FEASIBILITY OF RUN-OF-RIVER HYDROPOWER FOR RURAL AND AGRICULTURAL PRODUCTIVITY IN SOUTH AFRICA

By

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PREFACE

I ....Lazola Qhawe Mfundo Makalima............... declare that:

i. This dissertation is my original work except where indicated.
ii. This dissertation has not been submitted for examination in any other Institution or University.
iii. Pictures, data, graphs, and other information contained in this dissertation obtained from different sources have been referenced.
iv. Where direct text has been obtained from the source, the words have been paraphrased and the author has been referenced.

Signed………………………………………

Supervisor…………………………………..

Co-supervisor……………………………….

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ABSTRACT

The Southern African Community Development (SADC) intends to increase its irrigated area to increase the agricultural productivity of the land. Run-of-river hydropower systems present an attractive solution of providing energy where it is not feasible for alternative energy sources and extend the grid infrastructure to improve the livelihood of rural communities and increase agricultural productivity. The site geographical location and topography of power plants have made it impossible to guarantee fixed costs from suppliers and manufacturers, leading researchers to develop formulae that predict the cost behavioural tendencies of the electro-mechanical components of the power plant as a function of hydropower parameter inputs and other costs. Hydropower systems are very site-specific as they are affected by their geographical location and the site's topography. The difficulties from suppliers and manufacturers in failing to guarantee fixed costs have resulted in designers using developed formulae to determine the scheme's costs. This investigation aimed to develop a model that would allow designers to determine whether run-of-river hydropower would be feasible or not for a specific location in South Africa. This was achieved through a pre-feasibility model based on a '3 Pillar Concept' of social, environmental, and economic test for sustainability, which according to research, has 49 sustainability indicators for run-of-river hydropower systems measured directly or indirectly. The Levelised Cost of Electricity (LCOE) from hydropower was used to determine the economic feasibility of hydropower systems. From previous research, LCOE evaluation for small hydropower projects in developing countries ranged between 0.02USD/kWh and 0.10USD/kWh, making small scale hydropower systems very cost competitive for electricity generation to the grid or schemes for off-grid rural electrification. Run-of-River hydropower systems are classified as small hydropower systems and generate from 1MW to 20MW. The projects demonstrated in this report were Micro and Mini hydropower systems which are significantly larger than Pico hydropower systems.

The sites selected for the study are U2H014 located downstream of Albert Falls dam, U3H005 downstream of the Hazelmere dam, U2H052 downstream of Inanda dam, and V1H002 downstream of Woodstock dam. The potential power of the available energy was quantified using available streamflow data. Flow duration curves were developed from streamflow data and were used to develop power duration curves for the hydropower plants. LCOE for the investigated sites ranged between 0.02USD/kWh and 0.10USD/kWh. The power duration

curves showed that the smallest power plant was U3H005 and generated 48kW. The groundwater pumping requirements for rural and agricultural productivity is found to be 31.1kW. Results obtained at sites U2H014 and V1H002 were 238kW and 314kW, respectively. The smallest power plant could generate enough power for rural and agricultural productivity with power savings that could be sold to the grid or power the community. The results obtained at the sites were positive and acceptable.

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1. INTRODUCTION

The Southern African Community Development (SADC) region intends on increasing its agricultural productivity by increasing its area under irrigation. The proposed idea is to increase agricultural production so that surplus yields of households of defined advantages would supply regions of less potential with agricultural products to meet demands. This also serves as means of ensuring food security and improve livelihoods through employment creation. Although there is a high potential for irrigation in southern Africa, most agriculture activities remain rainfed (Mabhaudhi *et al.*, 2019). Extended dry periods and unsure rainfall impose stress on farming production. Some benefits of run-of-river hydropower systems are that they can provide power in isolated areas or reduce the load on the grid. They can also be used to assist in pumping water out from deep underground aquifers when required. Potential free groundwater resources exist that can be used to supplement water deficits during droughts. Those groundwater sources can be tapped into using one of many potentially feasible renewable energy systems, such as hydropower systems.

The feasibility study of a hydropower system considers numerous factors, such as the economic viability, social and environmental impacts for a given demand (Kumar and Katoch, 2014). These factors are broken into several indicators, while some factors are measured tangibly, such as the displaced number of people due to a project, employment opportunities created due to the project, and other factors. Others are measured intangibly as social value changes, noise pollution, and related factors (Kumar and Katoch, 2014). Run-of-river hydropower systems have 49 sustainability indicators (Kumar and Katoch, 2014) and are site-specific, resulting in challenges in obtaining costs from suppliers and manufacturers (Van Vuuren *et al.*, 2011). Researchers have developed different costing equations for hydropower plants. These costing equations allow designs to determine the cost of a hydropower plant from hydropower inputs when used carefully. This allows designers to assess and determine the feasibility of run-of-river hydropower systems at the initial stages of the investigations.

Four gauging sites were selected for this investigation to determine the feasibility of run-of-river hydropower for rural and agricultural productivity in South Africa. These were U2H014 which is downstream of Albert Falls dam, U2H052 which is downstream of Inanda dam, U3H005 which is downstream of Hazelmere and V1H002, which is downstream of Woodstock dam. Rural productivity refers to the electrification of rural households using green energy from fossil fuels.

This investigation does not consider any CO_2 pricing, or the benefits of reduced local air pollution, or the benefits of contaminating the environment. This is because when the Kyoto protocol was signed, an average reduction in emissions of 5.2% of the measured levels was required in industrialised countries in 1990 over the period 2008 to 2012. Developing countries like South Africa could sell this to countries obligated to meet their emissions target. This was adopted for this report too (Van Vuuren *et al.*, 2011).

1.1 Research Background

There is a potential to provide sustainable power to areas where it is not feasible to extend the existing grid in developing countries using small-scale off-grid systems (Kusakana, 2014). Run-of-river hydropower systems present a viable solution for rural and agricultural productivity in any site where it is feasible for this hydropower system. South Africa is a typical developing country with a huge potential for these systems. According to Mandelli *et al.* (2016), rural areas are characterised by low living standards and high illiteracy rates. The implementation of these systems can potentially increase these living standards and increase their illiteracy through the provision of electricity. Implementing these systems can increase the livelihood of the people living in these areas, together with reducing the migration of the people from rural to urban areas. The increase in agricultural activity in remote locations would result to employment creation through increased agricultural productivity. Subsequently, resulting in the gradual development and upliftment in rural areas and communities.

The difficulties faced in the design of off-grid systems include the participation from the locals in the preliminary stages of the design. However, a design of questionnaires, group discussions and statistical analysis of data collection can be measures used to address some of these challenges (Rojanamon *et al.*, 2009). Van Vuuren *et al.* (2011) discussed another technique called the line vulnerability diagram for social and environmental considerations. The line vulnerability diagram is a rating scale between extreme and low vulnerability for different criteria. The line vulnerability diagram technique will be used in this study because it allows the designer to rate each criterion based on expert opinion.

The key drivers for the selection of this dissertation are listed below:

a) The potential of using the energy available in stream flow or rivers to generate electricity for rural and agricultural productivity at minimum social and environmental impact.
b) The promotion of clean energy to curb environmental challenges.

c) The provision of sustainable energy to power remote agricultural systems to meet rising food demand
d) The improvement of social issues in South Africa, especially for people living in rural or isolated areas
e) To attract investors and increase the level of confidence in these systems by demonstrating their affordability, sustainability and reliability as a good energy source for rural and agricultural productivity in South Africa

1.2 Research Motivation

A significant impact of climate change in the Southern African region includes an increase in the region's aridity, which has reduced the required rainfalls for agricultural productivity. There is a potential to tap groundwater that can be utilised to supplement deficit water resources and in the case of a shortage of rainfalls. This groundwater can be sourced through a run-of-river hydropower system that promotes the use of renewable energy for groundwater pumping and power generation. Through these systems serving as stand-alone energy sources in isolated areas and rural areas, irrigation can become more viable than rainfed farming instead of extending the existing grid, resulting in greater costs. Rural and isolated areas would be more socially included, and more jobs would be created. This would minimise the rural urban migration in these areas. Considering the run-of-river hydropower system as a tool for the water, energy and food security nexus, one of the challenges would then be to create a model that would be a pre-feasibility test for designers to assess whether a run-of-river hydropower system would be feasible or not for rural and agricultural productivity in South Africa. This can be achieved by developing a model whose assessment criteria depend on the three pillars of sustainability: social, environmental, and economic criteria. Each of these criteria has sustainability indicators, measured as tangible or intangible.

1.3 Aims and Objectives

The aim of this project is to conduct a feasibility study for Run-of-River (RoR) hydropower systems as a power source for rural and agricultural productivity using suitable sustainable indicators.

The objectives of this project are to:

1. Determine the most relevant sustainability indicators for RoR hydropower systems.

2. Find a cost model for electro-mechanical equipment and civil works costs based on South African figures for the run-of-river hydropower system.
3. To determine the Levelised Cost of Electricity (LCOE (USD/kWh)) from hydropower and to determine:
    - Investment cost of the run-of-river hydropower system (USD/kW)
    - Annual operations and maintenance costs (USD/kW)
    - The payback period for the design life of the system (years)
4. Develop a model that can be used as a pre-feasibility assessment tool of a potential run-of-river hydropower system in the early design stage considering the '3 Pillar Concept' and measurability aspects. The model should be based on input/collected data of an area in South Africa, with the output of the model either being 'ACCEPTABLE' or 'NOT-ACCEPTABLE'.

1.4 Scope of Study

The potential of providing feasible renewable energy using run-of-river hydropower systems for rural and agricultural productivity in South Africa is investigated in this study. There are many challenges associated with the design of hydropower systems, and some include determining the cost of the project at the preliminary stage of the investigation. In ideal cases, Civil and technical costs should be obtained from manufacturers and suppliers for costing hydropower systems, as opposed to the costing formulas used. This proved to be impossible due to the excessive data from different manufacturers. This study investigates the different costing models developed for hydropower schemes to determine the best suitable model for South Africa.

1.5 Research Structure

This dissertation was divided into 5 chapters excluding the references, namely the following:

Chapter 1 is the introduction chapter where the author talks about what the Southern African Community Development (SADC) intends to do for the rural and agricultural sectors and how run-of-river hydropower systems can play a vital role in this development. The author talks about the feasibility of run-of-river hydropower systems and what defines a feasible run-of-river hydropower system. The research background, research motivation, aims and objectives, and scope of study are presented.

Chapter 2 is the literature review chapter of the document. This chapter presents the holistic study of hydropower systems from large systems to small systems, classified as run-of-river hydropower systems. The in-depth definition and considerations of what defines a feasible run-of-river hydropower system, including how this would work for rural and agricultural productivity, has been discussed. This chapter also captures the costing model for electrical, mechanical and civil costs for hydropower models. Levelised Cost of Electricity (LCOE) from hydropower, flow duration and power duration curves and turbine selection for the power plant are also discussed.

Chapter 3 is the research methodology which talks about how the investigations were conducted. It is broken down into sub-sections, and the selected sites, together with their streamflow data, are presented. The determination of the flow and power duration curves for each site is discussed, and calculations are made easier to follow using flowcharts. The final pre-feasibility model is presented, and the model outcomes are discussed.

Chapter 4 discusses the results that were obtained from the pre-feasibility model. It also shows the steps that were used to reach those results.

Chapter 5 concludes the project as it consolidates the aims and objectives with the results and discussion. It reflects on the information obtained from literature and the results obtained during each model trial to determine whether each system is feasible. It also reflects on what these systems would mean for rural and agricultural productivity as the discussion includes those results.

2. LITERATURE REVIEW

This Chapter gives an overview of hydropower systems, the sustainability of hydropower systems and discusses the generation of hydropower potential. The costing equations for the feasibility assessment of a hydropower plant are also presented and discussed in this chapter.

2.1 Hydropower Systems

Hydropower plants are considered a cleaner energy source than other energy sources such as fossil fuels and can be classified under two categories. These are Storage or Reservoir hydropower plants, such as dams and run-of-river (RoR) hydropower plants (Jager and Smith, 2008). The primary objective of a hydropower plant is to generate maximum energy whilst meeting upstream and downstream water requirements of water extraction and water release. These also include meeting the needs of the environment (Jager and Smith, 2008). Run-of-river hydropower plants present an attractive and sustainable solution to addressing such problems compared to reservoir or storage hydropower plants. This is due to their minimal land area requirements because of little to no water retention and less social and environmental interference (Kumar and Katoch, 2014).

Many factors are considered for a hydropower system, such as economic viability, social and environmental impacts for a given demand. Storage based hydropower systems typically generate greater power than run-of-river hydropower systems. However, they are known to be more costly and less environmentally friendly (Jager and Smith, 2008). This is largely due to their excessive land area requirements, resulting in much costs required for land preparation (Ansar *et al.*, 2014), population displacement and excessive environmental impacts such as the impedance of fish migration. Jager and Smith (2008) describe more detrimental effects of storage-based hydropower systems such as the large-scale disturbance of a free-flowing river. This results in the water quality of downstream river reaches and in reservoirs being reduced. Jager and Smith (2008) further specify that less-obvious impacts of these reservoir-based systems include the disturbance of processes such as geomorphological which maintain the diverse water habitat, as they are required to sustain a healthy riverine ecosystem. Hydropower systems, therefore, serve to maximise energy revenue while meeting upstream water extraction requirements and downstream water release legal requirements (Jager and Smith, 2008). Anderson *et al.* (2015) state that run-of-river hydropower systems do not interfere with the river's natural flow, making them more environmentally and ecologically friendly. Table 2.1 shows the classification of hydropower systems (Irena, 2012).

Table 2.1: Classification of hydropower systems (Irena, 2012)

Scheme	Range
Large-scale	100 MW >
Medium-scale	20 MW to 100 MW
Small-scale	1 MW to 20 MW
Mini-scale	100 kW to 1 MW
Micro-scale	5 kW to 100 kW
Pico-scale	< 5 kW

In hydropower systems, power is generated by the kinetic energy of the water as it flows through the turbine. As seen from Table 2.1, a small-scale hydropower system generates power capacity of 1 MW to 20 MW range. Most small-scale hydropower systems are likely to be run-of-river hydropower (Irena, 2012). Generally, run-of-river hydropower systems do not retain water, as they rely on the natural flowing characteristics of the river, unlike reservoir (storage) hydropower systems.

2.2 Reservoir Hydropower Systems

2.2.1 Storage hydropower systems

According to Irena (2012), hydropower plants with large reservoirs behind dam walls generate an effective electricity generating system because they store significant quantities of water. Irena (2012) states that one of the advantages of hydropower plants with storage is that glacial melt or rainfall can be decoupled from the timing of power generation. For example, in areas where melted snow provides bulks of water inflows, these water volumes can be stored through the warmer seasons such as spring and summer, resulting in the cold climate countries with high demands being met in winter or meeting the peak electricity demand for cooling in summer. The unparallel flexibility offered by large-scale hydropower systems with reservoirs is a lot (Irena, 2012). The type of hydropower plant depends on the opportunities offered by the topography and stream flow. These factors influence the design and plant site determination of the hydropower plant. However, the techniques used in civil engineering to reduce costs mean that even with these techniques' improvements, what is economic is not fixed. Increased opportunities for cost reduction can be opened in tunnelling or canals by reducing those costs to generate electricity (Irena, 2012).

2.2.2 Pumped storage hydropower systems

In pumped storage hydropower systems, off-peak electricity is used to pump water from a lower reservoir or a river up to an elevated water storage to be released during peak times (Irena, 2012). According to Irena (2012), pumped storage plants are considered as energy storage devices as opposed to energy sources. The cost of storage also results from the losses incurred from the pumping process. However, Irena (2012) states that they can provide large-scale energy storage. They can also be a valuable tool for integrating variable renewables such as solar and wind and providing grid stability services (Irena, 2012). Conventionally, pumped storage hydropower systems cost more than large storage hydropower schemes. An additional challenge is that it is often challenging to find suitable sites to develop pumped hydropower storage systems (Irena, 2012). Pumped storage systems have significant potential, but they tend not always to be located near their demand centres (Irena, 2012).

2.3 Run-of-River Hydropower Systems

Irena (2012) states that most run-of-river schemes are generally found downstream of dams or water storage projects. This is because the power generation of one or more downstream run-of-river plants can be regulated. According to the author, the main advantage of this approach is that it is less expensive than a series of reservoirs or dams due to construction costs being reduced. However, Irena (2012) does state that in other cases, constraints do exist which limit a system to only being a run-of-river due to a large dam or reservoir on site not being feasible.

According to Irena (2012), run-of-river hydropower systems can either have or not have pondage. The general operation of run-of-river plants depends heavily on the available hydraulic head and the stream inflow. Some systems tend to have stable inflows, although it is difficult to generalise, while variations are experienced in others (Irena, 2012). The drawback for these systems is that flow is lost, or "spillage" will have to occur during high inflows when the storage available is full. Realising the lost opportunity this then presents in power generation, the plant capacity design then trades-offs high inflows occurring in a normal year to take advantage of the potential power generation it could make in that normal year (Irena, 2012). The trade-off between the plant capacity and the spilled water is determined by the value of the electricity generated, and this is considered when designing the scheme (Irena, 2012). Figure 2.1 shows a layout of a run-of-river hydropower system.

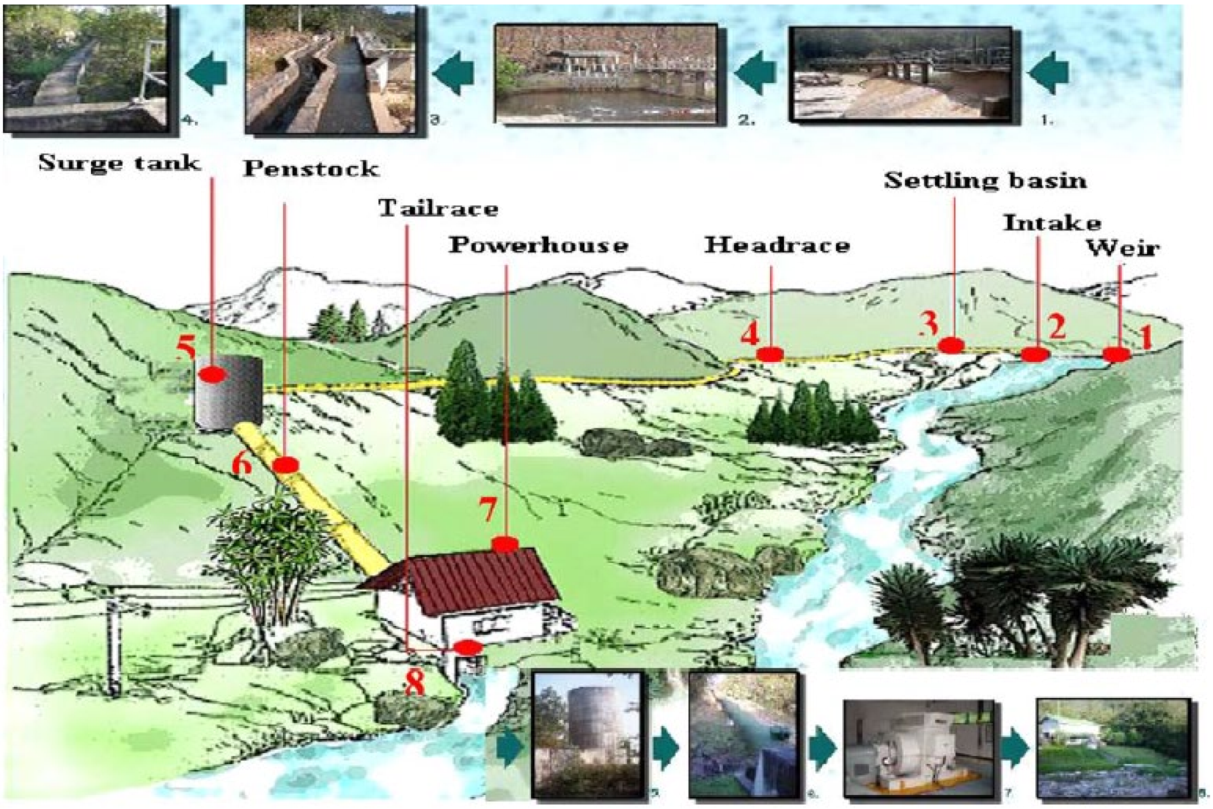

Figure 2.1: Components of a Run-of-River Hydropower System (Rojanamon *et al.*, 2009)

In run-of-river and reservoir hydropower plants, the natural flow of a river through an elevation drop is what drives the electrical production system. Run-of-river schemes generally rely on the flow of moving water and have no or little storage, although some run-of-river systems without storage do at times have a dam (Irena, 2012). Irena (2012) further states these run-of-river hydropower systems with dams are said to have "pondage". By having pondage, very short-term (hourly or daily) water storage is allowed. Water flow is regulated for plants with pondage to some extent and which allows power generation shifted over the day to when it is needed the most. Scheduled power generation is therefore not possible for plants without ponding. These schemes depend on river flow for the timing of power generation. A portion of the river is generally diverted to a penstock (pipeline) or channel where dams are not used (Anderson *et al.*, 2015).

2.4 Sustainability of Run-of-River Hydropower Systems

Run-of-river hydropower systems divert flow within a river channel for power generation and then re-diverts the flow back into the main river channel (Anderson *et al.*, 2015). Evaluating the sustainability of a project requires in-depth studies where the broad context is narrowed to fit the context of the project, which differs from project to project. Relationships exist between the activities of a project, and these relationships play a role in determining the project's overall sustainability. An example of these relationships in hydropower systems can be the influence of a system in flow patterns of a river which, could also influence the health of the downstream ecosystem.

Figure 2.2 shows a schematic of a run-of-river hydropower system installation. Generally, weirs are used as channel obstructions to regulate water levels, which allow for portions of river flow to be diverted to a secondary pipeline or channel (Anderson *et al.*, 2015). The flow is diverted to a turbine by a secondary channel before the flow is returned to the main channel downstream.

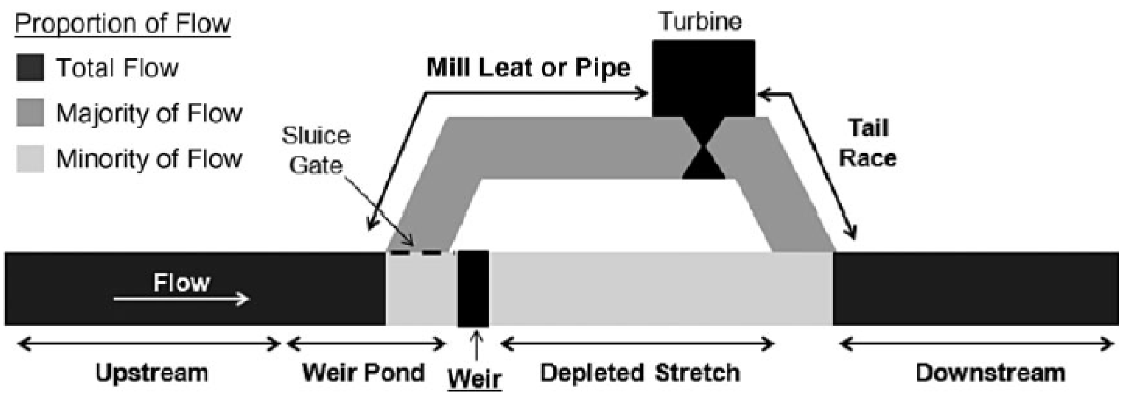

Figure 2.2: Run-of-River Hydropower System Schematic Representation (Anderson *et al.*, 2015)

In the development of run-of-river hydropower systems, sustainability is defined as systems which consider the potential physical, ecological, environmental, social, and economic impacts that they may impose once complete (Anderson *et al.*, 2015). These are discussed as follows:

2.4.1 Potential Physical, Ecological and Environmental Impacts

According to Poole (2010) and Newson *et al.* (2012), the physical habitat within rivers is determined by geomorphological and hydrological interactions. As a result of this, biological communities are also affected. Anderson *et al.* (2015) however states that very few studies have been done in run-of-river hydropower systems for this. To provide a greater understanding, Anderson *et al.* (2015) considers a broader study of the ecological and environmental impacts of geomorphological and hydrological changes in rivers. In their research, Anderson *et al.* (2015) divide the study into two categories, which are in-channel barriers and river flow regime change, resulting from run-of-river hydropower schemes.

To give an insight on the need for sustainability from an ecological and environmental impact point of view, Anderson *et al.* (2015) elaborates on the two categories and notes the considerations as shown below:

- In-channel barrier impacts
- Water flow depletion impacts
- Riverine habitat impacts
- Connectivity impacts
- Potential for mitigation

2.4.2 Social Impacts

Social impacts seek to identify the issues and benefits that may arise from proposed projects with local communities. Kumar and Katoch (2014) give examples of these issues, such as the livelihood interference of such projects, potential employment creation, the displacement of people, among other such factors. The acceptance of proposed projects and development by the local communities and their participation in decision making then becomes critical. Overlooked social issues come with potential consequences of unwelcome project plans, which may have long-term negative impacts on projects (Carrera and Mack, 2010). According to Kumar and Katoch (2014) and Singh *et al.* (2012), this category has unfolded as one of the most crucial sustainability considerations, with caution required when negotiating with communities of interest.

