	45	55	60	60	65	60	55	55	45	40
Voelvlei Dam	55	55	50	45	35	30	25	25	30	40	40	55
Vondo Dam	15	15	15	40	50	40	40	30	30	25	15	15
Vygeboom Dam	25	25	45	65	65	65	65	60	55	50	45	35
Wagendrift Dam	70	70	75	80	95	95	95	95	90	80	80	60
Warmbad Dam	0	30	30	30	30	30	30	30	20	20	10	10
Waterdown Dam	30	40	35	35	30	30	30	30	30	35	30	30
Welbedacht Dam	20	15	15	15	15	15	30	40	30	30	25	25
Wemmershoek Dam	70	65	65	55	55	50	40	40	45	45	60	65
Westoe Dam	20	15	10	20	20	20	25	20	20	20	15	15
Witbank Dam	40	45	45	45	50	50	50	50	50	50	40	40
Witklip Dam	30	35	35	35	40	40	45	40	45	40	40	40
Wolwedans Dam	45	45	45	65	65	65	60	60	60	30	50	30
Woodstock Dam	40	30	35	40	45	65	65	60	50	50	45	45
Wriggleswade Dam	15	15	20	15	15	15	15	20	15	20	15	15
Xilinxa Dam	10	10	10	10	25	25	25	20	20	15	15	15
Xonxa Dam	90	90	90	90	95	100	100	100	95	95	90	90
Zaaihoek Dam	40	40	40	35	50	55	60	45	50	45	45	45

APPENDIX C

C.1 INTRODUCTION

Appendix C contains the results for each dam used in the analysis.

C.2 RESULTS

Downstream Gauge	Dam Name	Height (m)	Power (MW)	Energy (GWh)	Flow (m^3/s)	Turbine Type	Nr turbines
A9H020	Albasini Dam	34	0.00834	0.032254629	0.2	Francis	1
U2H014	Albert Falls Dam	33	0.79519	3.429484829	8.88	Francis	1
C4H008	Allemanskraal Dam	38	0.00112	0.008388057	0.02	Francis	1
D2H026	Armenia Dam	22	0.00166	0.009117929	0.03	Francis	1
G1H077	Berg River Dam	60	1.1612	4.753165343	4.16	Francis	1
W4H016	Bivane dam	72	2.24931	7.273960386	6.27	Francis	1
C9H021	Bloemhof Dam	33	1.60868	6.582142114	58.57	Kaplan	1
B6H014	Blyderivierpoort Dam	71	6.08326	29.26756673	12.03	Francis	1
D7H008	Boegoeberg Dam	12	29.72449	131.6591473	104.42	Kaplan	3
C2H273	Boskop Dam	33	0.23535	1.353525929	1.11	Francis	1
A2H094	Bospoort Dam	28	0.00992	0.057256786	0.43	Francis	1
R2H029	Bridle Drift Dam	55	0.31518	2.605248986	1.72	Pelton	1
H7H013	Buffeljags Dam	24	0.53418	3.614822143	2.76	Francis	1
B4H021	Buffelskloof Dam	39	0.1691	0.663462757	1.06	Francis	1
E1H016	Clanwilliam Dam	43	2.16754	8.674326114	6.83	Francis	1
V2H016	Craigie Burn Dam	38	0.18306	0.987845571	0.95	Francis	1
X3H020	Da Gama Dam	38	0.03998	0.206023086	0.36	Francis	1
B8H053	Dap Naude Dam	23	0.06237	0.222396557	0.5	Francis	1
Q8H006	De Mistkraal Dam	27	0.16093	1.042273043	1.1	Francis	1
A6H027	Doorndraai Dam	29	0.00496	0.0176695	0.11	Francis	1
X1H049	Driekoppies Dam	50	0.74555	4.039594057	6.57	Francis	1
V1H058	Driel Barrage	22.6	4.48643	16.46623333	28.06	Kaplan	1
H8H003	Duiwenhoks Dam	37	0.16806	0.830969929	0.73	Francis	1
B8H064	Ebenezer Dam	61	0.14666	0.776937243	1.01	Pelton	1
Q5H007	Elandsdrift Dam	26	0.77524	3.712569743	8.74	Francis	1
H6H015	Elandskloof Dam	69	0.2138	0.617057557	0.88	Pelton	1
C4H010	Erfenis Dam	46	0.00538	0.023495171	0.07	Francis	1
K2H009	Ernest Robertson Dam	26	0.00804	0.053949629	0.06	Francis	1
C8H038	Fika-Patso Dam	65	0.00739	0.017417771	0.05	Pelton	1
B5H004	Flag Boshielo Dam	36	1.13024	4.375318529	9.43	Francis	1
J1H028	Floriskraal Dam	33	0.00553	0.0044425	0.4	Francis	1
J2H018	Gamka Dam	56	0.00057	0.000834686	0.02	Pelton	1
J2H016	Gamkapoort Dam	42	0.01589	0.0937748	0.91	Francis	1
K3H010	Garden Route Dam	39	0.01938	0.105642943	0.08	Francis	1
S7H001	Gcuwa Dam	19	0.10397	0.351868343	0.82	Francis	1
A6H029	Glen Alpine Dam	28	0.11489	0.3137446	3.29	Francis	1
W1H028	Goedertrouw Dam	88	1.02952	5.440250514	3.4	Francis	1