2.4.3 Economic Impacts

Accessing the economic viability of a hydropower project from a cost and benefits point of view is essential. Most development projects give top priority to this category because it gives an indication of the profits and losses of a hydropower project (Kumar and Katoch, 2014).

The need for relevant indicators

The information provided in section 2.4 above suggests a need for relevant indicators to ensure the sustainability of run-of-river hydropower systems (Hák *et al.*, 2016).

2.5 Sustainability Indicators and Classification

Indicators are tools used to provide clues to issues that are not necessarily easy to identify or detect immediately. According to (Morris and Therivel, 2001), indicators should be SMART (Specific, Measurable, Achievable, Relevant and Time bound), and they should be used with restraint and wisdom. Kumar and Katoch (2014) states that only then can they guide actions towards sustainability. According to Kumar and Katoch (2014), the assessment of the sustainability of hydropower projects requires a study and estimation of some indicators, indicating the sustainability of the project being studied. These indicators are referred to as Sustainability Indicators of hydropower projects (Kumar and Katoch, 2014).

Sustainability indicators assist in guiding the actions of those that use the indicators towards the design and implementation of sustainable projects (Moghaddam et al., 2011). Their broadness requires approval from various stakeholders, resulting in joint participation, yielding, and ensuring more sustainable outcomes (Carrera and Mack, 2010). Sustainability indicators are broadly classified into two categories (Kumar and Katoch, 2014):

i. Classification based on the '3 Pillar Concept'
ii. Classification based on Measurability

2.5.1 Classification based on the '3 Pillar Concept'

The three-pillar concept, also known as the Economic, Environmental and Social criteria, is an inter-linked criterion where numerous linkages allow some indicators to be classified into more than one criterion (Vera and Langlois, 2007). Examples of such linkages are understanding that economic developments that disregard the environment are likely to have social impacts, resulting in unsustainable developments, similar to environmental or social considerations that disregard the economy (Kemmler and Spreng, 2007). These linkages create an understanding of the trade-offs that exist among these three pillars for sustainable hydropower development (Morimoto, 2013).

2.5.1.1 Economic criteria

In general, these indicators represent the economic viability of hydropower projects from a cost and benefit point of view. A majority of development projects give top priority to this category because it gives an indication of profits and losses of a hydropower project (Kumar and Katoch, 2014).

2.5.1.2 Environmental criteria

The consideration of surrounding territories and ecology is critical when considering the environmental suitability of projects using these indicators (Rosso *et al.*, 2014). The emphasis has increased on these indicators due to the growing global environmental concerns. These indicators serve to assist decisions that aim to preserve the environment (Kumar and Katoch, 2014).

2.5.1.3 Social criteria

Social indicators are related to local communities accepting proposed projects and developments, and their decision making participation (Kumar and Katoch, 2014). They stand for potential consequences of unwelcomed plans, which may have long-term negative impacts on projects (Carrera and Mack, 2010). According to Kumar and Katoch (2014) and Singh *et al.* (2012), this category has unfolded as one of the most crucial sustainability indicators, with caution required when negotiating with communities of interest.

2.5.2 Classification based on Measurability

The determination of sustainability for hydropower development in this classification is not straightforward as it consists of multi-conflicting criteria that considers a number of parameters (Kumar and Katoch, 2014). According to Kumar and Katoch (2014), the measurability classification considers two types of sustainability indicators, Quantitative and Qualitative.

2.5.2.1 Quantitative (Direct/Tangible)

These indicators are based that are based on units of measurement and can be measured using a reliable unit (Kumar and Katoch, 2014). Examples of such indicators are plant power output and area covered by units. Kumar and Katoch (2014) further state that most economic sustainable indicators are quantitative type.

2.5.2.2 Qualitative (Indirect/Non-Tangible)

These are indicators that cannot be quantified or measured by a reliable unit and are generally impossible to define (Kumar and Katoch, 2014). Examples of these indicators are obtained from different thoughts and ideas of people, and they can be the potential visual impact of the project or community living standards (Kumar and Katoch, 2014). Expert/professional opinion and community participation generally play a huge role in determining these indicators.

2.6 Sustainability Indicators for Run-of-River Hydropower Projects

Sustainability indicators for Run-of-River hydropower projects are obtained from four sources: literature review, perception surveys, site visits and expert/professional opinion in project areas of interest (Kumar and Katoch, 2014). Literature investigations typically display a broad selection for the indicators, but the other three sources become more specific to a particular region under investigation or project (Kumar and Katoch, 2014).

According to (Kumar and Katoch, 2014), numerous researchers from across the globe have documented and listed sustainability indicators for Run-of-River hydropower projects. Table 2.2 shows a brief overview of these indicators, and Table 2.3 summarises the number and type of these indicators considering both the three-pillar concept and the measurability classifications.

Table 2.2: Sustainability indicators that are suggested for Run-of-River hydropower systems (Kumar and Katoch, 2014).

Social Indicators	Environmental Indicators	Economic Indicators
• Quantity of people displaced due to project (x, -) • Employment created due to project (x, +) • Public participation and acceptance during decision making (#, +) • Cultural heritage protection (#, +) • Living standards (#, +) • Social and corporate responsibilities (#, +) • Agricultural productivity (#, -) • Environmental issues such as air and water pollution (#, -) • Local and migrants conflicts (#, -) • Damage to land and properties due to operations (#, -) • Social value changes (#, -) • Transport and communication facilites (#, +) • Time wastages or delays due to project operation (#, -) • LADA (Local Area Development Authority) fund being effectively utilised (#, +) • Impacted cremation sites (#, -)	• Number of debris generated and disposal (x, -) • Required project land area (x, -) • Impoundment of reservoir (x, -) • Diverted stream length reach (x, -) • Silt quantity in stream (x, -) • GHGs emission (x, -) • Air pollution/quality (x, -) • Water pollution/quality (x, -) • Noise pollution (x, -) • National wildlife century/park within 10km of project site (x, -) • Soil erosion (#, -) • Impacts of transmission lines (#, -) • Mining/quarrying operations (#, -) • Aquatic life impacts (#, -) • Impacts on birds and terrestrial animals (#, -) • Natural hazards like cloudbursts, landslides, earthquakes, etc. (#, -) • Impacts on natural water or ground water (#, -) • Concerns of climate change (#, ±) • Impacts due to presence of other hydropower systems in the vicinity (#, -) • Visual impacts (#, ±)	• Capital (Initial investment) and recurrent cost (x, -) • State hydropower policies and central governments (#, ±) • Period of gestation (x, -) • Repayment period (x, -) • Cost of generation per unit (x, +) • Project accessibility from existing road (x, -) • Transmission line length (x, -) • Tourism impact (#, ±) • Impact on commerce, trade and industry (#, ±) • CDM benefits (x, +) • Efficiency of net generation (x, +) • Cost-benefit ratio (x, +) • Average annual project availability for generation (x, +) • Project affected people rehabilitation and resettlement cost (x, -)

Note: (x) = Quantitative, (#) = Qualitative, (+) = Potential positive impact on sustainability or directly proportional to sustainability, (-) = Potential negative impact on sustainability or inversely proportional to sustainability, (±) = May be a positive or negative impact on sustainability.

Table 2.3: Summary of the type and number of suggested sustainability indicators for Run-of-River hydropower systems (Kumar and Katoch, 2014).

Social Indicators = 15		Environmental Indicators = 20		Economic Indicators = 14		Total number of Sustainability Indicators = 49	
Qualitative (#) 12	Quantitative (x) 3	Qualitative (#) 10	Quantitative (x) 10	Qualitative (#) 3	Quantitative (x) 11	Qualitative (#) 25	Quantitative (x) 24

As seen in the summary provided in Table 2.3 above, there are 49 sustainability indicators for run-of-river hydropower systems in total (Kumar and Kotch, 2014).

2.6.1 Economic Indicators

(Boom, 2001) talks about the signing of the Kyoto Protocol. During the signing of the Kyoto Protocol, Capoor and Ambrosi (2008) states that an average reduction in emissions of 5.2% of the measured levels was required in industrialised countries in 1990 over the period 2008 to 2012. Besides the emission reductions, what arose is three flexible mechanisms, which allowed for the compensation from emission reductions. These included Emission Reduction Units (ERUs) and Certified Emission Reductions (CERs) which can be sold by developing countries, like South Africa, to countries that were obligated to meet emission targets. This results in the non-consideration of the CDM benefits indicator for this study. Van Vuuren *et al.* (2011) also state that the cost involved with constructing transmission lines can become significant for a remotely located power station, thus requiring the transmission lines to cover a considerable distance. Simplified methods were attempted to incorporate transmission line costs. However, due to there being many variables to consider, it makes it impossible to incorporate them (Van Vuuren *et al.*, 2011). Therefore, the transmission line cost is based on the designer's experience. Small run-of-river hydropower systems do not affect the river flow network significantly. This is shown in figure 2.1. Therefore, little to no displacement of people will also result in excluding the corresponding indicator for this study. Consequently, resulting in the consideration of a special economic analysis, denoted as the Levelised Cost of Electricity (LCOE) from hydropower which will be discussed later in this study. The indicators which will be reviewed are:

- Investment cost
- Recurrent costs
- LCOE
- Payback period

The social and environmental indicators are measured using a vulnerability line diagram. The vulnerability line diagram is a diagram that measures the vulnerability of each indicator between two set parameters. Vulnerability is defined as the characteristics determined by physical, social, environmental, and economic factors which increase the sensitivity of an individual, a community, systems or assets to the impacts of hazards.

2.7 Hydropower Generation

Two methods have been widely used of the several methods for the estimation of power potential from hydropower systems. The first method is the Flow Duration Curve (FDC) also known as the non-sequential and the second method is the Sequential Streamflow Routing method (SSR) (Karamouz, 1991). The SSR method is selected for assessing the feasibility of power at constructed flood control and water conservation projects (Karamouz, 1991;Karamouz *et al.*, 2003;Bekoe *et al.*, 2012;Younis and Hasan, 2014). Generally, FDCs are selected for run-of-river projects where the hydraulic head is usually fixed, for high head-projects, and for low-head projects where the hydraulic head varies with discharge. This review focuses on the FDC method.

To assess the hydropower potential from a potential site, the discharge and head of the site of interest are required. Improvements have been made in recent years in evaluating the river discharge and the hydraulic head. Improvements such as Geographic Information System (GIS) have made it easy to digitally map the topography of the sites of interest with features such as contour line drafting and terrain viewing being available, together with Remote Sensing (RS) which geographically scan the Earth and any place of interest. Tool combination allows for an effective hydropower evaluation method in developments of interests (Maidment and Morehouse, 2002). Such tools have the potential of aiding designers by highlighting potential hydropower sites for reservoir dams and run-of-river schemes when used as a collective, and these tools have been used in the U.S.A (Hall *et al.*, 2004) and South Africa (Ballance *et al.*, 2000).

The lack of data, or its availability, determines a method analysis used to obtain river discharge. This mainly depends on whether a catchment is gauged or not. For large sites, surface runoff can be determined successfully using water balance techniques (Yates, 1997).

2.7.1 Flow duration curves

The definition of a flow duration curve (FDC) is the relationship between discharge (Q) and the percentage of time of a particular discharge being analysed, whereby that particular discharge (Q) is equalled or exceed (Mimikou and Kaemaki, 1985;Vogel and Fennessey, 1994;Castellarin *et al.*, 2004;Niadas, 2005;Rojanamon *et al.*, 2007). A daily, weekly and monthly cumulative function of streamflow is what describes an FDC (Fennessey and Vogel, 1990;Vogel and Fennessey, 1994;Vogel and Fennessey, 1995). Kim (2004) states that FDC graphical representations show the relationship between discharge and the probability corresponding to it. Blanco *et al.* (2008) states that FDC are derived from streamflow data, which are used to determine the design flow for hydropower plants. FDCs cannot simulate the actual flow sequence of a river. Rather they can predict variability and availability of discharge. The basis of selecting mechanical equipment of a hydropower plant such as turbines and sizing civil works such as the channel or penstock is formed by FDCs. Figure 2.3 illustrates a typical flow duration curve.

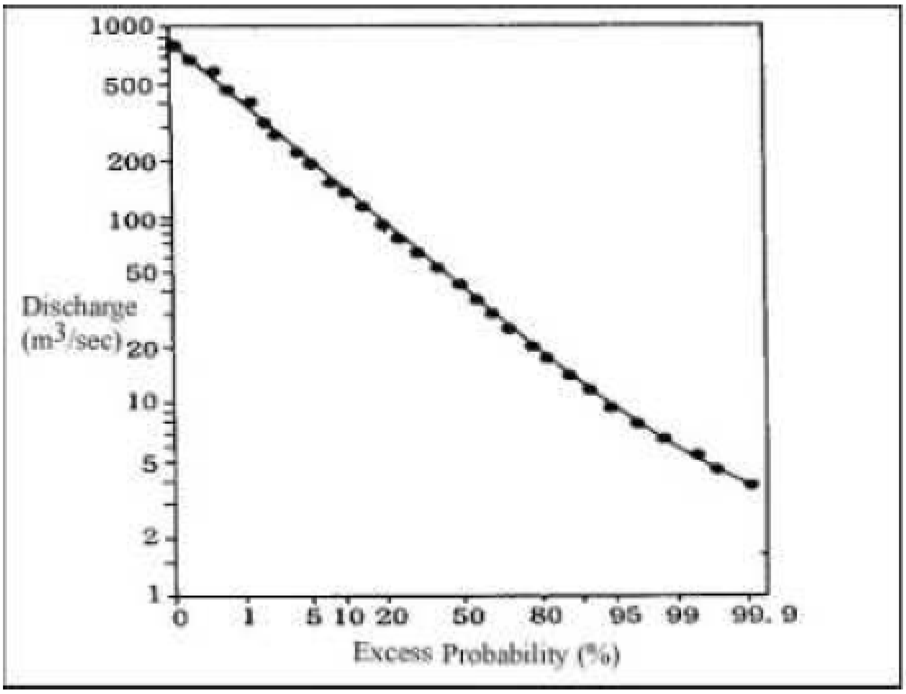

Figure 2.3: Example of a Flow Duration Curve (Karamouz *et al.*, 2003).

2.7.1.1 Regionalisation of flow duration curves

Castellarin *et al.* (2004) state that the ideal sites for small hydropower systems (SHPs) in most instances are ungauged. This results in the regionalisation method being necessary to estimate the required hydrological information at any point of interest in that site using what is available from the gauging stations. According to Smakhtin *et al.* (1998), flow estimation using regionalisation techniques is aimed at estimating a general discharge measure or some low-flow characteristics applicable to any particular ungauged location in a region. Regionalisation techniques are classified under flow duration curves, spatial proximity, and physical similarity categories (Nobert *et al.*, 2011;Archfield *et al.*, 2013;Shoaib *et al.*, 2013).

A FDC is derived from a historic river hydrograph which is a plot of historic streamflow. Longer hydrographs imply less sensitivity to abnormalities in flow variations for designs. A river hydrograph example is shown in Figure 2.4.

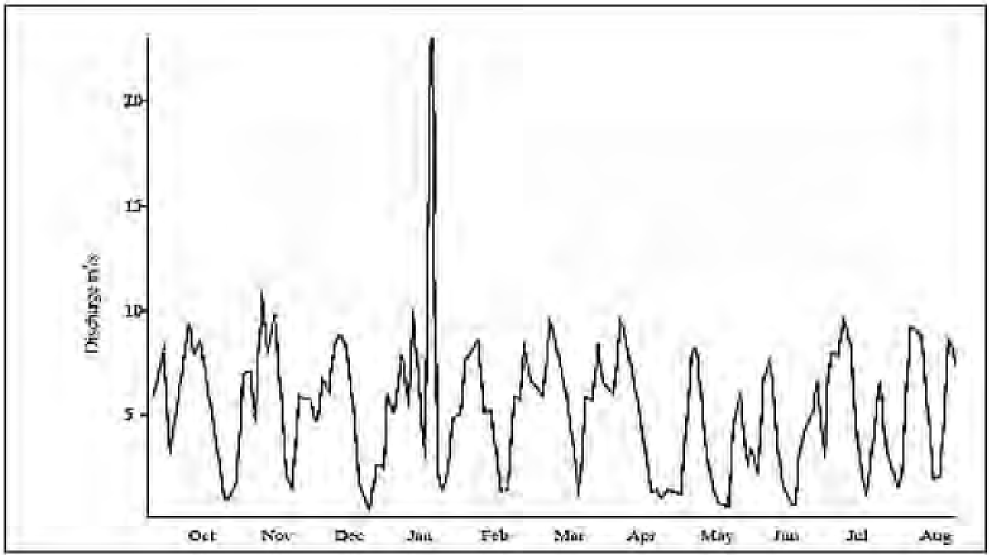

Figure 2.4: River Hydrograph example (Pelikan, 2004).

FDC are commonly constructed using two techniques. These are:

Ranked Flow technique

According to Fritz (1984), the flow time series is ranked according to the flow magnitude. Mean daily, weekly, monthly or annual flow records may be used. The flow data are ranked chronologically and assigned numbers, with the largest flow assigned with the smallest number being 1. The percentage of time that a particular mean discharge (month, week, and day) has been equalled or exceeded is determined by ranking the numbers chronologically, dividing them by their total and multiplying them by 100. A graphical representation of discharge vs probability of time exceedance is plotted for the period analysed (Fritz, 1984).

Class Interval technique

Time series discharge values are categorised into different class intervals. The classes for these discharge values range from highest to lowest. A score system for the number of discharges for each class is made which allows for the determination of values greater or less than each class. The percentage of time exceedance is determined by dividing the number of values greater than each class by the total number of discharges. The flow duration curve is obtained when these results are plotted vs the upper-class interval. It should be noted that using other discharge average periods besides daily averages periods generally has hidden information due to averaged values. Critical month periods should contain low and high discharge months for small hydropower schemes (Fritz, 1984).

2.7.2 Flow duration curve applications

There are many water resources development and management uses for Flow duration curves (FDCs), including small hydropower installation schemes (Yu *et al.*, 2002;Castellarin *et al.*, 2007). FDCs can be applied to various water resource problems. Some examples include hydropower planning, flood frequency analysis and water quality management (Vogel and Fennessey, 1994). Where hydropower estimation is concerned, FDCs are applied in feasibility studies for run-of-the river hydropower systems (Vogel and Fennessey, 1995;Nobert *et al.*, 2011). For preliminary or screening studies, the FDC method is a suitable method (Karamouz *et al.*, 2003). Sufficient streamflow data period is one of the main requirements for developing an FDC (Vogel and Fennessey, 1995;Nobert *et al.*, 2011). This method relates streamflow values and the percentage of time that different stream flow levels are exceeded. To obtain an FDC, the data is ranked according to discharge but not following the sequence in which they occurred. Karamouz *et al.* (2003) states that this means that the arrangement of the descending order of magnitude streamflow data can be used.

A river analysis of any river is necessary to plot its FDC, and this analysis requires its streamflow data over a sufficient data period. The data is ranked according to the probability of exceedance. Equation (2.1) gives formula for the probability of exceedance (P*ei*) (Karamouz *et al.*, 2003;Castellarin *et al.*, 2004):

$$P_{e_i} = \left(\frac{i}{N+1}\right) x\ 100 \qquad (2.1)$$

Where:

Pe_i	=	probability that a given flow will be equalled or exceeded (% of time),
i	=	rank in descending order position on the listing (dimensionless), and
N	=	number of events for period of record (dimensionless).

According to Fritz (1984) the estimation good of primary energy can be offered by the Q50 index. Good starting values for equipment sizing are the Q20 and Q30 flows. The Qi index denotes the discharge that is equalled at Pei (% time) probability of exceedance.

2.7.3 Power duration curves

Equation (2.2) can be used to convert flow duration curves to power duration curves (Karamouz *et al.*, 2003;Ramachandra and Shruthi, 2007):

$$P_i = \frac{e_i.\gamma.Q_i.H_i}{1000} \qquad (2.2)$$

Where:

P_i	=	power produced at percentage exceedance *i* (kW),
Q_i	=	turbine discharge ($m^3.s^{-1}$) at percentage exceedance *i* (%),
H	=	hydraulic head with discharge at percent exceedance *i* (m),
e_i	=	plant efficiency with turbine discharge equal to Q_i (%), and
γ	=	specific weight of water ($N.m^{-3}$)

Applying equation (2.2) allows for the application which can consider from plant intake, through the channel or penstock (pipeline), turbine intake, draft tube, and tail race (Vogel and Fennessey, 1995). Generally, the manufacturer provides the turbine's characteristics where the relationship between the the discharge its operating head and the turbine efficiency can be obtained (Vogel and Fennessey, 1995).

Equation (2.2) can be used to estimate the power production for each calendar month. An example of an FDC and a power duration curve (PDC) is shown in Figure 2.5. The maximum power that can be generated by the power plant and the firm energy can be determined from the power duration curve. To draw the power duration curve, the maximum power potential of the plant is first calculated and plotted using the design flow from the flow duration curve. This flow remains constant until it reaches a probability where Q50 < Qdesign. Then the design flow becomes the lower flow until the PDC reaches 100%.

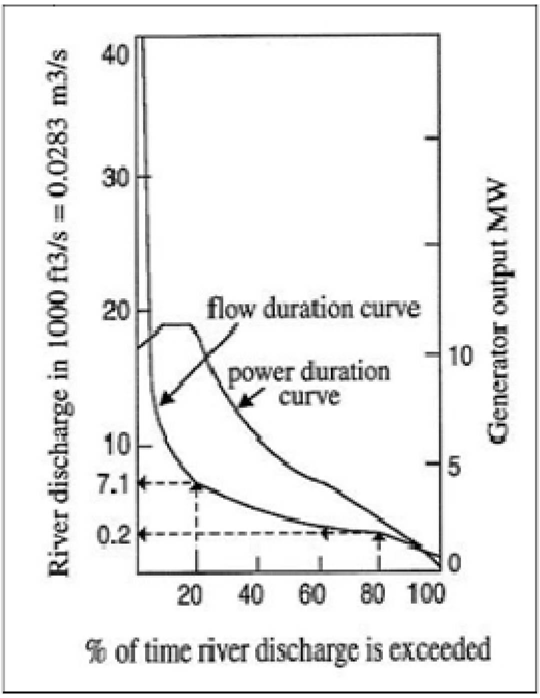

Figure 2.5: Example of FDC and PDC (Karamouz *et al.*, 2003).

2.8 Turbine Selection

There are two types of turbines. These are “impulse” turbines and "reaction" turbines. Reaction turbines are water pressure head driven turbines. Impulse turbines use the momentum of the water as it flows to extract energy, as opposed to the pressure applied from the weight of the water (Irena, 2012). Due to the selected sites having low design flow rates, which will be seen later in the generated FDCs for each site, impulse turbines have been selected for this study.

The most efficient and appropriate turbine for the design of a hydropower project depends on the site of the hydropower scheme. The key considerations are flow rate and head, as shown in figure 2.6 (Irena, 2012). The most widely used turbine in hydropower is the Francis turbine and it is a reaction turbine. This is because of the high efficiency of Francis turbines which allow them to be used for a variety of flow rates and head. The Kaplan turbine is also a reaction turbine derived from the Francis turbine. But, (Irena, 2012) states that the Kaplan turbine only allows for efficient hydropower production for head ranges between 10 and 70 metres.

Impulse turbines such as the Crossflow, Turgo and Pelton are also available. The most commonly used impulse turbine is the Pelton turbine with high heads. Crossflow turbines have lower efficiencies but also require less maintenance and depend less on discharge (Irena, 2012). The operating areas of different types of turbines is shown in Figure 2.6.

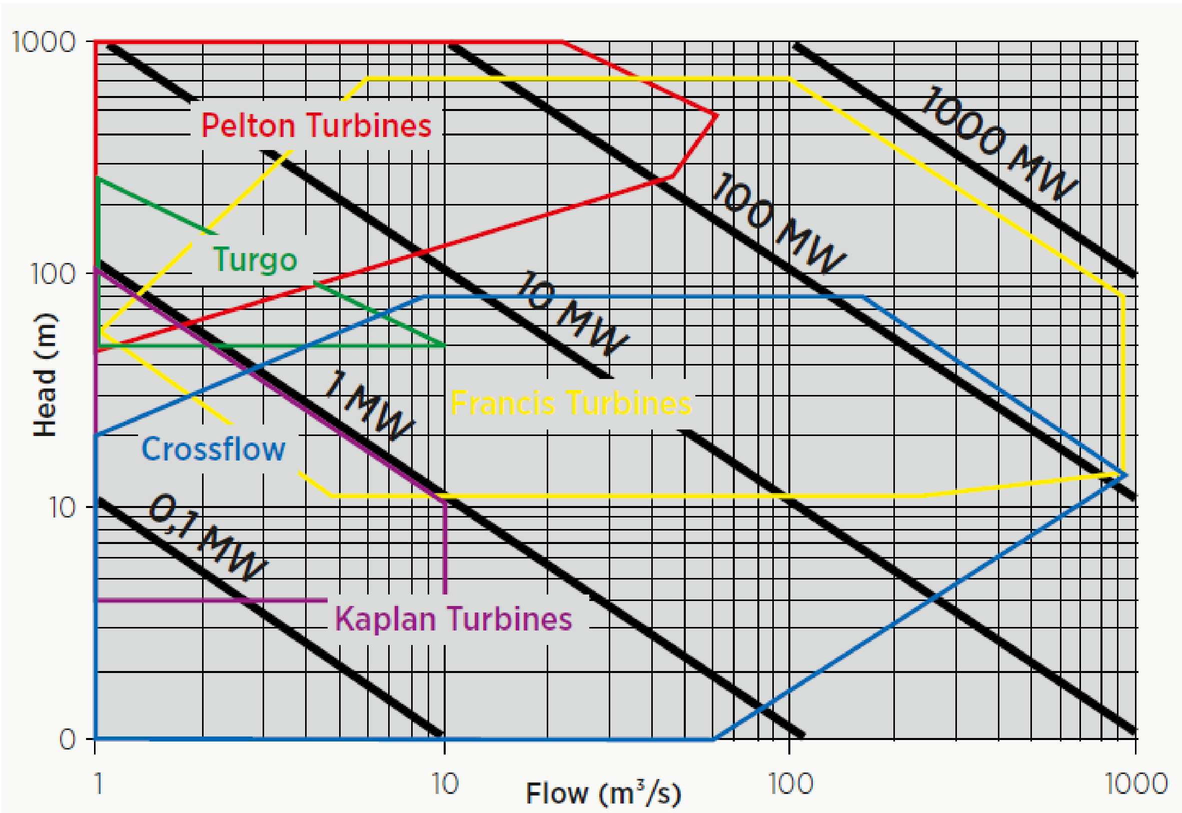

Figure 2.6: Operating areas of different types of turbines (Irena, 2012).

Attempts were initially made to contact turbine manufacturers for costs, however, this proved difficult due to the limited information obtained. This resulted in the literature references and in particular the work of (Alvarado-Ancieta, 2009). The formula of Alvarado-Ancieta (2009) to determine costs (converted to Rands) of all necessary electro-mechanical equipment for Crossflow turbines was chosen because of its least error of 5% to 10% and that it encompasses for all electro-mechanical components, is straightforward to use, is recent and was a recommendation from local manufacturers (Van Vuuren *et al.*, 2011).

2.9 Economic Feasibility

Run-of-river hydropower and reservoir (storage) hydropower plants and of all sizes utilise the same basic technologies and components, but run-of-river hydropower plants are more likely to be small hydropower plants than large hydropower plants (Irena, 2012). According to Irena (2012), the development of large and small hydropower plants for rural areas face similar technical, environmental, social, and economic considerations.

2.9.1 The Levelised Cost of Electricity (LCOE) from Hydropower

LCOE is the price of electricity required to break-even. This is when revenues costs would equal revenues, but also making an investment return that equals the discount rate. An electricity price above this, would result in a greater investment return while a price below this would result at in a slow investment return, or at a loss (Irena, 2012).

What is important to note is that the data presented by Irena (2012) is actually prices as opposed to costs as mentioned by the author, and the author states that the data available is not the true market average price but price indicator. The cost and price differences would be seen in a competitive market. This is because the amount is used to note these differences as they are evaluated above or below the normal profit. Irena (2012) states that all costs presented in this investigation are real 2010 USD after inflation has been taken into account.

Market surveys or other sources are generally used to obtain the cost of the equipment. Often difficulties are encountered in gathering sources of data the same period and trying to understand why data of the same period differs. Total capital project costs tend to vary significantly from project to project as the balance often depends on local content. This is because the cost structure for hydropower plants varies widely due to the actual power generation equipment depending on where the project is being developed (Irena, 2012).

The LCOE of renewable energy technologies varies by country, technology and is based on the renewable energy project being developed. It is affected by variables such as costs which include operational and maintenance costs, capital costs, together with the overall performance of the system throughout its design life (Irena, 2012).

2.9.1.1 Electro-mechanical Equipment Costs

Different studies have been conducted to analyse the electro-mechanical equipment costs for hydropower plants as a function of power plant head and potential power. Equation (2.3) describes recent work that has looked at the relationship between costs and the potential power and head of a small hydropower scheme (Ogayar and Vidal, 2009):

$$\text{COST (per kW)} = \alpha P^{1-\beta} H^{\beta 1} \qquad (2.3)$$

Where:

P	=	Power of turbines (kW)
H	=	Head (m)
α	=	Constant
β	=	Power coefficient
β1	=	Head coefficient

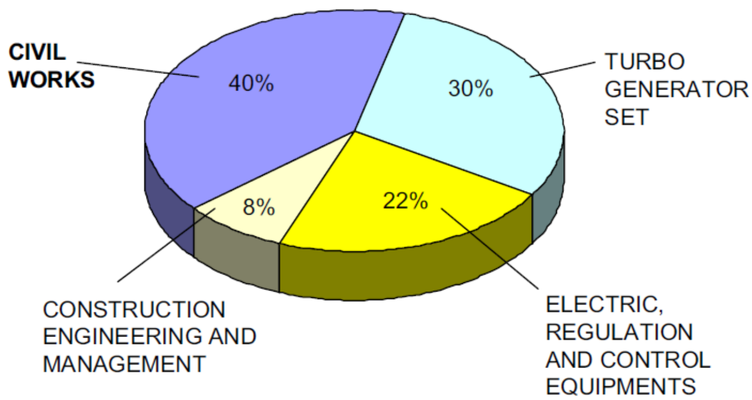

Figure 2.7: Contribution of cost for small hydropower by components (Ogayar and Vidal, 2009)

(Van Vuuren *et al.*, 2011) presents the results, converted to rands using the 2009 exchange rates, as follows:

Pelton: $$C_{em} = 201.645\,(10^{-3}P)^{-0.3644725} H^{-0.281735} \qquad (2.4)$$

Francis: $C_{em} = 292.878\ (10^{-3}P)^{-0.56013} H^{-0.127243}$ (2.5)

Kaplan: $C_{em} = 378.787\ (10^{-3}P)^{-0.58338} H^{-0.1113901}$ (2.6)

Where:

C_{em} = Electro-mechanical equipment cost [R/kW]

P = Power output [W]

H = Effective head [m]

According to Irena (2012), the majority of these studies are 10 years old or more. But the cost estimation results analysis using this methodology are available for a range of developed countries. Spain's recent hydropower analysis of small hydropower plants, which analysed the analysis of recent costs separately for Fransis, semi-Kaplan, Pelton and Kaplan turbines, yielded a good fit for the equations (Ogayar and Vidal, 2009).

A trend conducted by Alvarado-Ancieta (2009) in a study of 81 hydropower projects and 32 countries around the world was to determine a trend between electro-mechanical costs and power output of the plant. The data comprises approximately 9 in Africa hydropower projects, 28 hydropower projects in America (90% Latin America), 9 in Europe and 35 in Asia. The electro-mechanical costs include auxiliary systems, turbines, cooling and drainage systems, generators, valves, transformers, cranes, workshops and control equipment costs. Alvarado-Ancieta (2009) found an expression which describes the general tendency of electrical and mechanical costs as a function of power capacity for the different turbines. Van Vuuren *et al.* (2011) describes the expression in Equation (2.7) below in Rands using the 2009 exchange rate:

$$C_{em} = 9.742\ P^{-0.7634} \tag{2.7}$$

Where:

C_{em} = Electro-mechanical equipment costs [R]

P = Power output [W]

Alvarado-Ancieta (2009) states that formulae based on parameters such as hydraulic head, design discharge, number of units or power have an extensive range of variability in cost results. Therefore, depending on different head ranges and discharge amongst others, they should be limited. Alvarado-Ancieta (2009) also state that this formula has an error range of 5% to 10%, which is significantly better than Ogayar and Vidal (2009). Figure 2.8 shows the costs of electro-mechanical equipment and installed power capacity in the powerhouses for 81 hydropower plants in Africa, Asia, America and Europe. These are divided by type of turbine: Pelton, Francis pump-turbine or Bulb, Francis, Kaplan-Rohr, Kaplan (Alvarado-Ancieta, 2009).

According to Irena (2012), cost data existing from global manufactures for electro-mechanical equipment has been used to check these types of results obtained from this type of analysis, as seen in figure 2.8 (Alstom, Andritz, Gilbert Gilkes & Gordon Ltd, NHT and Voith Siemens). The findings were statistically consistent with real cost data from existing plants. Although this type of analysis is a useful for first order estimate of costs, Irena (2012) states that these results need to be treated with caution. This is due to the real-world cost ranges that are experienced.

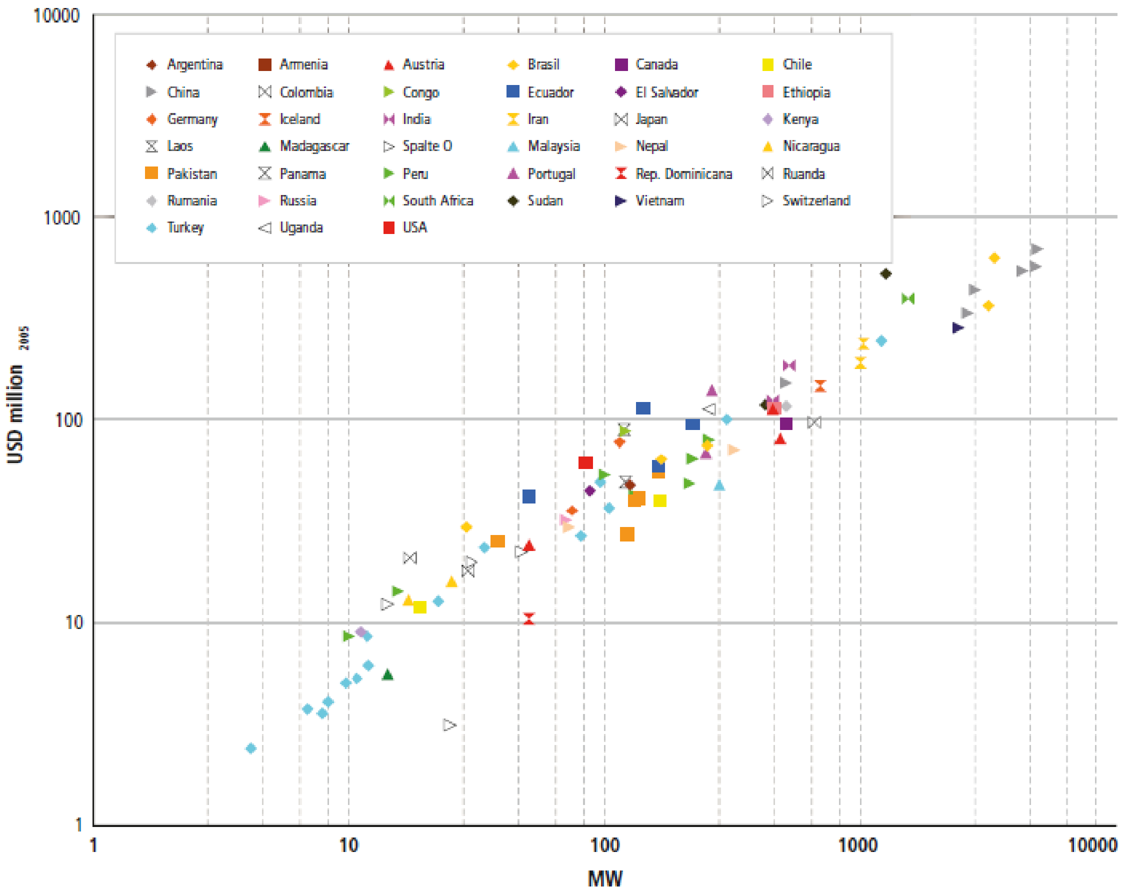

Figure 2.8: E&M cost of installed equipment and power capacity in powerhouses for 81 hydropower plants in Africa, Europe, Asia and America (Alvarado-Ancieta, 2009).

Alvarado-Ancieta (2009) states that the mechanical and electrical costs of equipment in a powerhouse were valid for 2009 as shown in Figure 2.8. However, because of the findings made by Irena (2012) previously stated, the tendency for costs shall be assumed to remain constant for this study. Therefore, equation of Alvarado-Ancieta (2009) to calculate electrical and mechanical equipment in a powerhouse will be used for this study.

The discount cash flow (DCF) analysis is used in the analysis present below. This method is based on the cost of calculating renewable energy technologies over the project lifetime based on discounting financial flows (monthly, quarterly or annual) to a common basis. It takes into consideration the concept of time value of money. This results in the weighted average cost of capital (WACC) for most renewable power generation technologies, given the capital-intensive and the fact that fuel costs are low, or often zero. Often, for the LCOE evaluation, the LCOE is critically impacted by what is also referred to as the discount rate 4 (Irena, 2012). Equation (2.8) describes the formula for calculating LCOE:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(I+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(I+r)^t}} \qquad (2.8)$$

Where:

- I_t = expenditures investment in the year t
- M_t = expenditures of operations and maintenance in the year t
- F_t = expenditures of fuel in the year t
- E_t = generation of electricity in the year t
- r = discount rate
- n = economic life span of the system

Hydropower has no fuel cost, is capital-intensive and has low O&M costs (Irena, 2012). The interest rates and investment costs greatly affect the LCOE, but the lifespan does not affect it that much, given the typical lifespan range for a hydropower plant. The calculation of each term in Equation (2.8) is shown in Appendix A, Table 6.1.

The cost band ranges for small and large hydropower systems by country are shown in Figure 2.9 (Irena, 2012).

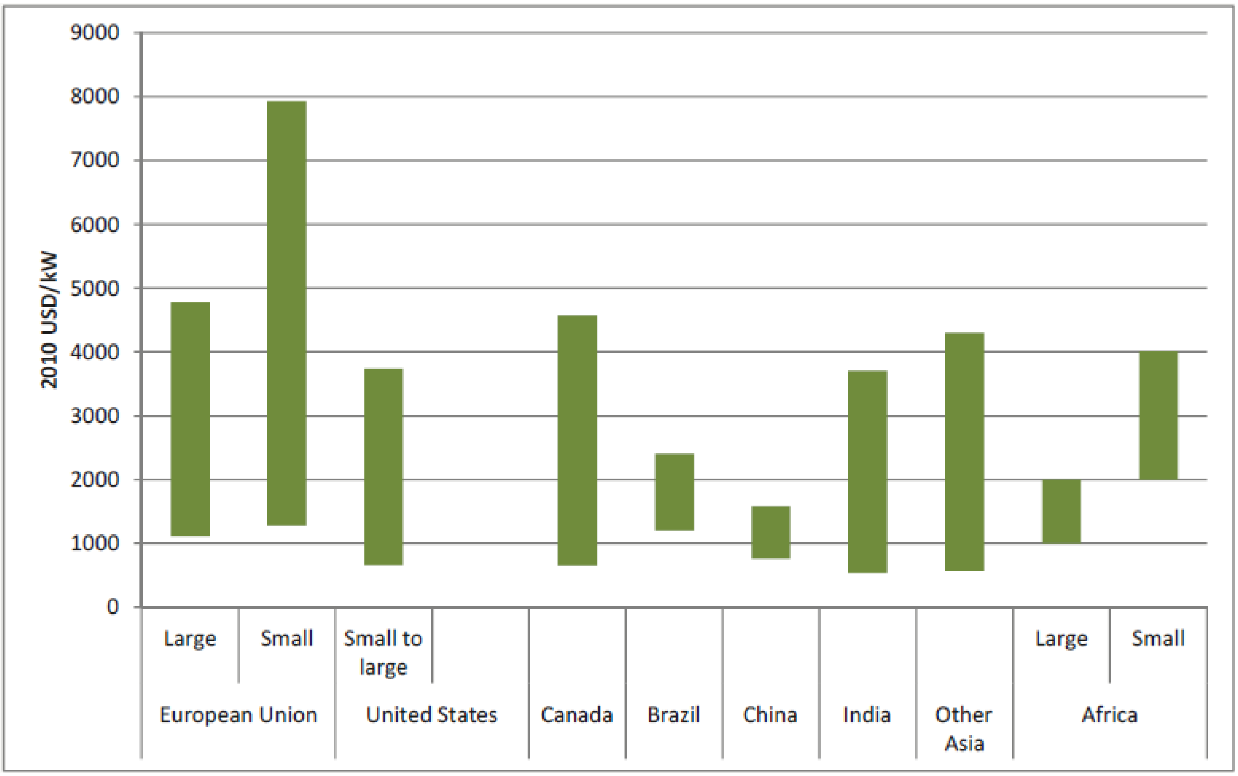

Figure 2.9: Cost ranges of total installed hydropower by country (Irena, 2012).

Figure 2.10 shows the capital cost for installed small hydropower systems by capacity in developing countries (Irena, 2012). A vital step also then becomes the check of Figure 2.10 on Figure 2.9 as a validation of the design in the initial design stages of the hydropower system.

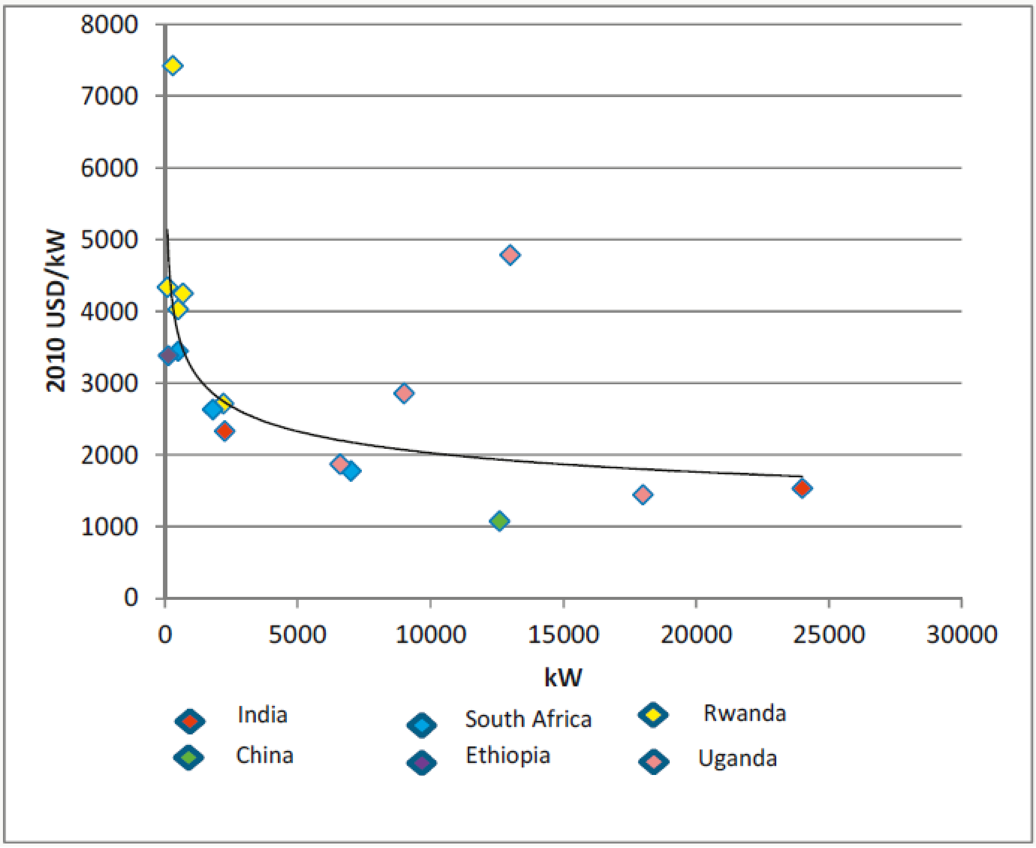

Figure 2.10: Small hydropower installed capital cost in developing countries by capacity (Irena, 2012).

2.9.1.2 Operation and Maintenance Cost

According to Irena (2012), annual operational and maintenance (O&M) costs are often noted as a percentage of the investment cost per kW per year. It is also stated by Irena (2012) that O&M values which range from 1 % to 4 % are typical. The IEA assumes 2.2% to 3% for small projects and 2.2% for large hydropower projects.

This usually includes electrical and mechanical refurbishment equipment like turbine overhaul, reinvestments in communication, generator rewinding and control systems. However, the replacement of penstocks, tailraces and vital components or major electro-mechanical equipment are not covered. An advantage stated by Irena (2012) hydropower projects is that these kinds of replacements are infrequent with both design lives of 50 years or more for the refurbishment of tail races and penstocks and 30 years or more for the electro-mechanical equipment which are not normal (Irena, 2012).

2.9.1.3 Capital Costs Contribution to Civil Works

Capital costs dominate civil works for large hydropower projects (Irena, 2012). In hydropower, each project is tailor-made for a particular location. Hydropower projects are also highly site-specific technology for a particular location to meet specific energy needs and water management within a given river basin. Many factors influence the cost of civil works such as the development scale, the site and the technology that is considered most economical (Irena, 2012).

The correlations for the cost of dam-toe hydropower small hydro-power (SHP) schemes is shown in Table 2.4, in Rs/kW, for one to four unit power plants, each unit with civil works equipment and electro-mechanical equipment (Singal and Saini, 2008).

Table 2.4: Cost for dam-toe correlations SHP schemes (Rs/kW) (Singal and Saini, 2008)

Components of work/equipment	**Cost per kW for alternative layout (Rs.)**			
	With one unit	**With two units**	**With three units**	**With four units**
Civil works				
Intake (C_1)	$14382\ P^{-0.2368}\ H^{-0.0598}$	$17940\ P^{-0.2366}\ H^{-0.0596}$	$21191\ P^{-0.2367}\ H^{-0.0597}$	$24164\ P^{-0.2371}\ H^{-0.0600}$
Penstock (C_2)	$4906\ P^{-0.3722}\ H^{0.3866}$	$7875\ P^{-0.3806}\ H^{0.3804}$	$9001\ P^{-0.369}\ H^{0.389}$	$10649\ P^{-0.3669}\ H^{0.3905}$
Powerhouse building (C_3)	$62246\ P^{-0.2354}\ H^{-0.0587}$	$92615\ P^{-0.2351}\ H^{-0.0585}$	$121027\ P^{-0.2356}\ H^{-0.0589}$	$146311\ P^{-0.2357}\ H^{-0.0589}$
Tail-race channel (C_4)	$28164\ P^{-0.376}\ H^{-0.624}$	$28164\ P^{-0.376}\ H^{-0.624}$	$28164\ P^{-0.376}\ H^{-0.624}$	$28164\ P^{-0.376}\ H^{-0.624}$
Electro-mechanical equipment				
Turbine with governing system (C_5)	$39485\ P^{-0.1902}\ H^{-0.2167}$	$63346\ P^{-0.1913}\ H^{-0.2171}$	$83464\ P^{-0.1922}\ H^{-0.2178}$	$101464\ P^{-0.1920}\ H^{-0.2177}$
Generator with excitation system (C_6)	$48568\ P^{-0.1867}\ H^{-0.2090}$	$78661\ P^{-0.1855}\ H^{-0.2090}$	$105046\ P^{-0.1859}\ H^{-0.2085}$	$127038\ P^{-0.1858}\ H^{-0.2085}$
Mechanical and electrical auxiliaries (C_7)	$31712\ P^{-0.1900}\ H^{-0.2122}$	$40860\ P^{-0.1892}\ H^{-0.2118}$	$49338\ P^{-0.1898}\ H^{-0.2080}$	$56625\ P^{-0.1896}\ H^{-0.2121}$
Main transformer and switchyard equipment (C_8)	$14062\ P^{-0.1817}\ H^{-0.2082}$	$18739\ P^{-0.1803}\ H^{-0.2075}$	23051 P-0.1811 $H^{-0.2080}$	26398 P-0.1809 $H^{-0.2079}$
Cost per kW of civil work (C_c) (Rs.) = $C_1+C_2+C_3+C_4$				
Cost per kW of electro-mechanical equipment (C_{em}) (Rs.) = $C_5+C_6+C_7+C_8$				
Total cost per kW (Rs.) = $1.13x(C_c+C_{em})$				

Table 2.5 shows the correlations for the cost of dam-toe of SHP schemes for civil works, as presented by Van Vuuren *et al.* (2011). These are the values that appear in the first column of Table 2.4 above, however, Van Vuuren *et al.* (2011) presents them in R/kW.

Table 2.5: Correlations for cost of dam-toe SHP schemes (R/kW) (Van Vuuren *et al.*, 2011).