Downstream Gauge	Dam Name	Height (m)	Power (MW)	Energy (GWh)	Flow (m^3/s)	Turbine Type	Nr turbines
Q1H023	Grassridge Dam	24	0.05367	0.232228671	1.38	Francis	1
C1H019	Grootdraai Dam	42	1.97903	7.976044543	7.15	Francis	1
S6H004	Gubu Dam	36	0.02281	0.123238157	0.15	Francis	1
A2H083	Hartbeespoort Dam	59	1.20834	5.066376757	8.52	Francis	1
K1H017	Hartebeestkuil Dam	27	0.00139	0.008297071	0.06	Francis	1
U3H005	Hazelmere Dam	50	0.4146	2.123669757	1.99	Francis	1
W5H039	Heyshope Dam	29	0.48076	2.0309084	2.76	Francis	1
W3H022	Hluhluwe Dam	36	0.07396	0.301419529	1.23	Francis	1
K9H003	Impofu Dam	75	0.04363	0.218347071	0.23	Pelton	1
U2H054	Inanda Dam	65	2.65071	13.02452214	8.17	Francis	1
X3H011	Inyaka Dam	53	0.57408	2.561805314	2.37	Francis	1
W5H034	Jericho Dam	22	0.00285	0.017193986	0.04	Francis	1
C5H049	Kalkfontein Dam	36	0.00077	0.004272714	0.03	Francis	1
J3H029	Kammanassie Dam	41	0.00608	0.037485529	0.36	Francis	1
Q9H026	Katrivier Dam	55	0.05925	0.465217714	0.37	Pelton	1
A3H042	Klein-Maricopoort Dam	27	0.00047	0.002185243	0.02	Francis	1
W2H030	Klipfontein Dam	28	0.16473	0.686617057	1.24	Francis	1
A2H106	Klipvoor Dam	30	0.29733	1.923480143	3.77	Francis	1
D2H028	Knellpoort Dam	50	0.02494	0.061254129	0.4	Francis	1
H9H010	Korentepoort Dam	35	0.0593	0.312960843	0.36	Francis	1
A2H104	Kosterrivier Dam	30	0.00282	0.018087829	0.11	Francis	1
L8H006	Kouga Dam	81	0.13449	0.790521871	1.99	Pelton	1
A3H032	Kromellenboog Dam	23	0.00026	0.000990329	0.01	Francis	1
K9H001	Kromrivier Dam	15	0.04196	0.154363757	0.75	Francis	1
C5H039	Krugersdrift Dam	26	0.04672	0.226329229	2.16	Francis	1
X2H070	Kwena Dam	52	0.53682	2.942304286	4.17	Francis	1
Q4H008	Lake Arthur Dam	38	0	0	1.48	Francis	1
H2H016	Lakenvallei Dam	56	0.04708	0.242235471	0.22	Pelton	1
X2H065	Longmere Dam	29	0.03414	0.186959357	0.36	Francis	1
B3H017	Loskop Dam	54	1.52353	7.236805614	11.3	Francis	1
S2H005	Lubisi Dam	52	0.20371	1.2935119	1.05	Pelton	1
A8H009	Luphephe Dam	42	0.01573	0.076058386	0.45	Francis	1
B8H046	Magoebaskloof Dam	43	0.37946	1.4337531	1.5	Francis	1
A3H029	Marico-Bosveld Dam	34	0.01817	0.066157471	0.32	Francis	1
B1H015	Middelburg Dam	36	0.09702	0.498946114	0.65	Francis	1
B8H071	Middel-Letaba Dam	34	0.00156	0.0059285	0.06	Francis	1
U2H048	Midmar Dam	32	1.00816	4.340337029	6.23	Francis	1
J1H031	Miertjieskraal Dam	24	0.00097	0.002529743	0.1	Francis	1
G1H075	Misverstand Dam	26	0.75224	4.368651543	3.48	Francis	1
A4H010	Mokolo Dam	57	0.5709	3.0459637	2.58	Francis	1
A3H034	Molatedi Dam	23	0.01201	0.066602057	0.63	Francis	1
W5H038	Morgenstond Dam	43	0.01795	0.084618329	0.14	Francis	1
R3H003	Nahoon Dam	44	0.0402	0.249973043	0.22	Francis	1
A9H030	Nandoni Dam	47	1.36757	5.890008886	3.68	Francis	1
X1H033	Nooitgedacht Dam	42	0.01313	0.070321714	0.13	Francis	1