Civil works costs per kW (Saini and Singal, 2008)	
Component	**Cost per (R/kW)**
Intake (C_1)	2 792 $(10^{-3}P)^{-0.2368} H^{-0.0598}$
Penstock (C_2)	952 $(10^{-3}P)^{-0.3722} H^{0.3866}$
Powerhouse building (C_3)	12 084 $(10^{-3}P)^{-0.2354} H^{-0.0587}$
Tail-race channel (C_4)	5 468 $(10^{-3}P)^{-0.376} H^{-0.624}$
Total	1.13 $(C_1 + C_2 + C_3 + C_4)$

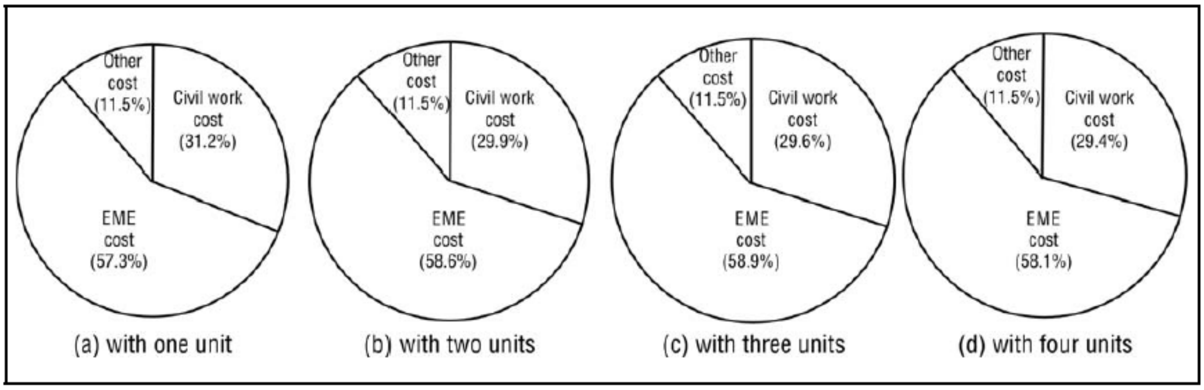

Figure 2.11: Cost break-up of dam-toe SHP scheme. EME = electro-mechanical equipment (Singal and Saini, 2008).

Van Vuuren *et al.* (2011) bases the hydropower retrofitting model (HRM) on Table 2.5, which is a one-unit power plant, as seen in Table 2.4. Figure 2.11 then gives the cost breakdown of the one-unit power plant, and it is worth noting that cost breakdowns are similar for all four power plants. It is also worth noting that in Figure 2.11, the average of the EME costs is approximately 58%, and the civil works cost is approximately 30% (Singal and Saini, 2008). According to Ogayar and Vidal (2009), civil works are approximately 40%, and EME costs are approximately 52%, as seen in Figure 2.7.

However, the Singal and Saini (2008) correlations, which Van Vuuren et al. (2011) used for the South African hydropower modelling, only apply to retrofitting dams. Irena (2012) also warns about hydropower plants being site specific and Van Vuuren used an Indian based model. Irena (2012) also states that the Ogayar and Vidal (2009) results from Figure 2.7 only produced results that were accurate for Spain. Irena (2012), as shown in Figure 2.12 presents variable

EME costs and civil works, together with more details than the other authors, and is more recent. Figure 2.12 shows the cost breakdown for each component as a percentage of the overall project for small hydropower schemes in developing countries (Irena, 2012). The concern then becomes hydropower projects appearing feasible when they are not. This is why the approach of Alvarado-Ancieta (2009) is adopted for this study, also considering that data was collected in South Africa, and Irena (2012) will be used for run-of-river hydropower systems in South Africa for this study.

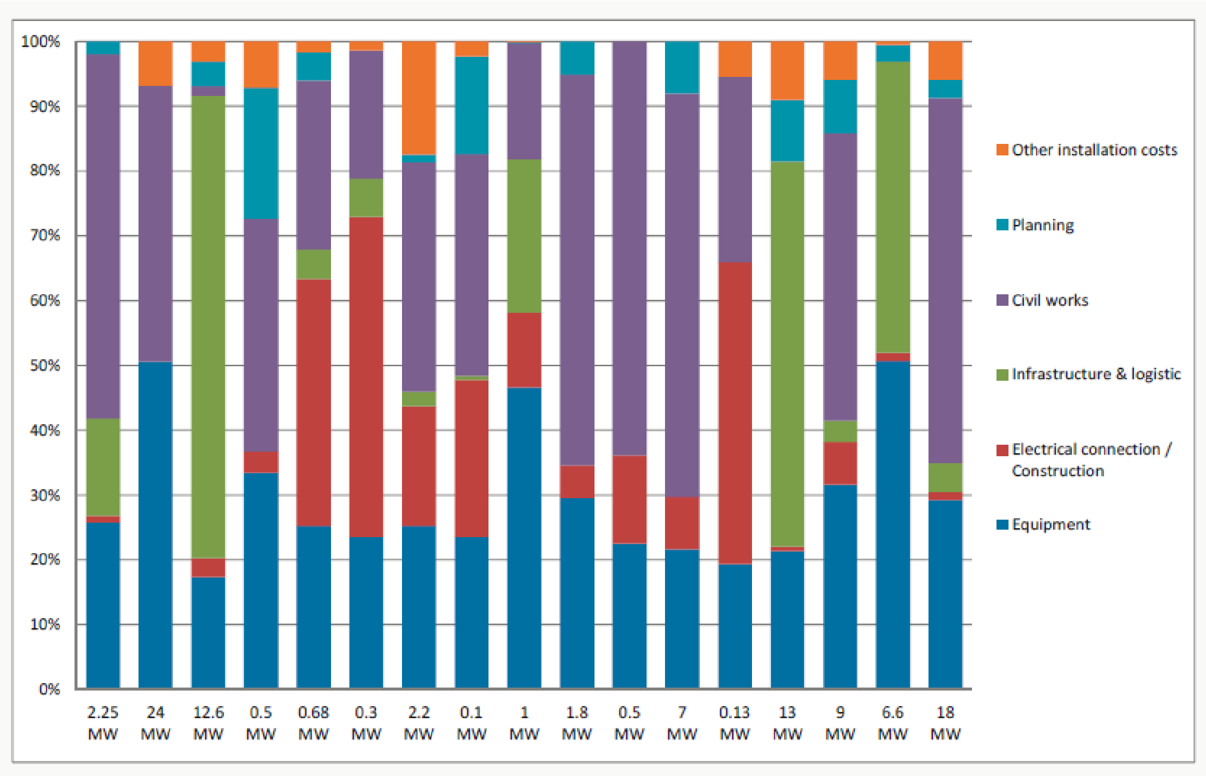

Figure 2.12: Cost breakdown for each component as a percentage of the overall project for small hydropower schemes in developing countries (Irena, 2012).

The concern, therefore, could be to qualify projects as feasible when they should not.

2.9.1.4 The Levelised Cost of Electricity (LCOE) Analysis

The LCOE of run-of-river hydropower systems require critical assumptions for it to be calculated and these are:

- Installed capital cost
- Economic life
- Capacity factor

- Operational and maintenance costs
- The cost of capital

The cost of capital (discount rate) is 10% and is assumed to calculate LCOE (Irena, 2012;Foster *et al.*, 2014). The amortisation period is assumed to be 30 years (Foster *et al.*, 2014). The capacity factor ranges between 23% and 95%, with the average of hydropower projects being 50% (Irena, 2012). The other assumptions have been sourced from the previous sections of this study.

Summary:

- Installed capital cost = Figure 2.10
- fuel cost = 0,
- electricity generation = calculate through FDC,
- O&M = 3% installed of capital cost
- Economic life (t) = 30 years
- The cost of capital (discount rate) = 10%
- Capacity factor = 0.95 (run-of-river)
- Evaluate LCOE = $\frac{\Sigma_{t=1}^{n}\frac{I_t + M_t + F_t}{(I+r)^t}}{\Sigma_{t=1}^{n}\frac{E_t}{(I+r)^t}}$
- Annual Income = Tariff (R/kWh) x Electricity generated (kW) x 18 hours/day (h) x 260 days/year

The boundaries of the renewable power generation and cost indicators are shown in Figure 2.13 below (Irena, 2012).

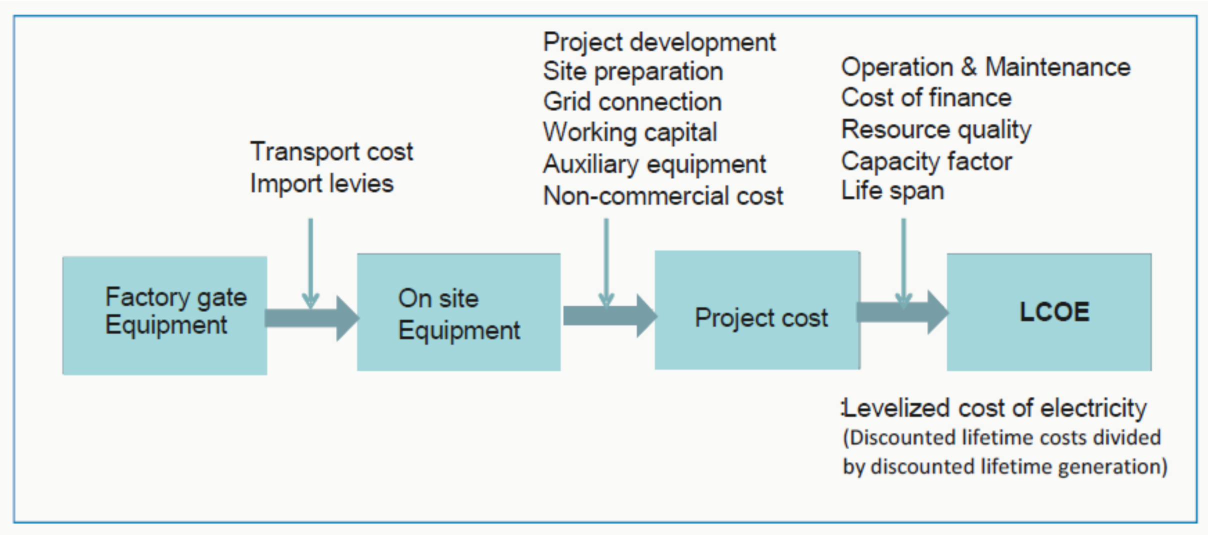

Figure 2.13: Renewable power generation boundaries and cost indicators (Irena, 2012).

2.10 Rural and Agricultural Productivity

Figure 2.14 shows the profile of a rural household power usage.

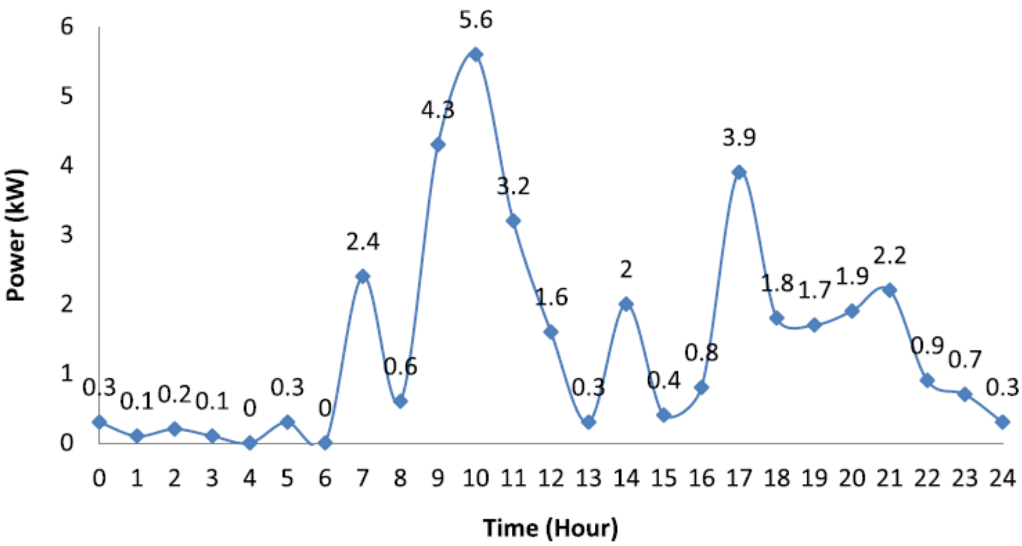

Figure 2.14: Rural Household Load Profile (Kusakana, 2014)

The Southern African Community Development (SADC) region intends on increasing its agricultural productivity by increasing its irrigated area (Mabhaudhi *et al.*, 2019). By increasing agricultural production, the idea is that surplus agricultural yields of households of defined advantages would supply regions of less potential. This would also serve as a mechanism to ensure food security and improve livelihoods (Mabhaudhi *et al.*, 2019).

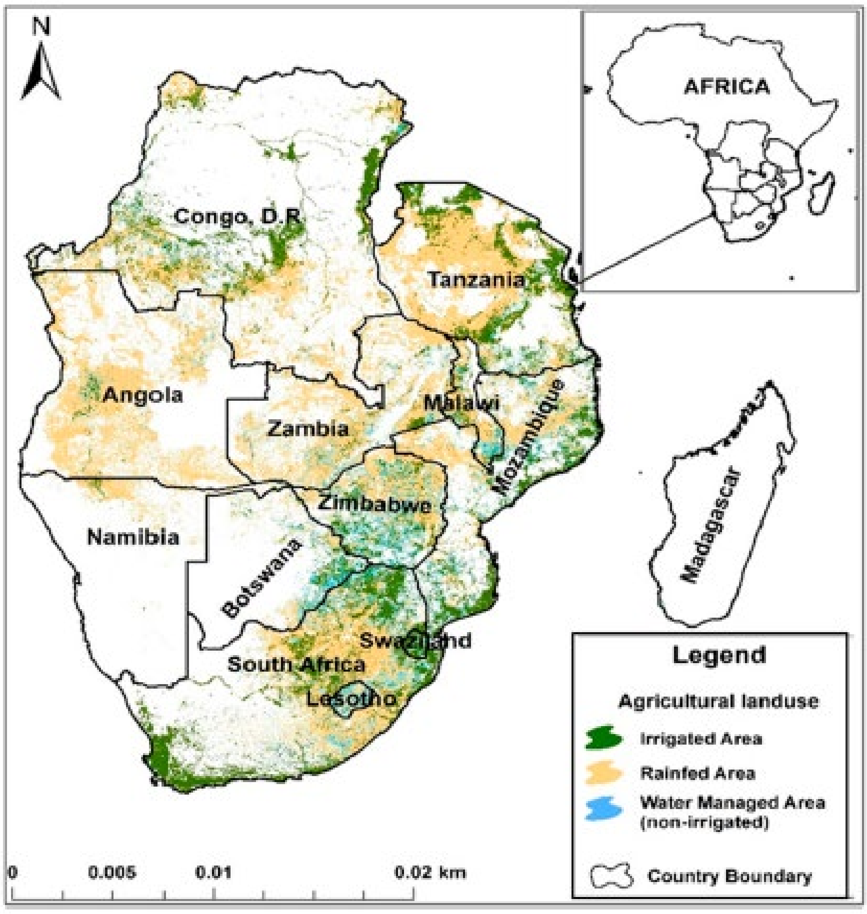

Figure 2.15: Southern African Development Community (SADC) locational map of countries showing agricultural land use in Africa. Source: Adapted from Mabhaudhi *et al.* (2019).

According to (Mabhaudhi *et al.*, 2019), as seen in Figure 2.14, although there is a high potential for irrigation in Southern Africa, the majority of agriculture remains rainfed. Mpandeli *et al.* (2018) state that the SADC region consists of a combined 986 246 000 ha land area, with only 6.11% being cultivated. In Southern Africa, small scale farmers who rely on rainfed agriculture contribute about 90% of the agricultural produce (Livingston *et al.* (2011). Nevertheless, the challenges of food insecurity in the region are very great, mainly affecting the rural population (Wlokas, 2008).

Figure 2.15 shows an example of decreased agricultural productivity in the SADC region from 15% to 50% by 2080 due to climate change (Ahlenius and UNEP/GRID-Arendal, 2009). This is concerning because the region already faces deficits of the major staple crops, except for South Africa and Zambia. Mpandeli *et al.* (2018) further state that any further decreases in agricultural productivity would worsen regional food and nutrition insecurity.

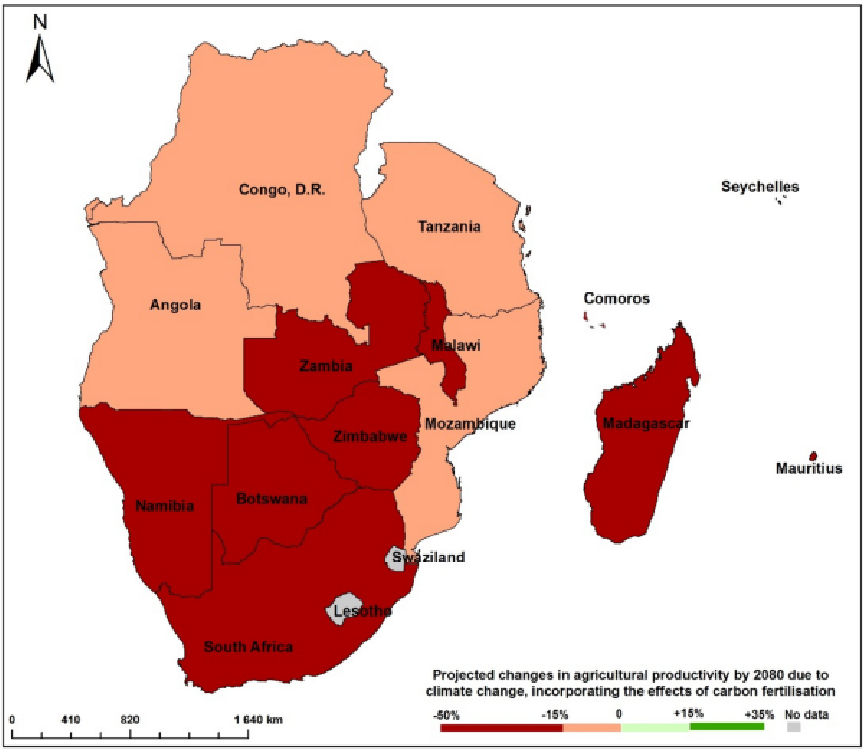

Figure 2.16: Changes projected in agricultural productivity in 2080 due to climate change. Source: Adapted from Mabhaudhi *et al.* (2019).

Wlokas (2008) states that more extended dry periods and unsure rainfall put more stress on farming production. One of the benefits of run-of-river hydropower systems would then be to assist in pumping water out from deep underground aquifers when required, with the available energy. There are potential free groundwater resources which can be used during droughts and winter seasons to supplement water deficits (MacDonald *et al.*, 2012;Nhamo *et al.*, 2019). According to climate change predictions, South Africa for instance, will become warmer and drier (Wlokas, 2008). Some sectors are expected to be significantly affected, particularly water resources, biodiversity, agriculture, and human health. These potential impacts without a doubt have detrimental effects on South Africa's priority issues such as poverty alleviation, housing, employment creation, access to and provision of services, food security and provision of potable water (Wlokas, 2008).

The focus of this study for site selection will be South Africa KwaZulu-Natal. Figure 2.14 shows a great potential of the implementation of these systems due to the combined rainfed area, the water managed area, and the targets of the SADC.

Figure 2.16 shows the African continent groundwater storage expressed as water depth in millimetres.

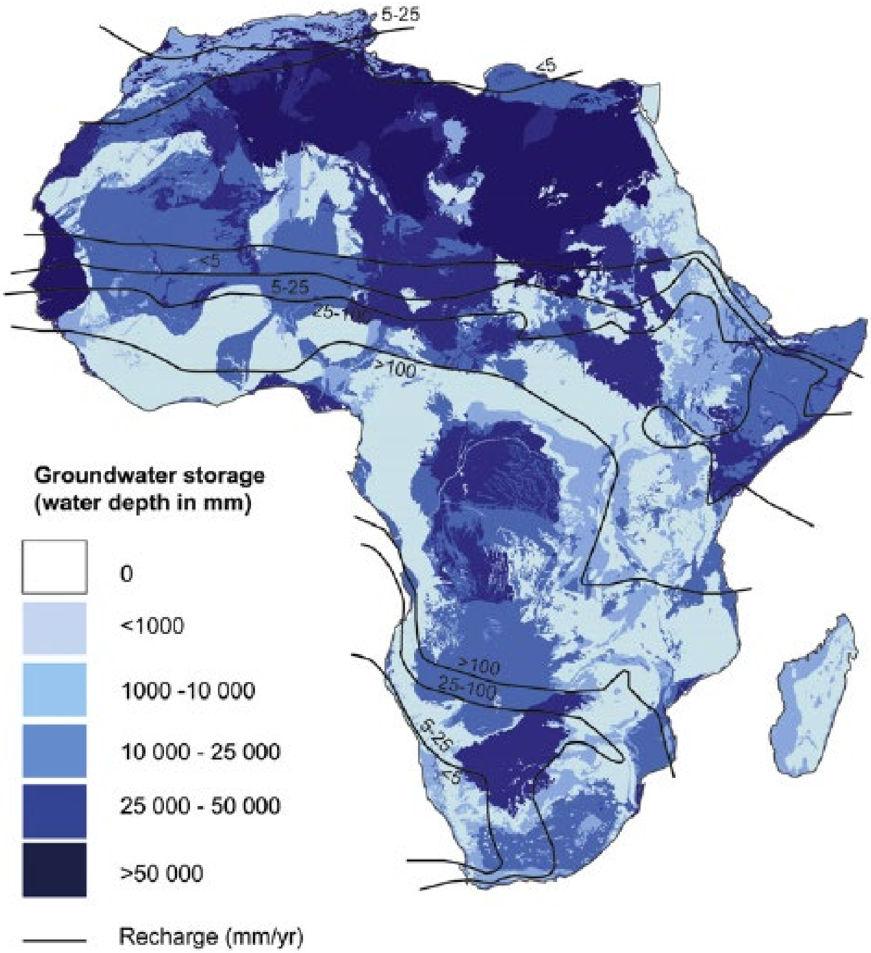

Figure 2.17: African continent groundwater storage expressed as water depth in millimetres with modern annual recharge for comparison (MacDonald *et al.*, 2012).

According to MacDonald *et al.* (2012), aquifers can be made productive through borehole drilling in order to access groundwater. The rate of groundwater abstraction is generally limited by the borehole yield.

Figure 2.17 shows the productivity of aquifers for Africa. The figure shows the likely interquartile range for drilled boreholes and their sites using appropriate techniques and expertise.

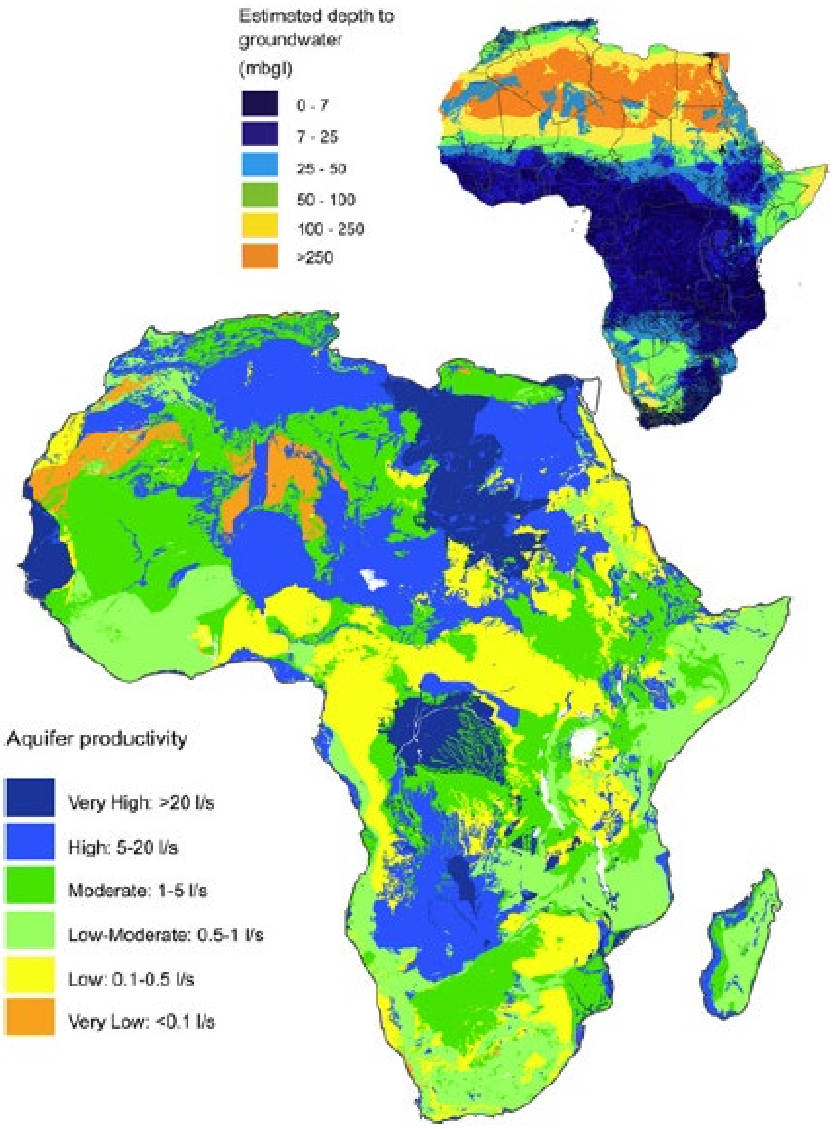

Figure 2.18: The productivity of aquifers for Africa showing the likely interquartile range for drilled boreholes and their sites using appropriate techniques and expertise. The approximate depth to groundwater is shown (Bonsor and MacDonald, 2011).

MacDonald *et al.* (2012) state that water levels at depths below 50m are not easily accessible using hand pumps. The author also states that intensive irrigated agriculture has higher borehole yields. This study considers the aquifer water yield as the agricultural demand. Therefore, the maximum water yield considered for groundwater power pumping requirements is the highest yield, which is $20l.s^{-1}$. The pumping head considered for this study is 100m. Appendix C shows that KSB pump manufacturers recommend the Etanorm 065-050-315/2P with a rated motor of 31.1kW for pumping a flow of $20l.s^{-1}$ and for a 100m head.

3. RESEARCH METHODOLOGY

3.1 Introduction

This chapter discusses the research methodology for this study. The research approach, data collection, site selection, streamflow data, flow duration and power duration curves, and the pre-feasibility model are discussed in this chapter.

Streamflow data is crucial in assessing the potential power of a run-of-river hydropower plant. The magnitude of the river discharge combined with the hydraulic head determines the potential power available for electricity generation at the site location. The streamflow data were collected using the Department of Water Affairs (DWA) online streamflow database for each gauge station. The streamflow data was then converted into flow duration curves (FDCs) for each gauge station to determine a design flow for the site. The magnitude of the design flow combined with the hydraulic head of each site was used to select the suitable turbine for each site, respectively. The selected turbine determines the efficiency of the power plant, which then determines the potential power of the plant. Power duration curves (PDCs) were then determined for each site, and a pre-feasibility model was then developed. The pre-feasibility model consisted of Social, Environmental, and Economic model components which needed to all prove ACCEPTABLE for the project to be concluded as feasible, as mentioned in section 1.3. This was the classification based on the '3 Pillar Concept' as discussed in section 2.5.2.
The selected sites are also discussed in this chapter, and the feasibility of run-of-river hydropower for rural and agricultural productivity in the South Africa model is discussed in this chapter.

3.2 Research Approach

The potential power of the available energy was quantified using streamflow data that was available from DWA. Flow duration curves were developed from streamflow data, which were then used to develop power duration curves for the hydropower plants. The aim of this study was to assess the feasibility of run-of-river hydropower systems in South Africa through a social, environmental, and economic cost modelling assessment for rural and agricultural productivity. These required a series of considerations, and the following steps were taken:

1. Identify primary South African rivers in proximity of rural communities or agricultural activity in KwaZulu-Natal.
2. Evaluate the streamflow data from the rivers and determine suitable potential site locations using head differences.
3. Conduct a socio-economic and environmental investigation analysis for each potential site for the community using the defined run-of-river indicators provided in section 2.2 Table 2.2.
4. Determine the groundwater pumping power requirements for irrigation yields to promote rural and agricultural productivity in South Africa.
5. Develop the flow duration curves (FDCs) and power duration curves (PDCs) for each site.
6. Compare the potential power outputs of each site using the PDCs with the groundwater pumping power requirements for irrigation as discussed in section 2.10 to determine the rural and agricultural feasibility of each system.
7. Use the cost estimation equations to cost each site. The equation of Alvarado-Ancieta (2009), as discussed in section 2.9.1.1 (Equation (2.7)), as selected to calculate the electrical and mechanical costs of the system.
8. Conduct a Levelised Cost of Electricity (LCOE) from hydropower analysis for each site.
9. Conclude on the final recommendation of each site based on the social, environmental and economic pre-feasibility model outcome analysis as discussed in section 1.3.

3.3 Data Collection

The primary rivers in KwaZulu-Natal were studied for the potential installation of the hydropower systems, which is the study for this work as mentioned in section 2.10. The main parameters that defined the geographical location of the systems were river flow, head available at the shortest distance, rural community within proximity or some agricultural activity to benefit from the system. The household densities were evaluated using Google Earth. This was used as a social consideration benefit and the number of people that would be affected by each system. The environmental considerations were made as mentioned in section 2.6 and Table 2.2. The river flow data were obtained from the DWA using their online streamflow database, and the head was determined using the altitude difference between points using Google Earth. The distance between two points was also measured using the Google Earth measuring feature.

As discussed in section 2.6 Table 2.2, the social and environmental indicators were used to develop the Social and Environmental models for sustainability, which will be discussed later. The Levelised Cost of Electricity (LCOE) from hydropower was used to develop the Economic model for sustainability, with the indicators being discussed in section 2.6.1. Impulse turbines were selected for this study, as mentioned in section 2.8.1.

3.4 Assumptions, Limitations and Uncertainty

For the study, the social and environmental model used to evaluate the communities in the selected catchment relied largely on statistics and data gathered from the reviewed literature. The models assume the best representation of the studied areas. However, limitations and uncertainties could arise as assumed estimates may not fully represent all walks of life in the communities.

3.5 Site Selection

As mentioned in section 2.10, the Southern African Community Development (SADC) intends to increase its irrigated area to increase the agricultural productivity of the land. The study focused on areas where local communities were identified to reside close to South African primary rivers in order to benefit from the systems. Other considerations included the benefits of agricultural or isolated areas and the hydro geographical areas.

The study was restricted to KwaZulu-Natal. The projected changes in agricultural productivity by 2080 which are due to climate change are shown in Figure 2.15. It can be seen that the whole of South Africa is negatively affected due to the agricultural decline. Figure 2.14 in section 2.10 shows the agricultural land use in Africa. It can be seen that KwaZulu-Natal has more water management than irrigated areas, which would allow for the potential for run-of-river hydropower systems for rural and agricultural productivity.

The sites selected for the study are U2H014, located downstream of the Albert Falls dam, U3H005 which is located downstream of the Hazelmere dam, U2H052, located downstream of the Inanda dam, and V1H002, located downstream of Woodstock dam. Figure 3.1 and Figure 3.2 are two site configurations of the same site. Figure 3.1 shows site 1 configuration 1 of U2H014 which is downstream of Albert Falls dams.

Figure 3.1: Site 1 configuration 1 downstream of Albert Falls dam (uMgeni river).

Figure 3.2 shows site 1 configuration 2 of U2H014 downstream of Albert Falls dam.

Figure 3.2: Site 1 configuration 2 downstream of Albert Falls dam (uMgeni river).

Table 3.1 shows the details of the selected sites of U2H014 and also shows the chosen configuration for site 1.

Table 3.1: Chosen configuration of Site 1 for this study.

Streamflow Gauge	Site Positioning		Latitude (dd:mm:ss)	Longitude (dd:mm:ss)	Elevation (m)
U2H014	Configuration 1	Intake	29º26'16" S	30º26'20" E	624
	L = 500 m	Powerhouse	29º26'28" S	30º26'33" E	621
	Configuration 2	Intake	29º27'53" S	30º27'42" E	607
	L = 360 m	Powerhouse	29º28'04" S	30º27'39" E	601

The chosen configuration for site 1 was configuration 2. This is because of the higher energy potential available at a head of 6m, at a distance of 360m which is more socio-economical and environmentally friendly than 500m.

Figure 3.3 shows site 2 configuration 1 and 2 of U3H005 which is downstream of the Hazelmere dam.

Figure 3.3: Site 2 configuration 1 and 2 downstream of Hazelmere dam (Mdloti river).

Table 3.2 shows the details of the selected sites of U3H005 and also shows the chosen configuration for site 2.

Table 3.2: Chosen configuration of Site 2 for this study.

Streamflow Gauge	**Site Positioning**		**Latitude (dd:mm:ss)**	**Longitude (dd:mm:ss)**	**Elevation (m)**
U3H005	Configuration 1	Intake	29º35'49" S	31º02'43" E	58
	L = 610 m	Powerhouse	29º35'49" S	31º03'06" E	54
	Configuration 2	Intake	29º35'57" S	31º03'09" E	54
	L = 375 m	Powerhouse	29º36'06" S	31º03'20" E	46

The chosen configuration for site 2 was configuration 2. This is because of the higher energy potential available at a head of 8m and at a distance of 375m which is more socio-economical and environmentally friendly than 610m.

Figure 3.4 shows site 3 configuration 1 and 2 of U2H052 which is downstream of the Inanda dam.

Figure 3.4: Site 3 configuration 1 and 2 downstream of Inanda dam (uMgeni river)

Table 3.3 shows the details of the selected sites of U2H052 and also shows the chosen configuration for site 3.

Table 3.3: Chosen configuration of Site 3 for this study.

Streamflow Gauge	Site Positioning		Latitude (dd:mm:ss)	Longitude (dd:mm:ss)	Elevation (m)
U2H052	Configuration 1	Intake	29º42'43" S	30º51'58" E	116
	L = 600 m	Powerhouse	29º42'59" S	30º52'12" E	102
	Configuration 2	Intake	29º42'23" S	30º52'45" E	99
	L = 955 m	Powerhouse	29º42'23" S	30º53'21" E	88

The chosen configuration for site 3 was configuration 1. This is because of the higher energy potential available at a head of 14m and at a distance of 600m which is more socio-economical and environmentally friendly than 955m.

Figure 3.5 shows the configuration of site 4. Various configurations were considered, and this configuration was selected because of the head potential of 5m that was available in the shortest distance of 210m, as opposed to other alternatives.

Figure 3.5: Site 4 configuration downstream of Woodstock dam (Tugela river)

Table 3.4 shows the details of the selected sites of V1H002 and also shows the chosen configuration for site 3.

Table 3.4: Chosen configuration of Site 4 for this study.

Streamflow Gauge	**Site Positioning**		**Latitude (dd:mm:ss)**	**Longitude (dd:mm:ss)**	**Elevation (m)**
V1H002	Configuration	Intake	28º43'43" S	29º23'11" E	109
	L = 210 m	Powerhouse	29º43'29" S	29º23'18" E	104

Alternative configurations were considered for site 4, and the chosen configuration was based on the head energy potential of 5m available at a distance of 210m. The chosen configuration proved to be the most environmental and socio-economically friendly option than the other considerations.

3.6 Streamflow Data

The DWA online database was used to obtain the streamflow data for the different selected gauging stations mentioned in section 3.4. Figure 3.6 to Figure 3.9 show the river hydrographs of the mean monthly discharge for the different gauging stations, which were the sites that considered for the scope of this study. Appendix B shows an example of the streamflow data that was obtained from the DWA online database.

Figure 3.6 shows the U2H014 mean daily discharge river hydrograph from the period of 1964 to 1999 of reliable data.

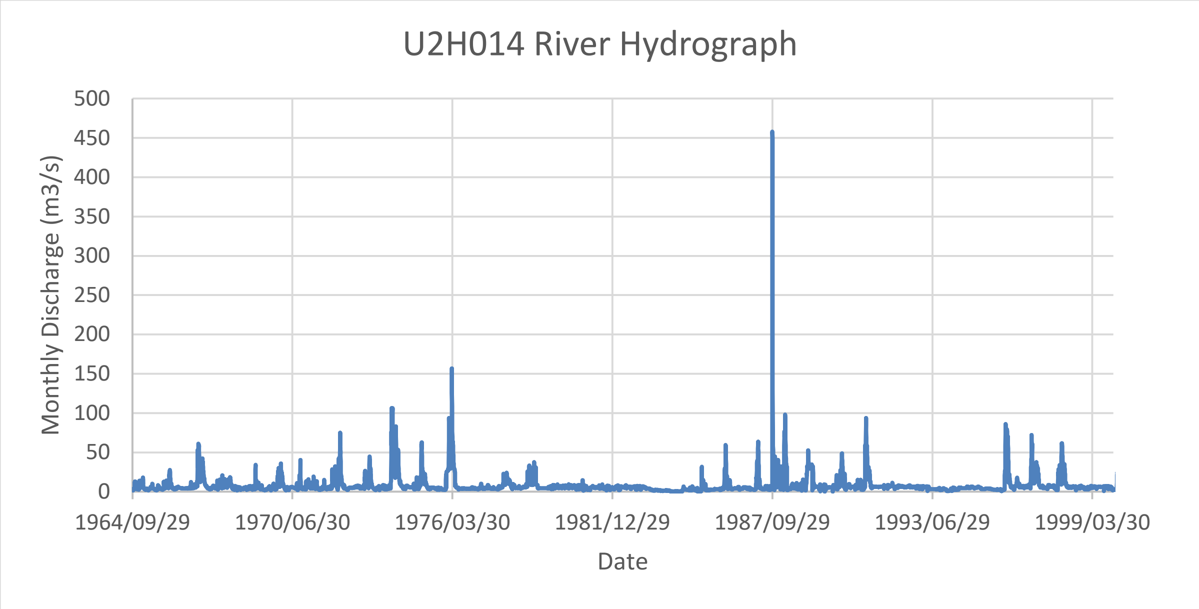

Figure 3.6: U2H014 mean daily river hydrograph from 1964 to 1999.

Figure 3.7 shows the U2H052 mean monthly discharge river hydrograph from the period of 1993 to 2018 of reliable data.

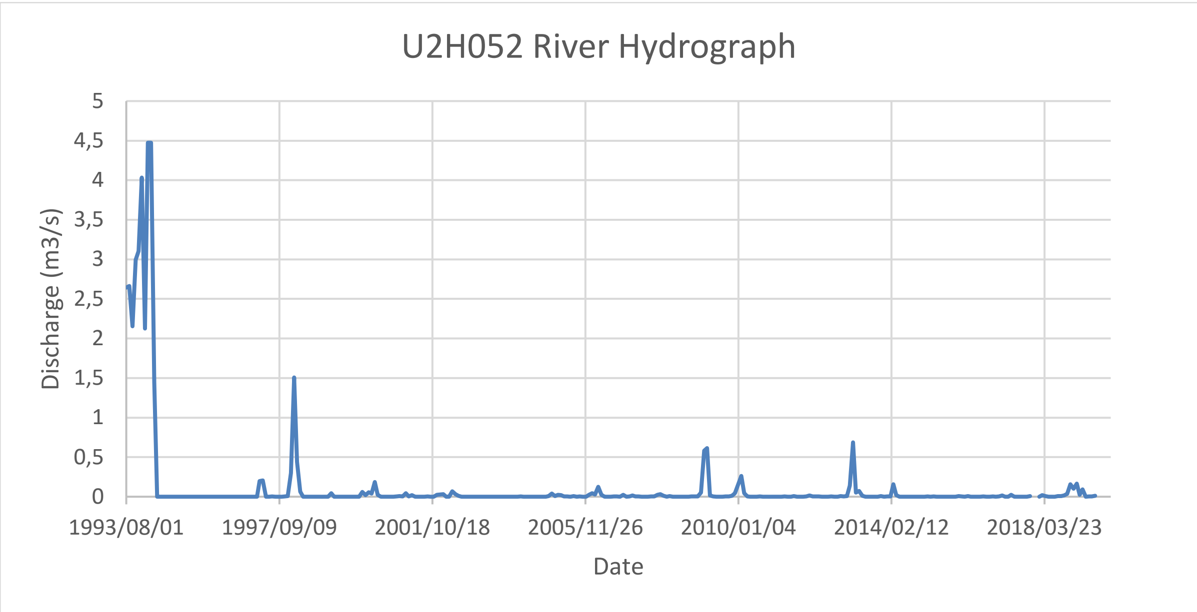

Figure 3.7: U2H052 mean monthly river hydrograph from 1993 to 2018.

Figure 3.8 shows the U3H005 mean monthly discharge river hydrograph from the period of 1975 to 2016. However, there are periods of missing data.

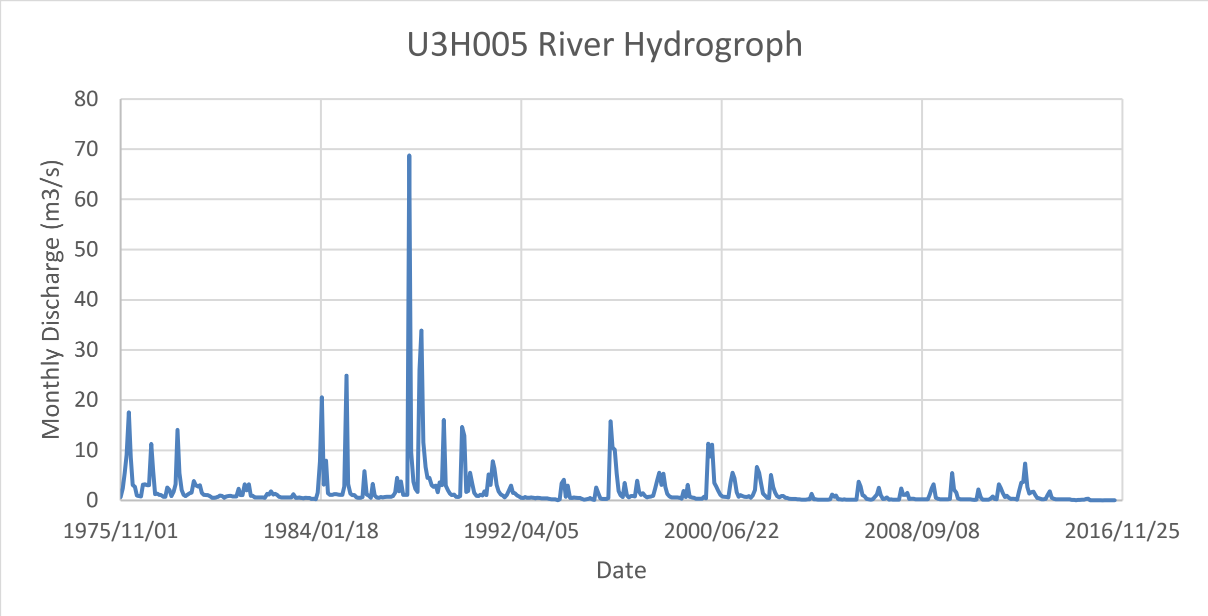

Figure 3.8: U3H005 mean daily river hydrograph from 1975 to 2016.

Figure 3.9 shows the V1H002 mean monthly discharge river hydrograph from the period of 1931 to 1968. However, there are periods of missing data.

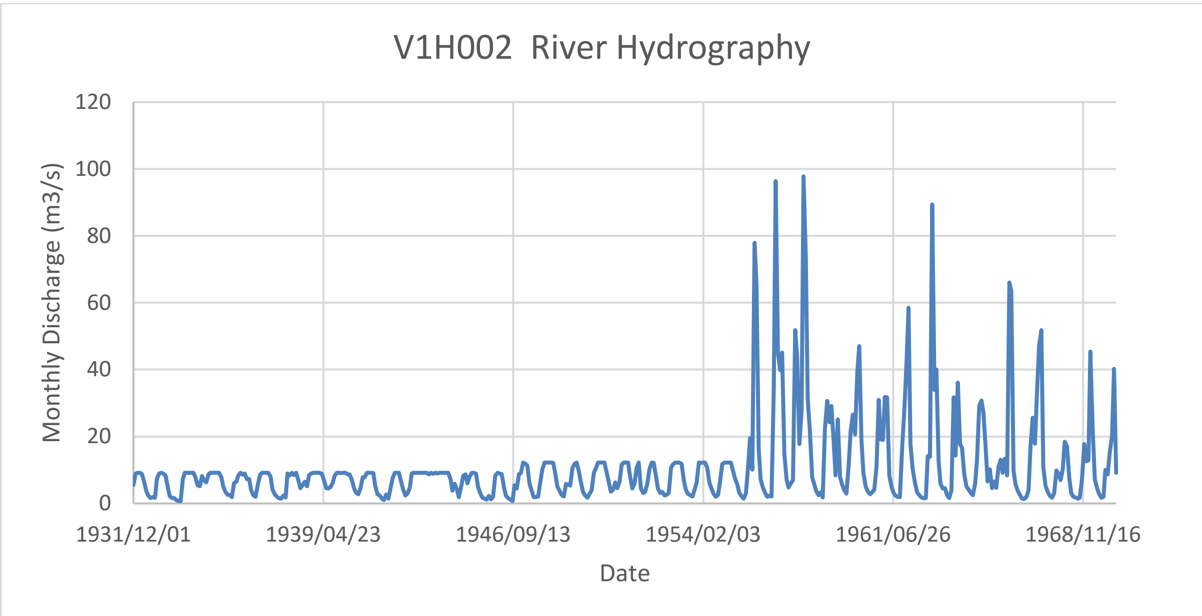

Figure 3.9: V1H002 mean monthly river hydrograph from 1931 to 1968.

3.7 Flow Duration Curves

The Flow Duration Curves (FDCs) for each site were constructed following the procedures described from section 2.7.1 to section 2.7.2. Figure 3.10 shows a flow chart for the flow duration curve.

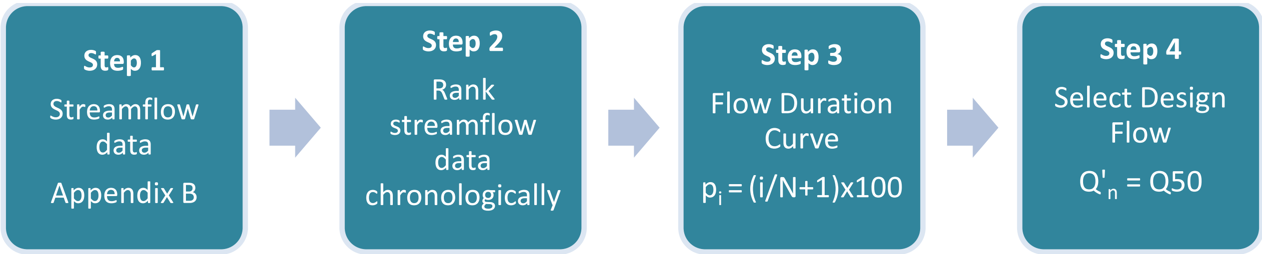

Figure 3.10: Flow duration curves flow chart.

3.8 Power Duration Curves

The Power Duration Curves (PDCs) for each site were constructed following the procedures described from section 2.7.1 to section 2.7.2. Figure 3.11 shows a flow chart for the power duration curve.

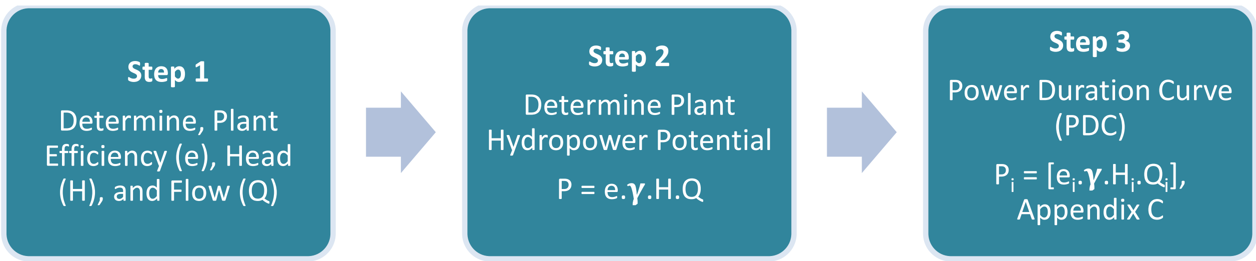

Figure 3.11: Power duration curves flow chart.

3.9 Pre-Feasibility Model

The recommended assessment of the pre-feasibility model will be based on the following considerations:

- Environmental

- Social
- Economic

If all outcomes yield a positive output, that is, if the outcome is ACCEPTABLE for all considerations, then the pre-feasibility assessment for the project shall be concluded as FEASIBLE. If the outcome is NOT ACCEPTABLE for any consideration, the pre-feasibility assessment for the project shall be concluded as NON-FEASIBLE.

3.9.1 Environmental model

The environmental model follows the procedure of Van Vuuren *et al.* (2011) for the evaluation, which is the vulnerability line diagram, but instead uses the run-of-river hydropower indicators presented in Table 2.2 for the analysis. The vulnerability line diagram is a rating scale between extreme and low vulnerability. The criterion can be anything and the assessor rates the criteria either based on professional experience, expert opinion or case studies. The most rating between low and extreme vulnerability indicates the vulnerability of the model. Table 3.5 shows an example of an environmental vulnerability line drawing diagram. The model will be used as a manual input survey for designers or researchers who cannot go to the site with questionnaires to obtain an expert opinion.

Table 3.5: Example of a line drawing selection of environmental vulnerability for Site (Van Vuuren *et al.*, 2011).

Table 14 Line drawing selection of environmental vulnerability for the Bethlehem case			
Criterion	Extremely vulnerable (5)		Low vulnerability (1)
Development	Completely undeveloped	----X-------------	Developed urban area
Rehabilitation	Impossible	------------X----	Definitely possible
Endangered species	Many	----------------X	None
Rareness of habitat	Very rare	------------X----	Common
Vegetation and wildlife	Extremely abundant	---------X--------	Very little

3.9.2 Social model

Positive social impacts will be considered separately from the negative impacts, unlike the environmental impacts. This is because they are rated through a different checklist. A checklist was developed by Van Vuuren *et al.* (2011), a retrofitted hydropower project which aimed at assessing whether projects would promote growth and sustainable development in the region being implemented. The checklist can, however, be adopted for different suitable hydropower schemes. The checklist is as follows:

- Will the roads in the community that can serve the surrounding area be built or upgraded?
- Will other types of infrastructure or services need to be built or upgraded that will benefit residents?
- Will the project result in increased investments in the region?
- Will the project result in employment creation during and after construction?
- Will the project result in fewer emissions?
- Will there be a potential for the locals to benefit from the power produced, or will the construction of new transmission lines benefit the community? (Van Vuuren *et al.*, 2011)

An example of a line drawing selection model for social vulnerability is shown in Table 3.6. The model is the same as the environmental line vulnerability diagram, as explained in section 3.8.1. This model will use the social indicators presented in Table 2.2. The model will be used as a manual input survey for designers or researchers who cannot go to the site with questionnaires to obtain an expert opinion.

Table 3.6: Example of a line drawing selection of social vulnerability for Site (Van Vuuren *et al.*, 2011).