Downstream Gauge	Dam Name	Height (m)	Power (MW)	Energy (GWh)	Flow (m^3/s)	Turbine Type	Nr turbines
V3H027	Ntshingwayo Dam	25	0.22871	0.908739486	1.83	Francis	1
A8H010	Nwanedzi Dam	36	0.03287	0.1102902	0.27	Francis	1
A8H015	Nzhelele Dam	47	0.06247	0.289088543	0.8	Francis	1
B6H011	Ohrigstad Dam	52	0.02213	0.117733886	0.51	Pelton	1
S3H012	Oxkraal Dam	36	0.03187	0.185831314	0.35	Francis	1
H3H015	Pietersfontein Dam	33	0.00005	0.000385129	0	Francis	1
W4H013	Pongolapoort Dam	89	4.66754	27.97492534	15.75	Francis	1
J1H022	Prinsrivier Dam	34	0.00097	0.004465843	0.03	Francis	1
B3H020	Rhenosterkop Dam	36	0	0	0.53	Francis	1
A2H009	Rietvlei Dam	21	0.00618	0.048821186	0.07	Francis	1
H2H015	Roode Els Berg Dam	72	0.14194	0.528313329	0.46	Pelton	1
A2H019	Roodekopjes Dam	25	0.18507	0.785836486	5.93	Francis	1
A2H102	Roodeplaat Dam	59	0.22794	1.075533157	1.16	Pelton	1
B3H014	Rust De Winter Dam	31	0.00122	0.0072941	0.03	Francis	1
R1H017	Sandile Dam	61	0.36897	1.858696657	1.42	Pelton	1
A3H037	Sehujwane Dam	24	0.001	0.006756129	0.01	Francis	1
V1H057	Spioenkop Dam	53	10.95355	35.7173554	27.91	Kaplan	1
C8H032	Sterkfontein Dam	93	0.12634	0.566315414	0.65	Pelton	1
A2H107	Swartruggens Dam	15	0	0	0.21	Francis	1
H6H012	Theewaterskloof Dam	38	0.73398	2.549398829	9.28	Francis	1
B4H016	Tonteldoos Dam	16	0.01677	0.065570614	0.14	Francis	1
B7H002	Tours Dam	29	0.03075	0.132250314	0.31	Francis	1
C2H122	Vaal Dam	33	6.02473	34.40853147	28.72	Kaplan	1
C9H008	Vaalharts Weir	11	3.36319	17.285085	52.47	Kaplan	1
A2H111	Vaalkop Dam	32	0.04242	0.167965414	0.64	Francis	1
B4H017	Vlugkraal Dam	17	0.00296	0.0131361	0.04	Francis	1
X1H036	Vygeboom Dam	48	2.44398	8.323505771	9.41	Francis	1
V7H020	Wagendrift Dam	41	4.53005	15.17850299	13.97	Francis	1
D2H033	Welbedacht Dam	32	2.75184	11.40882799	68.88	Kaplan	1
W5H036	Westoe Dam	26	0.01972	0.064370671	0.46	Francis	1
B1H010	Witbank Dam	44	0.8146	2.596364786	4.45	Francis	1
X2H068	Witklip Dam	21	0.04273	0.218033429	0.61	Francis	1
K2H006	Wolwedans Dam	70	0.10494	0.540592286	0.29	Pelton	1
S6H005	Wriggleswade Dam	35	0.05194	0.265077086	1.19	Francis	1
S1H004	Xonxa Dam	49	1.02188	3.701796971	2.51	Francis	1
V3H028	Zaaihoek Dam	46	0.18672	0.953484129	0.87	Francis	1