Table 15 Line drawing selection of social vulnerability for the Bethlehem case			
Criterion	Extremely vulnerable (5)		Low vulnerability (1)
Education	Extremely low/none	----X------------	Very good
Historical importance	Very significant	-------------X----	None
Cultural bond with the area	Extremely strong	---------X --------	Insignificant
Traditional practices	Prevalent	---------X--------	None - modernised
Communication with external sources	Non-existent	--------- X--------	Free and good

3.9.3 Economic model

The economic model has been broken down into a series of considerations. These are initial investment costs, electro-mechanical costs, civil works costs, operational and maintenance costs (O&M), and the Levelised Cost of Electricity (LCOE) from hydropower, as explained in the sections above.

3.9.3.1 Initial capital costs

Figure 2.9 gives a total installed hydropower cost ranges by country per hydropower plant scale (Irena, 2012). Given this bandwidth, Figure 2.10 gives the installed capital cost for small hydropower in developing countries by capacity. This will then assist in acting as a guide in providing more accurate initial capital costs.

3.9.3.2 Electro-mechanical cost

Several authors have been mentioned in this study for the determination of electro-mechanical costs. However, what has been mentioned is that according to Irena (2012), the results from the Ogayar and Vidal (2009) cost estimation analysis methodology are available for a range of developed countries, but most of these studies are 10 years old or more. The recent analysis of small hydropower plants in Spain, which analysed the costs separately for Pelton, Francis, Kaplan, and semi-Kaplan turbines yielded the equations a good fit in Spain (Ogayar and Vidal, 2009).

This study also mentions that the formula of Alvarado-Ancieta (2009), as described above, has an error range of 5% to 10%, which is significantly better than Ogayar and Vidal (2009). The formula of Alvarado-Ancieta (2009) has also been checked against existing cost data for electro-mechanical equipment from global manufacturers by Irena (2012) which a more recent source, as mentioned in section 2.9.1.1. This is why the method of Alvarado-Ancieta (2009) of electro-mechanical costs calculation has been chosen for this study.

Despite Van Vuuren *et al.* (2011) being a retrofitting model, the author based the model on an Indian model (Singal and Saini, 2008). (Irena, 2012) mentions that hydropower is a highly site-specific technology where each project is tailor-made for a particular location within a given river basin to meet specific energy and water management needs. The variability in the cost breakdown of small hydropower plants per power generated can also be provided in Figure 2.12, which shows a different view of those shown in Figure 2.11 used by Van Vuuren *et al.* (2011).

3.9.3.3 Civil works cost contribution

Civil works costs were determined by deducting the electro-mechanical costs obtained from the Alvarado-Ancieta (2009) equation, Equation (2.8), costs being deducted from the installed capital costs. This process is reflected in Step 1 to Step 3 in the economic flow chart, figure 3.12.

3.9.3.4 Operational and maintenance costs (O&M)

The annual operating and maintenance costs will be determined as a percentage of the installed capital cost mentioned in section 2.8.2.2. This will be set at 3% for small hydropower projects (Irena, 2012).

3.9.3.5 Levelised cost of electricity (LCOE) from hydropower

(Tran and Smith, 2018) and Irena and (Amanda *et al.*, 2018)

- Installed capital cost = Figure 2.10
- fuel cost = 0,
- electricity generation = calculated through FDC,
- O&M = 3% installed of capital cost
- Economic life (t) = 30 years
- The cost of capital (discount rate) = 10%
- Capacity factor = 0.95 (run-of-river)
- Evaluate LCOE = $\frac{\Sigma_{t=1}^{n} \frac{I_t + M_t + F_t}{(I+r)^t}}{\Sigma_{t=1}^{n} \frac{E_t}{(I+r)^t}}$ (Appendix B)
- Annual Income (R/yr) = R/kWh x kW x hr/day x day/year

The systems are to operate 18 hours/day x 260 days/year. The income was calculated based on the assumed tariff of 51.7c/kWh. The exchange rates were based on the value as of 17 June 2009, which was R8.07/USD. The assumed tariff and the exchange rate were adopted from Van Vuuren to maintain consistency in the cost calculations, including determining the income from each system.

3.9.4 Model outcome

- Environmental Model: ACCEPTABLE
- Social Model: ACCEPTABLE
- Economic Model: ACCEPTABLE

Feasibility models based on Environment and Social considerations in general whereby the system considers harm to the ecosystem and the community's livelihood through rural development will be considered separately. These models will be done using the vulnerability line diagram, similar to the one used by Van Vuuren but using the RoR indicators. Financial feasibility will be measured using the LCOE. The amortisation period for small hydropower projects, also considered as run-of-river hydropower projects, is 30 years. The LCOE is the price of electricity required for a project where costs would equal revenues, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yield a lower return on capital or even a loss (Irena, 2012).

Figure 3.12 shows the economic flow chart that describes each process that will be followed to execute the economic model successfully, as described in the sections above.

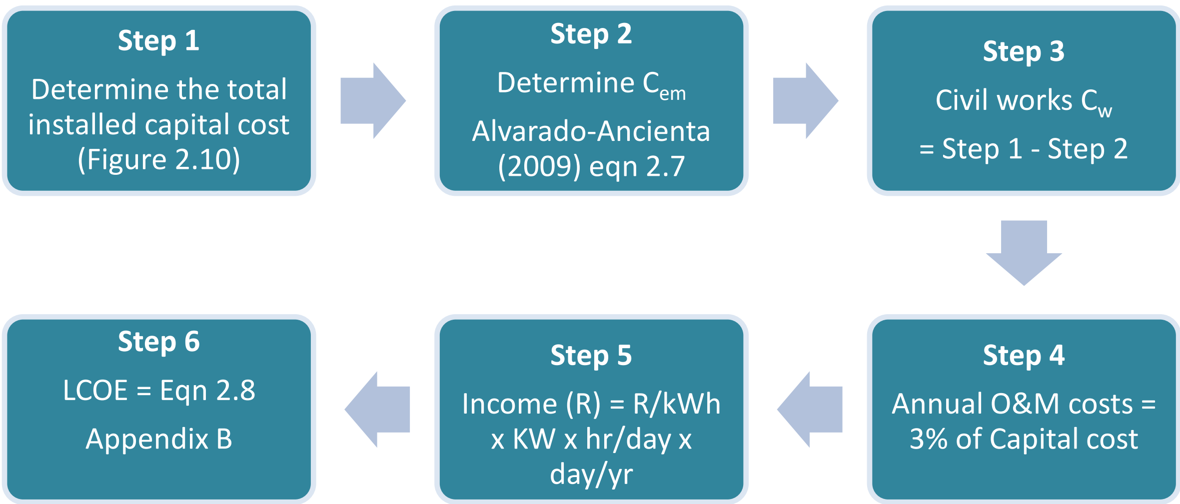

Figure 3.12: Economics flow chart.

The project is said to be feasible when each of the pillars classified under the sustainability of run-of-river hydropower projects through the '3 Pillar Concept' is satisfied. These are the Environmental, Social, and Economic tests for sustainability, and their indicators are measured both directly and indirectly, as discussed in section 2.5. With each positive model outcome for each pillar, the outcome is ACCEPTABLE. If all outcomes are ACCEPTABLE, then the project is FEASIBLE, else the project is NOT FEASIBLE.

4. RESULTS AND DISCUSSION

This chapter discusses the results obtained from the literature investigations and following the research methodology described in the previous chapters.

4.1 Introduction

The results of the potential power generation for each site selected are presented and discussed. Flow duration curves (FDCs) are constructed using the streamflow data to determine the potential power generation for each site, using the recommended design flow of 50% for primary energy, [Qd > Q50] as mentioned in section 2.7.2. Section 2.7.2 also mentions that Q20 and Q30 values are good starting flows for equipment sizing. The turbine selection was then carried out from the flow determination and the head being known from the site conditions. This then made the determination of the plant efficiency possible, thereby determining the potential power generation of each plant. The power duration curves (PDCs) were also developed for each site.

Each power plant breaks down into a series of costs such as investment costs, electrical and mechanical costs, civil works costs, operational and maintenance costs, depending on which type of scheme it is. The determination of these costs can be complex, especially because hydropower systems are very site specific, as mentioned in section 2.8.2.3. This means that the costing models developed for certain regions may not produce accurate results for other regions if they were not developed for those regions. The costing model, which was discussed in section 3.8.3, was used for the economic model. Finally, the social and environmental models both considered their sustainability indicators as indicated in section 2.6 using the vulnerability line drawing selection diagram to complete the pre-feasibility model.

4.2 Pre-feasibility Model Analysis

This section details the steps taken in the pre-feasibility assessment model of run-of-river (RoR) hydropower plants in South Africa.

4.2.1 Flow Duration Curves

Figure 4.1 shows the flow duration curve (FDC) for U2H014 for the years from 1964 to 1993.

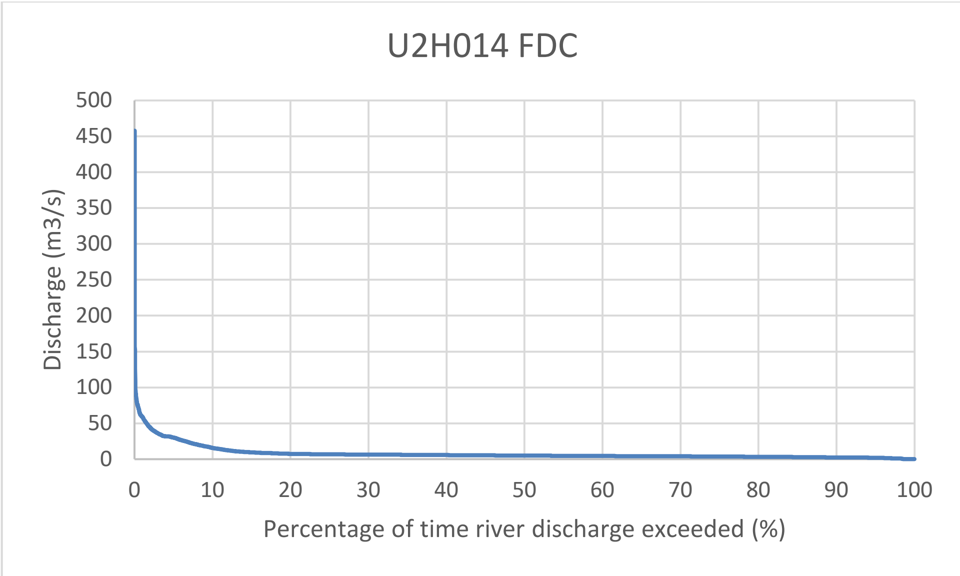

Figure 4.1: U2H014 site 1 configuration 2 FDC downstream Albert Falls dam.

Figure 4.2 shows the flow duration curve (FDC) for the site U3H005 for the years from 1975 to 2016.

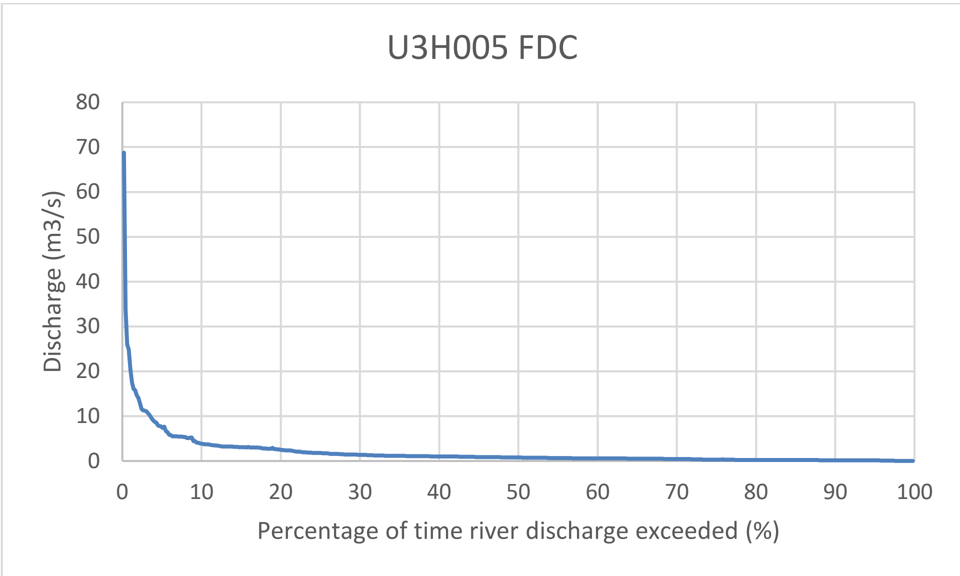

Figure 4.2: U3H005 site 2 configuration 2 FDC downstream Hazelmere dam.

Figure 4.3 shows the flow duration curve (FDC) for the site U2H052 for the years from 1993 to 2018.

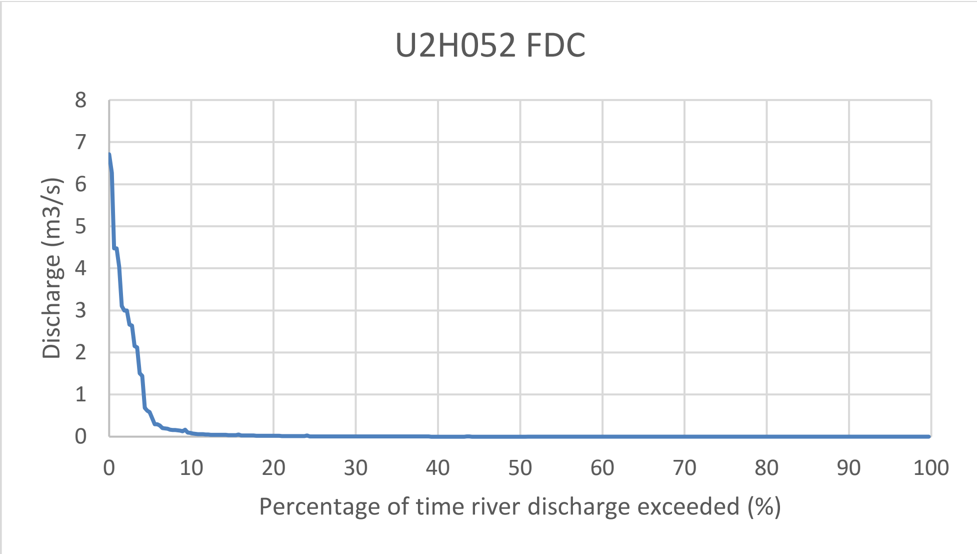

Figure 4.3: U2H052 site 3 configuration 1 FDC downstream Inanda dam.

The design flow for U2H052 Qd = Q50 was 0 $m3.s^{-1}$ as seen in Figure 4.3. U2H052 site 3 was therefore disregarded for this investigation. Site 3 shows that U2H052 suffers from drought and would therefore result in no power generation for the community during periods of drought.

Figure 4.4 shows the flow duration curve (FDC) for the site V1H002 for the years from 1931 to 1970.

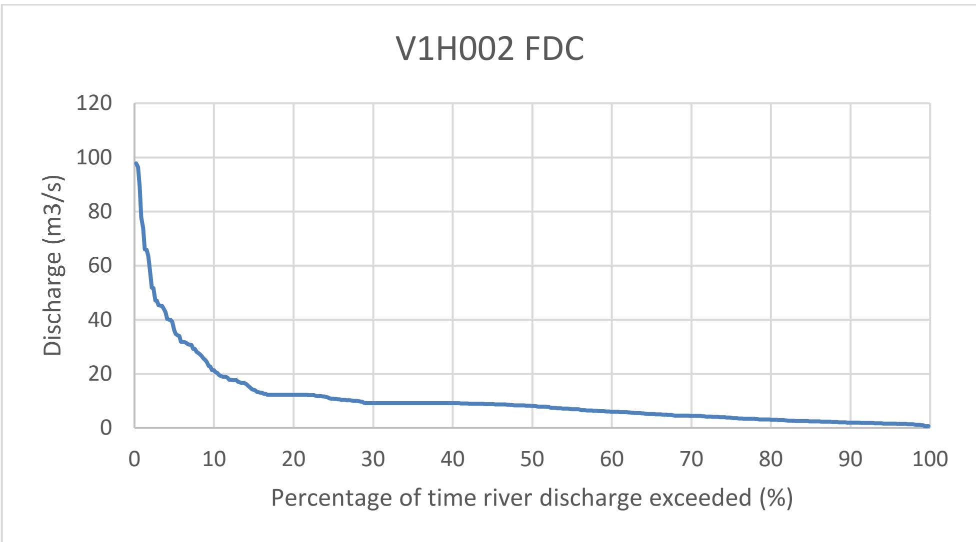

Figure 4.4: V1H002 site 4 FDC Thukela river.

4.2.2 Turbine Selection and Efficiency Curve

The design flow for U2H014 was 5m^3/s with the head being 6m. Figure 2.6 identifies this region as the crossflow turbine operating region. Figure 4.5 shows the efficiency vs discharge of the crossflow turbine at site U2H014 site 1.

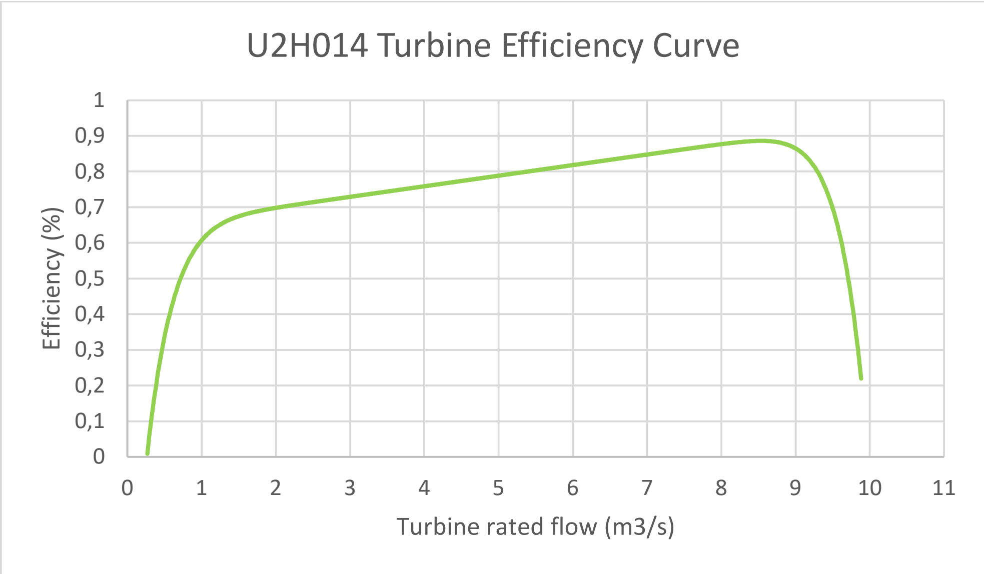

Figure 4.5: U2H014 site 1 configuration 2 turbine efficiency curve.

The design flow for U3H005 was 0.8m^3/s, with the head being 8m. Figure 2.6 identifies this region as the crossflow turbine operating region. Figure 4.6 shows the efficiency vs discharge of the crossflow turbine at site U3H005 site 2.

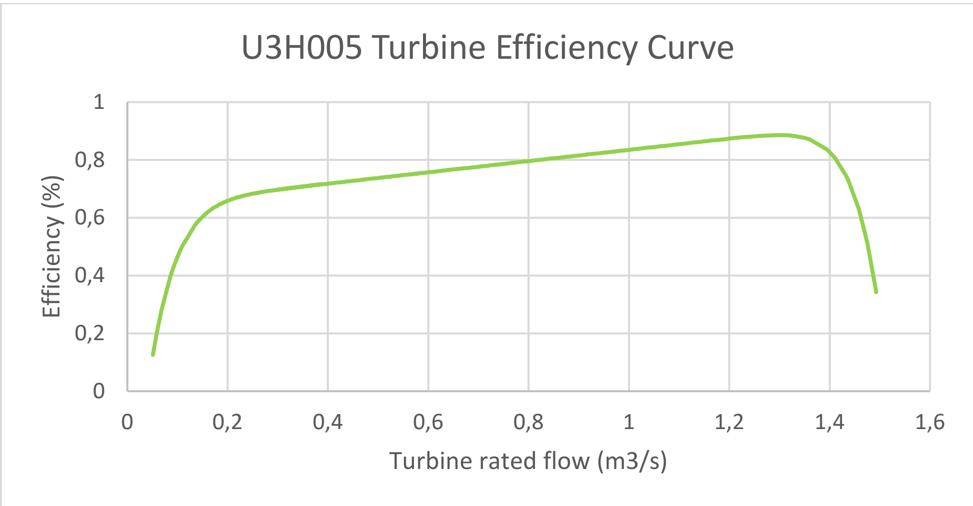

Figure 4.6: U3H005 site 2 configuration 2 turbine efficiency curve.

The design flow for V1H002 was $8m^3/s$, with the head being 5m. Figure 2.6 identifies this region as the crossflow turbine operating region. Figure 4.7 shows the efficiency vs discharge of the crossflow turbine at site V1H002.

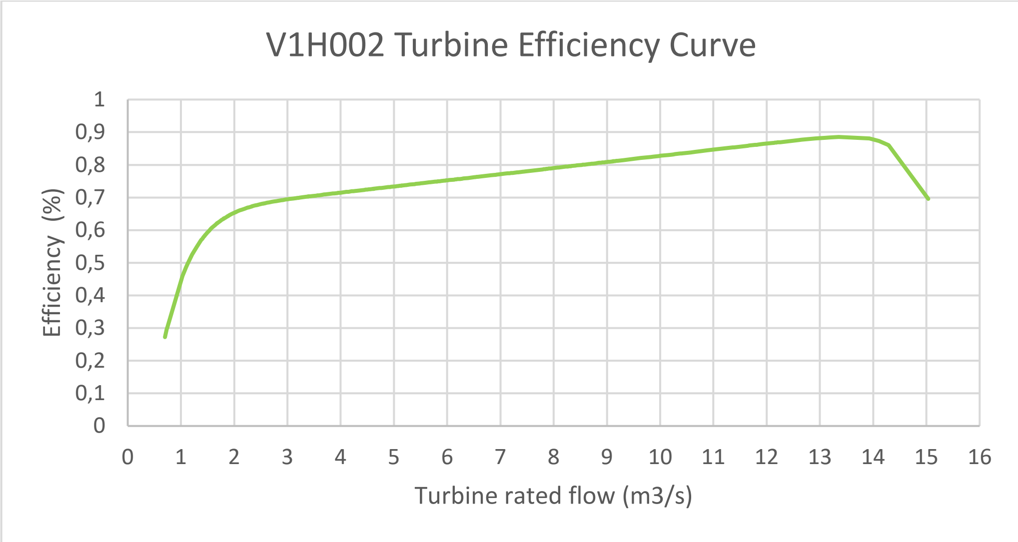

Figure 4.7: V1H002 site 4 turbine efficiency curve.

4.2.3 Power Duration Curves

Figure 4.8 shows the power duration curve (PDC) for the site U2H014, with the potential maximum power output being 238kW. This means that the system is a Mini hydropower system, as listed in Table 2.1 section 2.1.

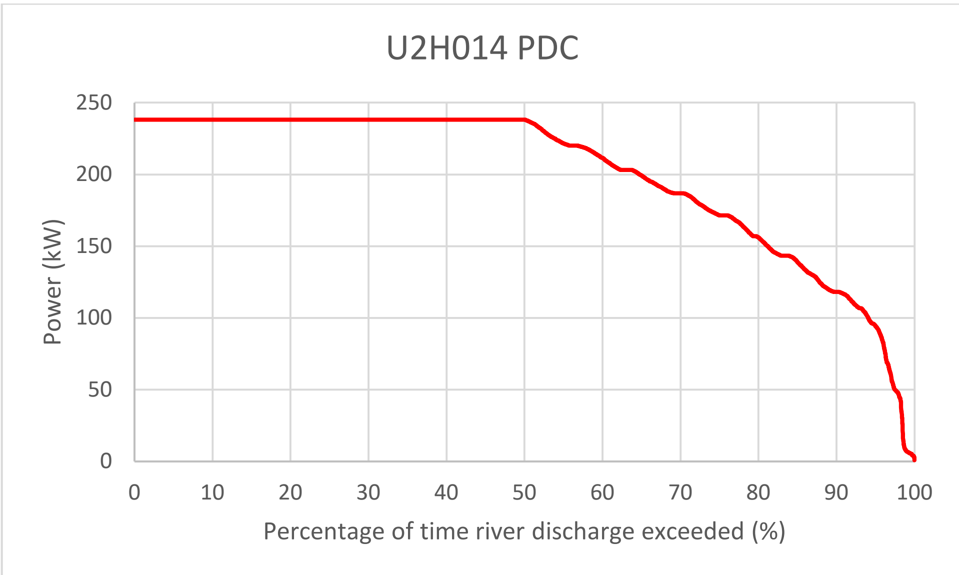

Figure 4.8: U2H014 site 1 configuration 2 PDC downstream Albert Falls.

Figure 4.9 shows the power duration curve (PDC) for the site U3H005 with the potential maximum power output being 48kW. Meaning that the system is a Micro hydropower system, as listed in Table 2.1 section 2.1.

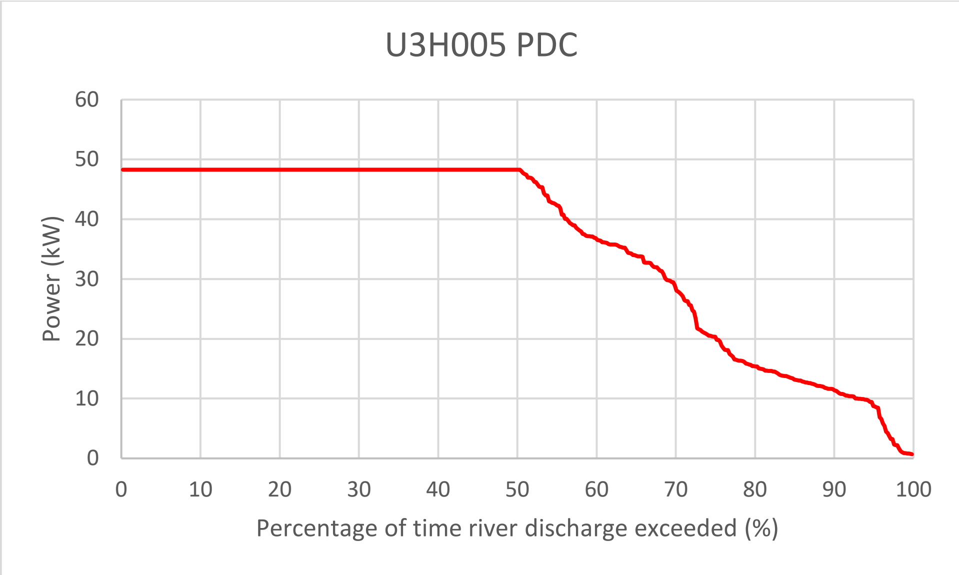

Figure 4.9: U3H005 site 2 configuration 2 PDC downstream Hazelmere dam.

Figure 4.10 shows the power duration curve (PDC) for site V1002, with the potential maximum power output being 314kW. This means that the system is a Mini hydropower system, as listed in Table 2.1 section 2.1.

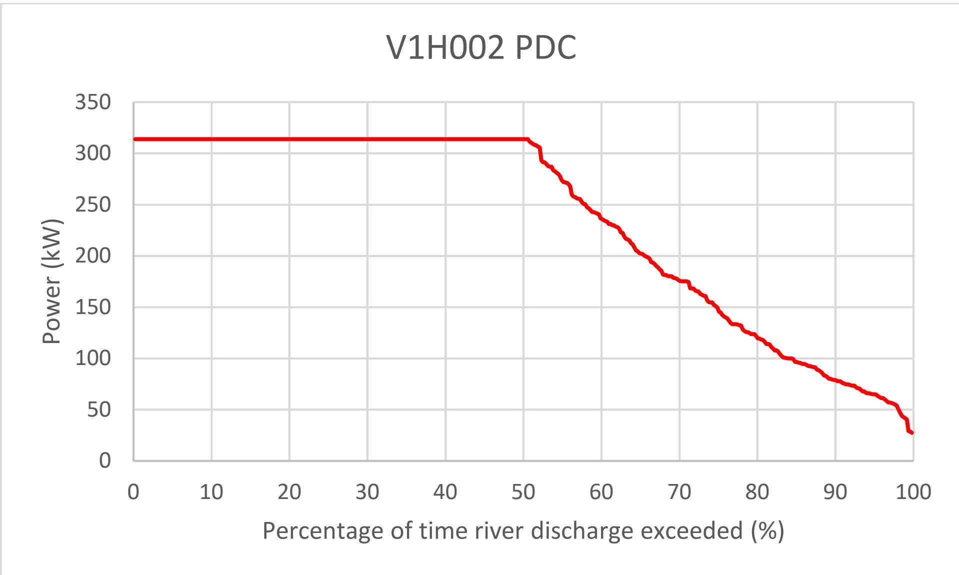

Figure 4.10: V1H002 site 4 PDC downstream Tugela river.

Appendix C shows the groundwater power pumping requirements required by a pump for rural and agricultural productivity, which are 31.1kW. This is below each of what these systems produce, implying that savings would be realised and potentially sold to the grid to reduce the load on the grid.

4.2.4 Number Of Rural Households Electrified

Figure 2.14 in section 10 shows the rural household load profile. Section 4.2.3 shows the power duration curves for sites U2H014, U3H005, and V1H002. The number of households was obtained by dividing the capacity of each site by the peak power consumption of each household which was obtained from Figure 2.14. Table 4.1 shows the number of households electrified on each site.

Table 4.1: Number of households electrified on each site

Site	Capacity (kW)	Peak Power Consumption per Household (kW)	Number of Households
U2H014	238	5.6	43
U3H005	48	5.6	9
V1H002	314	5.6	56

4.2.5 System Operation and Income

Table 4.2 shows the system energy generated and annual income.

Table 4.2: Annual Energy Generated and Annual Income.

Site	Capacity (kW)	Energy Generated (MWh/yr)	Annual Income (USD/yr)	Annual Income (R/yr)
U2H014	238	1114	71 309	575 460
U3H005	48	226	14 461	116 701
V1H002	314	1469	94 025	758 784

4.2.6 Environmental Model

The following results were obtained for U2H014 environmental model:

Table 4.3 shows the results obtained for the line drawing selection of the environmental vulnerability criterion of site U2H014. It can be seen that most of the outcomes resulted in a low vulnerability test, which resulted in an ACCEPTABLE pre-feasibility test for the environmental model.

Table 4.3: U2H014 line drawing selection for the environmental vulnerability criterion.

Criterion	Extremely vulnerable		Low vulnerability
Number of debris generated and disposal	Significant	---------------------X---	Non-significant
Land area required	Significant	--------------X----------	Non-significant
Impoundment of reservoir	Minimum	---------------------X---	None
Area development	Poor/Underdeveloped	--X----------------------	Developed urban area
Length of diverted stream	Long diverted stream	---------------------X---	Short, diverted stream
Silt quantity in stream	Minimum	------------------X------	None
Water quality/pollution	Minimum water pollution	-----------------------X-	None
Air quality/pollution	Minimum air pollution	-----------------------X-	None
Noise pollution	Minimum noise pollution	---------------------X---	None
Impacts of transmission lines	Significant	-----------------------X-	Minimum
Aquatic life impacts	Significant	---------------------X---	Minimum
Impacts on birds and terrestrial animals	Significant	---------------------X---	Minimum
Natural hazards like landslide, earthquakes, etc.	Minimum impacts	-----------------------X-	None

Impact on groundwater	Minimum impact	-----------------------X-	None
Impacts due to presence of other hydropower systems in the vicinity	Significant	-----------------------X	None
GHG Emissions	Emission of GHG	---------------------X--	None
National wildlife century within 10km of project site	Minimum impact	-------------------X----	None
Soil erosion	Minimum impact	---------------------X---	None
Mining operations	Mining operations	------------------------X	None
Climate change concerns	Minimum impact	-----------------------X-	None
Visual impacts	Minimum impacts	-----------------------X-	None

4.2.7 Social Model

The following results were obtained for U2H014 social model:

Table 4.4 shows the positive social indicator checklist for site U2H014. It can be seen that all outcomes yielded a positive result.

Table 4.4: U2H014 positive social indicators checklist.

Criterion	Outcome
Will the community roads be built or upgraded that can serve the surrounding area?	Yes
Will there be other types of infrastructure or services to be built or upgraded that will benefit residents?	Yes
Will there be a potential for the locals to benefit from the power produced, or will the construction of new transmission lines benefit the community?	Yes
Will the project result in fewer emissions?	Yes
Will the project result in increased investment in the region?	Yes
Will the project result in employment creation during and after the period of construction?	Yes

Table 4.5 shows the results obtained for the line drawing selection of the social vulnerability criteria for site U2H014. It can be seen that most of the outcomes resulted in a low vulnerability test, which resulted in a positive outcome for the line drawing selection for the social vulnerability criteria.

Table 4.5: U2H014 line drawing selection for the social vulnerability criterion.

Criterion	Extremely vulnerable		Low vulnerability
Number of people displaced	Minimum	---------------------X---	None
Air and water pollution	None	--------------------X---	Very good
Local and migrants conflicts	Minimum	------X-----------------	Very good
Damage to land and properties due to operation	None	--------------------X---	Very good
Effect on crop yields and agricultural productivity	Minimum/none	-----------------------X-	Very good
Changes in social values	None	--------------------X---	Very good
Delays due to project operation	Minimum	--------------------X---	Very good
Impacted cremation sites	None	-----------------------X-	Very good

Overall, the combined positive results for the social model for site U2H014 concludes on an ACCEPTABLE social model pre-feasibility outcome.

4.2.8 Economic Model

The exchange rate for the first trial analysis is based on the value as of 17 June 2009, which was R8.07/USD. The Eskom tariff was assumed to be 51.7c/kWh. These were adopted from the Van Vuuren *et al.* (2011) report for costing consistency and in order to keep the results of the equation of Alvarado-Ancieta (2009) consistent in this study when converting from USD to South African Rands.

4.2.8.1 Levelised Cost of Electricity (LCOE) from hydropower

Sample calculations have been demonstrated for year 1 of the LCOE from hydropower for U2H014. It should be noted that year 1 was an investment year, so the costs will display as negative, which can be seen in the cost column of Table 6.6 in Appendix B. It should be noted that the LCOE is also expected to be high due to the high investment cost at year 1. The LCOE and income results for all schemes can also be seen in Appendix B.

The model outcome for U2H014 is as follows:

- Total Installed capital cost (Figure 2.10) = 4000 USD/kW

Figure 2.9 does indeed verify that the installed capital cost of the system falls within the bandwidth of the African region for small hydropower plants.

- $C_{em} = 9.742\ P^{-0.7634}$ = 9.742 * 238.077$^{-0.7634}$ = R0.15 million/8.07

  = \$1857

- $Cw = (4000 * 8.07 * 238.076) - (0.15 * 1000\ 000)$ = R7 533 270/8.07

  = \$933 491

- Annual O&M Costs = 3% * 4000 = 120 USD/kW

- LCOE = $\dfrac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(I+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(I+r)^t}} = \dfrac{\frac{238*((4000)+(120))}{(I+0.1)^1}}{\frac{238*18*260}{(I+0.1)^1}} =$ 0.727558023 USD/kWh

According to Irena (2012), the LCOE evaluation for small hydropower projects in developing countries ranged between 0.02USD/kWh and 0.10USD/kWh, making small scale hydropower systems very cost competitive for electricity generation to the grid or schemes for off-grid rural electrification. Small hydropower systems generate from 1MW to 20MW, as shown in Table 2.1 section 2. Irena (2012) states that smaller hydropower projects have higher LCOE than 0.02USD/kWh to 0.10USD/kWh. The LCOE for pico hydropower systems can be 0.27USD/kWh or higher Irena (2012).

The projects demonstrated in this report were Micro and Mini hydropower systems as described in Table 2.1. Therefore, the LCOE results obtained, which are less than the pico-hydro system guidelines, and fall in the approximate range of small-scale hydropower as described above have been accepted. These results can be seen in appendix B on the LCOE column on the years where each system pays itself back.

Figure 4.11 shows is a graphical presentation of the LCOE at site U2H014 as the investment depreciates throughout its design life. Figure 4.12 shows the cumulative income and repayment period of the hydropower system that would be installed at site U2H014.

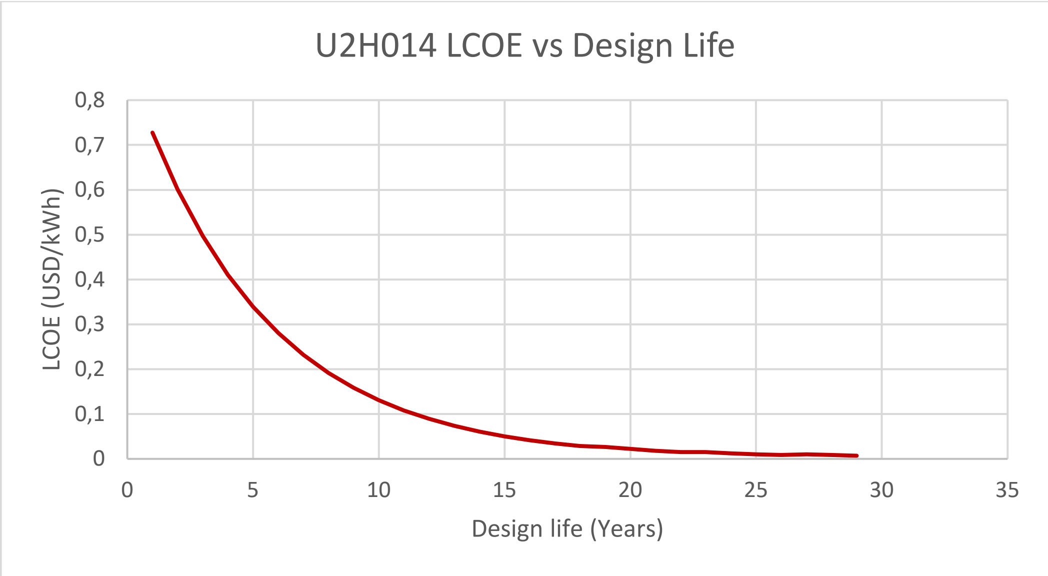

Figure 4.11: U2H014 site 1 configuration 2 LCOE (USD/kWh) vs Design life.

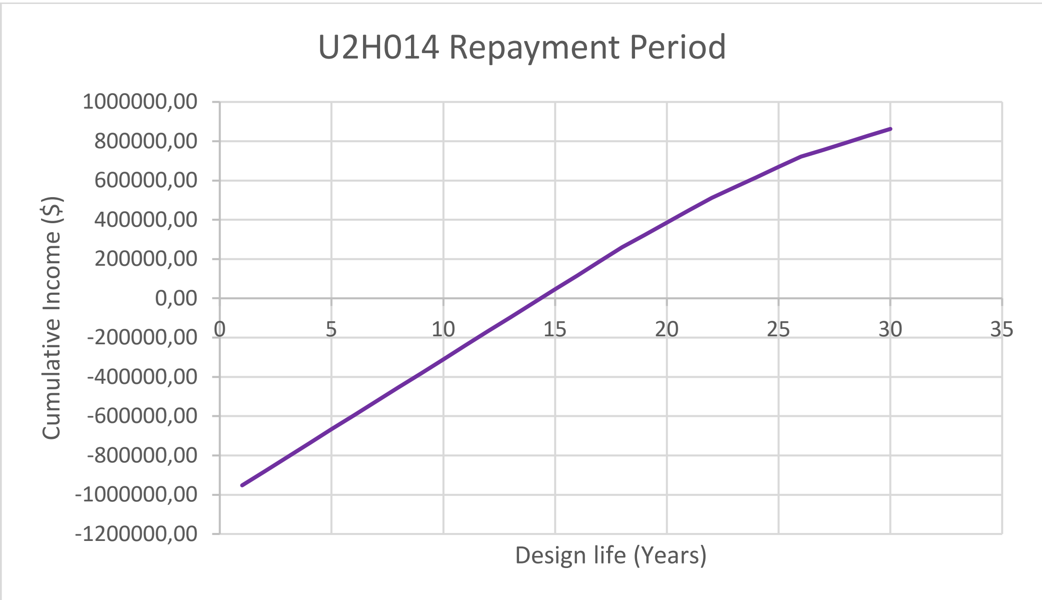

Figure 4.12: U2H014 site 1 configuration 2 Repayment period.

From Figure 4.12, it can be seen that the estimated repayment period for this system would be approximately 14.5 years once it is in operation. The results can be seen in Table 6.6, Appendix B.

Figure 4.13 shows is a graphical presentation of the LCOE at site U3H005 as the investment depreciates throughout its design life. Figure 4.14 shows the cumulative income and repayment period of the hydropower system that would be installed at site U3H005.

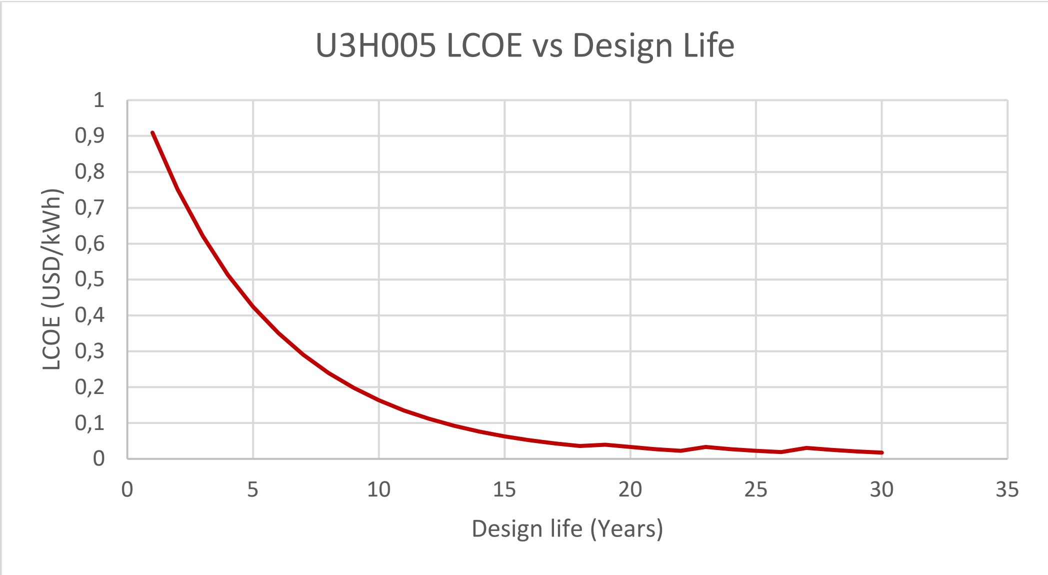

Figure 4.13: U3H005 site 2 configuration 2 LCOE (USD/kWh) vs Design life.

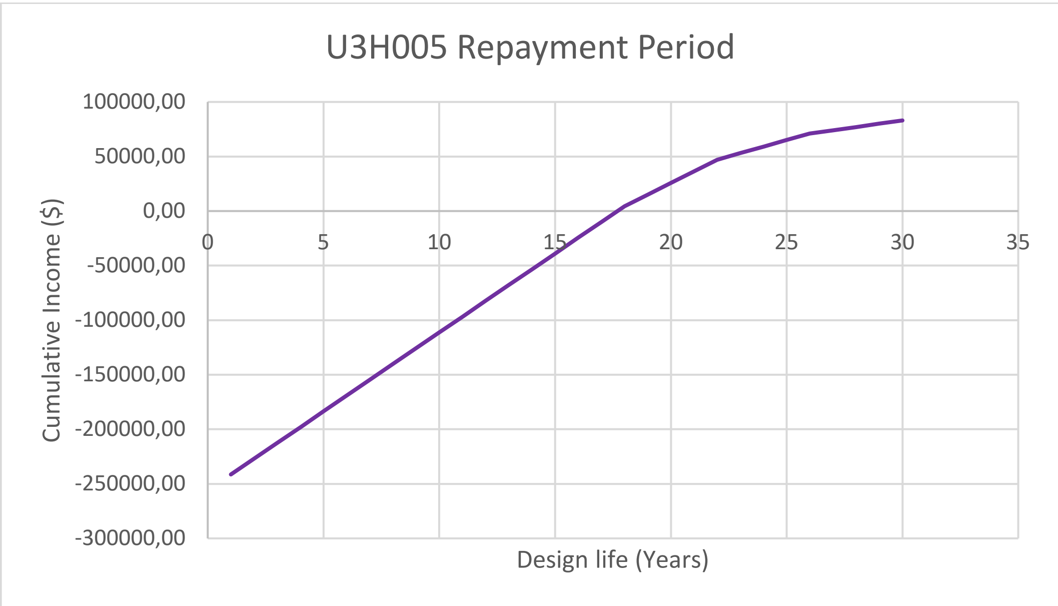

Figure 4.14: U3H005 site 2 configuration 2 Repayment period.

From Figure 4.14, it can be seen that the estimated repayment period for this project would be approximately 17.7 years once it is in operation. The results can be seen in Table 6.7, Appendix B.

Figure 4.15 shows is a graphical presentation of the LCOE at site V1H002 as the investment depreciates throughout its design life. Figure 4.16 shows the cumulative income and repayment period of the hydropower system that would be installed at site V1H002.

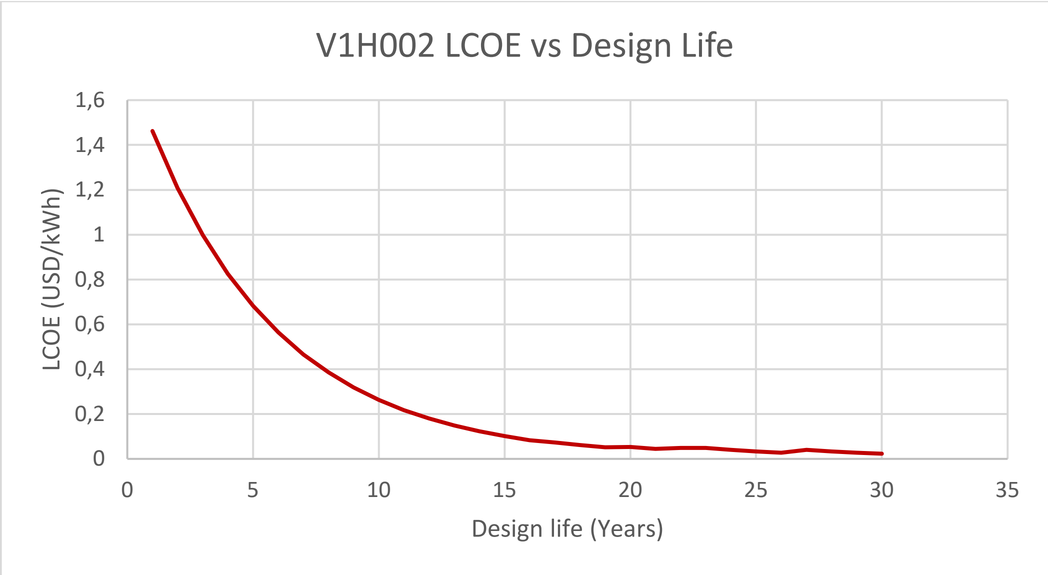

Figure 4.15: V1H002 site 4 LCOE (USD/kWh) vs Design life.

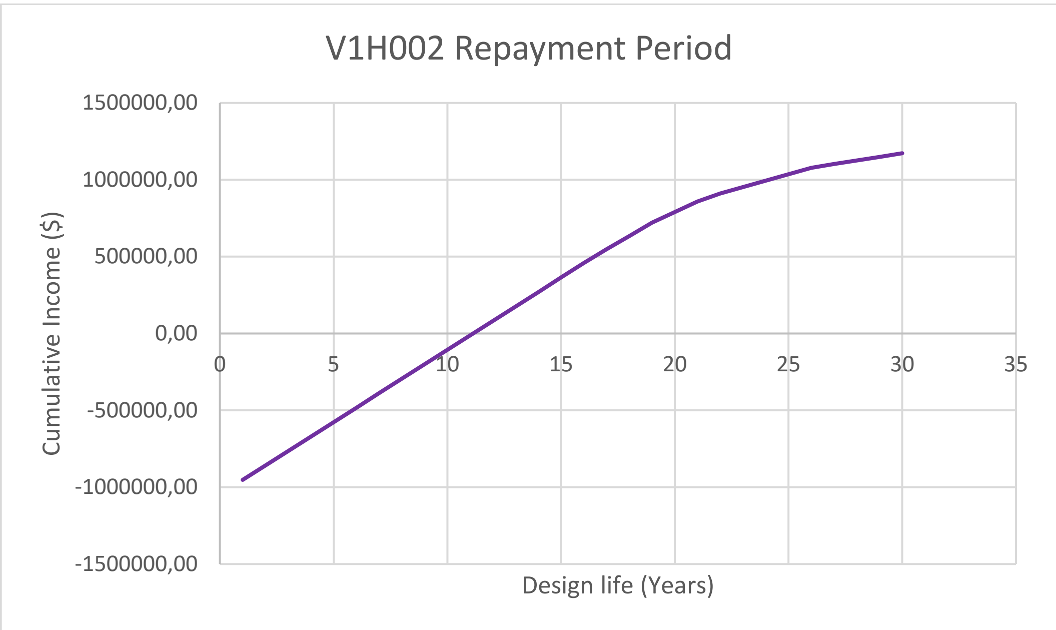

Figure 4.16: V1H002 site 4 Repayment period.

From Figure 4.16, it can be seen that the estimated repayment period for this system would be approximately 11.5 years once it is in operation. The results can be seen in Table 6.8, Appendix B.

The LCOEs initially start off high and gradually decline. This is due to the investment cost and the depreciating factor through the years as the systems reach their design life. Considering the LCOE of 0.02USD/kWh as the minimum for small hydropower projects according to the IRENA findings, the results of this report do agree with the IRENA findings. It can be seen that when the LCOE reaches and begins to fall below 0.02USD/kWh for sites U2H014 and U3H005, the projects' cumulative income rate begins to decline. This can be seen in Figure 4.12 and Figure 4.14. This also happens at site V1H002, when the LCOE reaches and begins to fall below 0.10USD/kWh, the project's cumulative income rate begins to decline. This can be seen in Figure 4.16. The corresponding LCOE results can be seen in Appendix B, Table 6.6 to Table 6.8, respectively. These findings agree with IRENA for LCOE for small hydropower projects in developing countries between 0.02USD/kWh and 0.10USD/kWh, as mentioned at the beginning of this section. In noting that the systems did pay themselves back in their lifespan and profits were also realised, the systems were concluded as economically viable.

Table 4.6 shows the financial costs of each scheme. The electro-mechanical costs were calculated using the Van Vuuren *et al.* (2011) equation. The civil works costs were obtained by subtracting the electro-mechanical cost from the total investment costs of each scheme. The annual operating and maintenance costs were taken as 3% of the total costs.

Table 4.6: Financial costs summary for each project.

Site	C_{em} (R)	C_w (R)	Annual $C_{o\&m}$ (R) (3% of Cem + Cw)
U2H014	0.15mil	7.53mil	230 479
U3H005	0.5mil	1.05mil	46 755
V1H002	0.12mil	10.06mil	305 520

It is worth noting that these systems were Micro and Mini scales hydropower systems, as discussed in section 2.1 Table 2.1. Should they have been small-scale hydropower systems, the economic analysis procedure would have only differed at the initial point of obtaining the cost breakdown for the power plant. The cost breakdown would have been obtained from Figure 2.12, and the formula of Alvarado-Ancieta (2009) would still have been used to calculate the electro-mechanical costs. All the other costs on Figure 2.12 would be obtained as a proportion of this cost, as described by Figure 2.12.

4.3 Pre-feasibility Model Assessment Outcomes

Table 4.7 shows the pre-feasibility model assessment outcome for site U2H014:

Table 4.7: U2H014 pre-feasibility model assessment outcome

Criterion	Acceptable or Not Acceptable	Project Outcome
Environmental Model	Acceptable	FEASIBLE
Social Model	Acceptable	
Economic Model	Acceptable	

Figure 3.1 shows a few houses located near the selected site for U2H014 and a lot of agricultural land being cultivated. This means that the installation of a hydropower plant would benefit the community to pump groundwater and power their irrigation systems, making their land more productive. Households would also benefit from the hydropower station by receiving renewable energy.

Table 4.8 shows the pre-feasibility model assessment outcome for site U3H005:

Table 4.8: U3H005 pre-feasibility model assessment outcome

Criterion	Acceptable or Not Acceptable	Project Outcome
Environmental Model	Acceptable	FEASIBLE
Social Model	Acceptable	
Economic Model	Acceptable	

Figure 3.2 shows a lot of agricultural land being cultivated for site U3H005. This means that the installation of a hydropower plant would benefit the area to pump groundwater and power their irrigation systems, making their land more productive. The few buildings would also benefit from the hydropower station by receiving renewable energy.

Table 4.9 shows the pre-feasibility model assessment outcome for site V1H002:

Table 4.9: V1H002 pre-feasibility model assessment outcome

Criterion	Acceptable or Not Acceptable	Project Outcome
Environmental Model	Acceptable	FEASIBLE
Social Model	Acceptable	
Economic Model	Acceptable	

Figure 3.3 shows quite a few houses near site V1H002. This means that the installation of a hydropower plant would benefit the community to power their households, making their houses receive renewable energy. Thus, solving climate change issues and generating electricity where it is not feasible to extend the existing grid in South Africa.

The potential sites for this model to work are sites with rural communities or agricultural activities in areas where primary rivers are identified in South Africa. This ensures that the hydropower plant installed does have the potential flow from the river, with the necessary head being determined to produce the potential power. Installing the hydropower plant next to these predetermined areas means that the existing communities benefit from the scheme. This means that planting more hydropower systems in South Africa has the potential of making rural and agricultural activities productive.

5. CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes this study based on its aims and objects and some of the research obtained. It also makes the necessary recommendations to ensure ways of improving the study and finally this chapter makes a suggestion of a future study.

5.1 Conclusion

Run-of-river hydropower projects have a significant role in providing electricity to rural and isolated areas where it is not feasible to extend the existing grid infrastructure.

A feasibility study of a run-of-river hydropower system would typically require considering the '3 Pillar Concept' test for sustainability. These are the social, environmental, and economic aspects tests for the sustainability of a project. Each of these pillars has indicators that are measured directly and indirectly, and all three pillars have an essential role in determining whether a project is feasible or not in its initial stages. According to this research, run-of-river hydropower systems have 49 sustainability indicators.

Four sites were selected for this study. U2H014 in Umgeni river downstream of Albert falls dam, U2H052 in Umgeni river downstream of Inanda dam, U3H005 in uMdloti river downstream of Hazelmere dam and, V1H002 in Tugela river downstream of Woodstock dam. The selection criteria of the area for this study were based on the issues mentioned in section 2.10, which aims to increase the area under irrigation in Southern Africa and increase rural and agricultural productivity by providing off-grid power. Another consideration for site selection was the ability for each scheme to generate energy in the shortest distance, making the selected options more potentially environmentally and socio-economically viable.

Table 4.5 in section 4.2.7 describes the cost model. The electromechanical costs were calculated using the Van Vuuren *et al.* (2011) equation which converted equation (2.7) into Rands. The civil works costs were calculated by subtracting the electromechanical costs from the total costs. It was found that the operational and maintenance costs were 3% of the total costs.

Section 4.2.7.1 shows a sample calculation for determining the LCOE (USD/kWh) of a hydropower plant at any given year. The repayment periods for each system are also shown in section 4.2.7.1. The full results for each system are shown in appendix B.

The rural and agricultural productivity was demonstrated in section 4.2.3, whereby each of the assessed sites demonstrated that the power produced was higher than the groundwater pumping power requirements. The groundwater pumping requirements for rural and agricultural productivity were 31.1kW, as seen in section 2.10. This was taken as the worst-case scenario using the groundwater yield of $20l.s^{-1}$ for this study as mentioned in section 2.10, which can also be seen in Figure 2.7. The ground water yield of $20l.s^{-1}$ is the aquifer productivity that was found to exist in small parts of South Africa. Although these were small areas, Figure 2.15 in section 2.10 shows the aridity concerns in South African, which is why the worst case was selected for the design life of these systems. With demonstrating system sustainability and potential power savings, the conclusion of run-of-river hydropower for rural and agricultural productivity in South Africa was FEASIBLE for the selected sites

The streamflow data for each site was obtained from the Department of Water Affairs online database. Impulse turbines were used for this study, and the power generated by each scheme concluded that the schemes were micro and mini hydropower systems.

The social and environmental indicators were separately combined to develop models that would allow the user to manually adjust the vulnerability index of each indicator using the vulnerability line diagram method. The conclusion of the viability of the social and environmental model was then based on the weighted average of the indicators based on either low vulnerability or extremely vulnerable. The social model was designed to have a separate consideration to evaluate positive social indicators to assess the project's potential of improving the livelihood of the community. The social and environmental feasibility assessment results for the three sites were ACCEPTABLE.

Ideally, costs should be obtained from manufacturers and suppliers. However, this proves impossible, resulting in the reliance on developed costing formulas by various authors. According to IRENA, hydropower systems are very site specific and therefore, the costing models developed need to be treated with caution. The findings in this investigation revealed that the costing model developed by Van Vuuren *et al.* (2011) was based on a one-unit power plant Indian model developed by Singal and Saini (2008), which according to this investigation, is not specific to South African conditions. Findings also show that the cost breakdown variations between the one-unit power plant to the four-unit power plant were similar for the Indian model, which could be the case for Indian conditions. The cost estimations using a model would result in similar outcomes between power plants, whereas it was not calibrated for another region. Recent research has revealed that hydropower systems are site specific and can lead to potential conclusions, especially when inconsistent outcomes are observed. The tested cases by Van Vuuren *et al.* (2011) in South Africa showed cases of cost modelling estimation inconsistencies for the different sites. This led to the conclusion that projects could be concluded as economically feasible when they are not using the Van Vuuren *et al.* (2011) model, which is modelled based on the Singal and Saini (2008) model. The costing model for electro-mechanical costs developed by Alvarado-Ancieta (2009) was suitable to South Africa as South Africa is one of the 81 countries to be investigated by the author. The results obtained from each scheme from this investigation did agree with the findings of IRENA for real world projects. IRENA investigations also include Alvarado-Ancieta (2009) findings. Each scheme fell within the guidelines of IRENA of a LCOE as low as 0.02USD/kWh to 0.10USD/kWh for projects in developing countries. The projects tested in each site were Micro and Mini hydropower systems which are bigger than pico hydropower system, as seen in section 2.1 Table 2.1. According to the IRENA findings, LCOE of 0.27USD/kWh or higher are expected for pico hydropower systems, and smaller systems experience higher LCOE. Findings showed a rate of income decline for each system as soon as the LCOE ranges of 0.02USD/kWh and 0.10USD/kWh were reached. The schemes did pay themselves back within their lifespan and profits were also realised. The conclusion was therefore the evaluated projects were feasibly ACCEPTIBLE.

A series of run-of-river hydropower systems can be a more feasible and attractive option than the construction of larger hydropower dams considering the '3 Pillar Concept' test for sustainability. This report has demonstrated that there is a potential power saving from each site and that the power savings realised could promote and enhance rural and agricultural productivity in South Africa. The power savings from the electricity generated presents an opportunity for electricity to be sold back to the grid, reducing the load into the grid.

5.2 Recommendations

The following items have been listed as the recommendations for this study:

- Where practical, if professional and site-specific costs are achievable, the model should be amended, and those professional and site-specific costs should be used.
- This model only applies to South African conditions.
- South Africa should have simpler methods that can be used to determine hydropower potential sites.

5.3 Suggested Future Study

Renewable energy systems are a thing of the future as the world moves towards climate change energy production friendly systems. The feasibility studies of different renewable energy systems each consider different factors which is one of the first differences which make some systems more feasible than others. However, in the same context, similar systems can also differ in terms of feasibility because they are site specific which is why it is not ok to generalise for each.

Consider a South Africa of integrated renewable energy systems connected to reduce the load into the grid as shown below in Figure 5.1. A potential future study can be a model that considers alternative power sources and gives an output of one power source as the best suited option when compared to the rest for the same power capacity in the similar investment range.

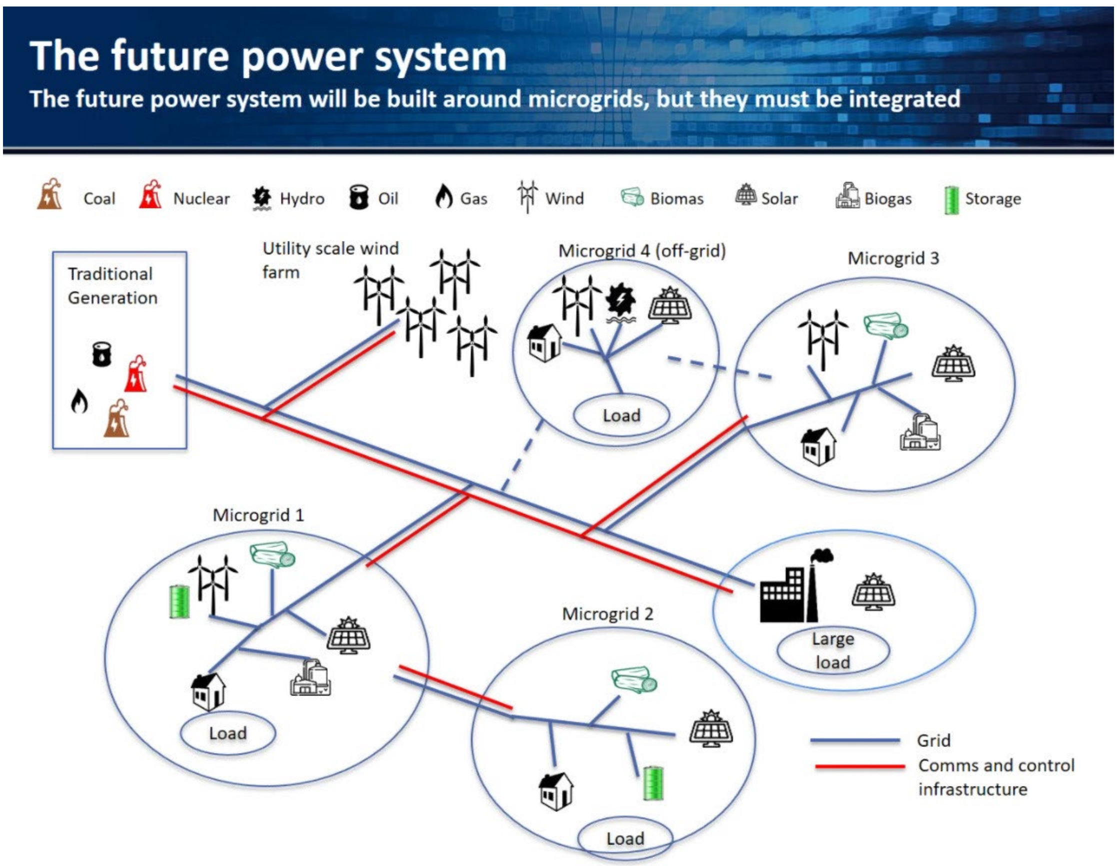

Figure 5.1: CSIR The Future of Power Systems

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APPENDICES

- Appendix A: Formulae
- Appendix B: Levelised Cost of Electricity (LCOE) from Hydropower
- Appendix C: KSB Pump Etanorm 060-050-315/2P

Appendix A – Formulae

Table 6.1: The Levelised Cost of Electricity (LCOE) from hydropower Function Interpretation (Foster *et al.*, 2014)

Parameter		Function, interpretation
It	Investment expenditure in the year *t*	$I_t = Capital\ Cost * Net\ Plant\ Output * 1000$
Mt	Operations and maintenance expenditure in the year t	$M_t = Fixed\ O\ \&\ M * Net\ Plant\ Output + Variable\ O\ \&\ M * Net\ Plant\ Output * hours\ in\ year * \frac{Capacity\ Factor}{100} + Carbom\ Price * \frac{Emissions}{1000} * Net\ Plant\ Output * hours\ in\ year * \frac{Capacity\ Factor}{100} + Sequestration\ Costs * \left(\frac{\frac{Emissions}{1000}}{\left(1 - \frac{Emissions\ Captured}{100}\right)} - \frac{Emissions}{1000} \right) * Net\ Plant\ Output * hours\ in\ year * \frac{Capacity\ Factor}{100}$
Ft	Fuel expenditure in the year t	$F_t = Fuel\ Cost * \frac{Net\ Plant\ Output}{\frac{Thermal\ Efficiency}{100}} * hours\ in\ year * \frac{Capacity\ Factor}{100}$
Et	Electricity generation in the year t	$E_t = Net\ Plant\ Output * hours\ in\ year * \frac{Capacity\ Factor}{100}$
r	Discount rate	The 10% discount rate is applied for all technologies
n	Amortisation period	Specific for technology types

Table 6.2: Francis, Kaplan and Propellor turbines runner size and specific speed

FRANCIS, KAPLAN AND PROPELLOR TURBINES (REACTION TURBINES):	
Reaction turbine runner size (d)	$d = kQ_d^{0.473}$ Equation B. 1 Where: d= runner throat diameter in m k= 0.46 for d<1.8 = 0.41 for d $\geq$ 1.8 Q_d= design flow (m^3/s)
Specific speed (n_q)	$n_q = kh^{-0.5}$ Equation B. 2 where: n_q= specific speed based on flow k= 800 for propeller and Kaplan turbines = 600 for Francis turbines h= rated head on turbine in m (gross head less maximum hydraulic losses)

Table 6.3: Kaplan and Propeller turbines specific speed adjustment, runner size adjustment and turbine peak efficiency

KAPLAN & PROPELLOR TURBINES:	
Specific speed Adjustment to peak efficiency ($\hat{}e_{nq}$)	$\hat{}e_{nq} = \left\{\frac{n_q - 1700}{700}\right\}^2$ Equation B. 3

Runner size adjustment to peak efficiency ($\hat{}e_d$)	$$\hat{}e_d = (0.095 - \hat{}e_{nq})(1 - 0.789d^{-0.2})$$ Equation B. 4
Turbine peak Efficiency (e_p)	$$e_p = (0.905 - \hat{}e_{nq} + \hat{}e_d) - 0.0305 + 0.005R_m$$ Equation B. 5 Where: R_m = Turbine manufacture design coefficient (2.8 – 4.5)

Table 6.4: Kaplan turbine peak efficiency flow and efficiency flows above and below peak efficiency flow

KAPLAN TURBINES:	
Peak efficiency flow (Q_p)	$$Q_p = 0.75\,Q_d$$ Equation B. 6
Efficiency at flows Above and below peak Efficiency flow (e_q)	$$e_q = \left(1 - 3.5\left(\frac{Q_d - Q}{Q_p}\right)^6\right)e_p$$ Equation B. 7

Table 6.5: Cross-flow turbines peak efficiency flow and efficiency

CROSS-FLOW TURBINES:	
Peak efficiency flow (Q_p)	$$\boldsymbol{Q_p = Q_d}$$ Equation B. 8
Efficiency (e_q)	$$\boldsymbol{e_q = 0.79 - 0.15\left(\frac{Q_d - Q}{Q_p}\right) - 1.37\left(\frac{Q_d - Q}{Q_p}\right)^{14}}$$ Equation B. 9

Appendix B – Levelised Cost of Electricity (LCOE) from Hydropower

Table 6.6: U2H014 LCOE from hydropower results

Year (t)	It = Investment ($/kW)	Mt ($/kW)	Et (kWh)	LCOE (USD/kWh)	Cost/Income ($)	Cumulative Income ($)
1	4000.00	120.00	1114195.68	0.727558023	-952304.00	-952304.00
2	4000.00	120.00	1114195.68	0.601287623	71308.52	-880995.48
3	4000.00	120.00	1114195.68	0.49693192	71308.52	-809686.95
4	4000.00	120.00	1114195.68	0.410687537	71308.52	-738378.43
5	4000.00	120.00	1114195.68	0.339411187	71308.52	-667069.91
6	4000.00	120.00	1114195.68	0.280505114	71308.52	-595761.38
7	4000.00	120.00	1114195.68	0.231822408	71308.52	-524452.86
8	4000.00	120.00	1114195.68	0.191588767	71308.52	-453144.34
9	4000.00	120.00	1114195.68	0.158337824	71308.52	-381835.81
10	4000.00	120.00	1114195.68	0.130857706	71308.52	-310527.29
11	4000.00	120.00	1114195.68	0.108146864	71308.52	-239218.76
12	4000.00	120.00	1114195.68	0.089377574	71308.52	-167910.24
13	4000.00	120.00	1114195.68	0.073865763	71308.52	-96601.72
14	4000.00	120.00	1114195.68	0.061046085	71308.52	-25293.19
15	4000.00	120.00	1114195.68	0.05045131	71308.52	46015.33
16	4000.00	120.00	1114195.68	0.041695298	71308.52	117323.85
17	4000.00	120.00	1114195.68	0.034458924	71308.52	188632.38
18	4000.00	120.00	1114195.68	0.028478449	71308.52	259940.90
19	4000.00	120.00	982800	0.026682547	62899.20	322840.10
20	4000.00	120.00	982800	0.022051692	62899.20	385739.30
21	4000.00	120.00	982800	0.018224539	62899.20	448638.50
22	4000.00	120.00	982800	0.015061602	62899.20	511537.70
23	4000.00	120.00	819000	0.014937126	52416.00	563953.70
24	4000.00	120.00	819000	0.012344733	52416.00	616369.70
25	4000.00	120.00	819000	0.010202258	52416.00	668785.70
26	4000.00	120.00	819000	0.008431618	52416.00	721201.70
27	4000.00	120.00	552240	0.010334313	35343.36	756545.06
28	4000.00	120.00	552240	0.008540755	35343.36	791888.42
29	4000.00	120.00	552240	0.007058475	35343.36	827231.78
30	4000.00	120.00	552240	0.00583345	35343.36	862575.14

Table 6.7: U3H005 LCOE from hydropower results

Year (t)	It = Investment ($/kW)	Mt ($/kW)	Et (kWh)	LCOE (USD/kWh)	Cost/Income ($)	Cumulative Income ($)
1	5000.00	150.00	225954.612	0.909444091	-241404.50	-241404.50
2	5000.00	150.00	225954.612	0.751606687	14461.10	-226943.40
3	5000.00	150.00	225954.612	0.621162551	14461.10	-212482.31
4	5000.00	150.00	225954.612	0.51335748	14461.10	-198021.21
5	5000.00	150.00	225954.612	0.42426238	14461.10	-183560.12
6	5000.00	150.00	225954.612	0.350630066	14461.10	-169099.02
7	5000.00	150.00	225954.612	0.289776914	14461.10	-154637.93
8	5000.00	150.00	225954.612	0.239485053	14461.10	-140176.83
9	5000.00	150.00	225954.612	0.197921532	14461.10	-125715.74
10	5000.00	150.00	225954.612	0.163571514	14461.10	-111254.64
11	5000.00	150.00	225954.612	0.135183069	14461.10	-96793.55
12	5000.00	150.00	225954.612	0.111721545	14461.10	-82332.45
13	5000.00	150.00	225954.612	0.092331855	14461.10	-67871.36
14	5000.00	150.00	225954.612	0.076307318	14461.10	-53410.26
15	5000.00	150.00	225954.612	0.063063899	14461.10	-38949.17
16	5000.00	150.00	225954.612	0.052118925	14461.10	-24488.07
17	5000.00	150.00	225954.612	0.043073492	14461.10	-10026.98
18	5000.00	150.00	225954.612	0.035597927	14461.10	4434.12
19	5000.00	150.00	166608	0.039899247	10662.91	15097.03
20	5000.00	150.00	166608	0.032974584	10662.91	25759.94
21	5000.00	150.00	166608	0.027251723	10662.91	36422.85
22	5000.00	150.00	166608	0.022522085	10662.91	47085.77
23	5000.00	150.00	93600	0.033131662	5990.40	53076.17
24	5000.00	150.00	93600	0.027381539	5990.40	59066.57
25	5000.00	150.00	93600	0.022629371	5990.40	65056.97
26	5000.00	150.00	93600	0.018701959	5990.40	71047.37
27	5000.00	150.00	46800	0.03091233	2995.20	74042.57
28	5000.00	150.00	46800	0.02554738	2995.20	77037.77
29	5000.00	150.00	46800	0.021113537	2995.20	80032.97
30	5000.00	150.00	46800	0.017449204	2995.20	83028.17

Table 6.8: V1H002 LCOE from hydropower results

Year (t)	It = Investment ($/kW)	Mt ($/kW)	Et (kWh)	LCOE (USD/kWh)	Cost/Income ($)	Cumulative Income ($)
1	4020.00	120.60	1469145.60	1.462386099	-952304.00	-952304.00
2	4020.00	120.60	1469145.60	1.208583553	94025.32	-858278.68
3	4020.00	120.60	1469145.60	0.998829382	94025.32	-764253.36
4	4020.00	120.60	1469145.60	0.825478828	94025.32	-670228.04
5	4020.00	120.60	1469145.60	0.682213908	94025.32	-576202.73
6	4020.00	120.60	1469145.60	0.563813147	94025.32	-482177.41
7	4020.00	120.60	1469145.60	0.465961278	94025.32	-388152.09
8	4020.00	120.60	1469145.60	0.385091966	94025.32	-294126.77
9	4020.00	120.60	1469145.60	0.318257823	94025.32	-200101.45
10	4020.00	120.60	1469145.60	0.263022994	94025.32	-106076.13
11	4020.00	120.60	1469145.60	0.217374375	94025.32	-12050.82
12	4020.00	120.60	1469145.60	0.179648244	94025.32	81974.50
13	4020.00	120.60	1469145.60	0.148469623	94025.32	175999.82
14	4020.00	120.60	1469145.60	0.122702168	94025.32	270025.14
15	4020.00	120.60	1469145.60	0.10140675	94025.32	364050.46
16	4020.00	120.60	1469145.60	0.083807232	94025.32	458075.78
17	4020.00	120.60	1404000.00	0.07247594	89856.00	547931.78
18	4020.00	120.60	1357200.00	0.061962901	86860.80	634792.58
19	4020.00	120.60	1357200.00	0.051209009	86860.80	721653.38
20	4020.00	120.60	1076400.00	0.053361885	68889.60	790542.98
21	4020.00	120.60	1076400.00	0.044100732	68889.60	859432.58
22	4020.00	120.60	795600.00	0.049310492	50918.40	910350.98
23	4020.00	120.60	655200.00	0.049485146	41932.80	952283.78
24	4020.00	120.60	655200.00	0.040896815	41932.80	994216.58
25	4020.00	120.60	655200.00	0.03379902	41932.80	1036149.38
26	4020.00	120.60	655200.00	0.027933075	41932.80	1078082.18
27	4020.00	120.60	369720.00	0.040910456	23662.08	1101744.26
28	4020.00	120.60	369720.00	0.033810294	23662.08	1125406.34
29	4020.00	120.60	369720.00	0.027942392	23662.08	1149068.42
30	4020.00	120.60	369720.00	0.023092886	23662.08	1172730.50

Appendix C – KSB Pump Etanorm 060-050-315/2P