DEPARTMENT OF MECHANICAL ENGINEERING
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The Potential of Renewable Energy for Rural Groundwater Supply in the Elundini Municipality

Dissertation in partial fulfilment for the Degree of Master of Science in Engineering

By

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Ad Majorum Dei Gloriam

To John and Dave Moore for their selfless acts of sacrifice in the protection of their family.

"The universe is so vast and so ageless that the life of one man can only be justified by the measure of his sacrifice"

- *WWII RAF pilot*

DECLARATIONS

I, Gordon Kernick, declare that I know the meaning of plagiarism and declare that all the work in this document, save for that which is properly acknowledged, is my own. This dissertation is in partial fulfillment of the Degree of Master of Science in Engineering (MSc Eng) at the University of Cape Town and has not been submitted for any other degree at any other University.

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Gordon Kernick

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GLOSSARY

Drawdown – The depth below the ground surface that water will drop to when an abstraction is placed on the aquifer.

Hydraulic conductivity – The volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the flow.

Storativity – The volume of water released from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to that surface.

Surface Roughness – The measure of the texture of a pipe surface and subsequent resistance to fluid flow

Transmissivity – The product of the average hydraulic conductivity and the saturated thickness of the aquifer.

ABBREVIATIONS

AC – Alternating Current

AFYM – Aquifer Firm Yield Model

BEM – Blade Element Theory

CIA – Central Intelligence Agency

DC – Direct Current

DHI – Direct Horizontal Insolation

DNI – Direct Normal Insolation

DOE – Department of Environment

DTU – Denmark University of Technology

GHI – Global Horizontal Insolation

GMS – Groundwater Model Suite

GRA – Groundwater Resource Assessment

GTI – Global Tilt Insolation

IAEA – International Atomic Energy Agency

kWh – Kilowatt hour

LCC – Life Cycle Cost

MDG – Millennium Development Goals

MPPT – Maximum Power Point Tracker

MWh – Megawatt hour

MWPS – Mechanical Wind Pumping System

NASA – National Aeronautics and Space Administration

NPV – Net Present Value

NREL – National Renewable Energy Laboratories

SANEDI – South African National Energy Development Institute

SAWS – South African Weather Service

SECO – State Energy Conservation Office

SPVP – Solar Photovoltaic Pump

SSE – Surface meteorology and Solar Energy

STATSSA – Statistics South Africa

UNEP – United Nations Environment Programme

USAID – United States Agency for International Development

USD – United States Dollar

WHO – World Health Organisation

WRC – Water Research Commission

WASA – Wind Atlas of South Africa

NOMENCLATURE

Symbol	Name/description	value/units
$\in$	absolute roughness	mm
f	friction factor	
g	acceleration due to gravity	9.81 m/s^2
λ	tip speed ratio	
μ	dynamic viscosity	kg/ms
Ω	angular velocity	radians/s
ρ	density	kg/m^3
ν	kinematic viscosity	m^2/s

ABSTRACT

The Elundini municipality, situated in the interior Eastern Cape of South Africa, as with many other municipalities with a large portion of rural inhabitants, is beset with the challenge of needing to provide clean drinking water to these far lying people in an efficient and cost effective manner. Due to the large distances between villages as well as from any town or major infrastructure, supplying water via traditional pipe networks is not feasible. Historically, groundwater has been the water source of choice and abstracted via the use of diesel powered borehole pumps. These pumps are however noisy, require constant maintenance and are associated with high running costs associated with the ever increasing price of fuel. Not only is the fuel expensive in itself, but it is also required to be transported long distance to the boreholes on a regular basis.

This study then investigated how solar and wind powered borehole pumps compared with diesel powered options. This was done by assessing the natural resource potential of the region (wind and solar power) as well as the groundwater abstraction potential of a sample of villages. Notional solar, wind and diesel powered systems were then designed for each of the villages with each of their unique water supply requirements and then compared against one another with a life cycle cost analysis for each system being performed.

The study found that, not unlike other similar studies in other regions of the world, that over their lifetime, wind and solar powered borehole pumps were cheaper than their diesel counterparts. This was especially true for solar powered options as the solar resource for the region is superior to that of wind. Although traditionally shunned due to high capital costs, solar powered pumps have been commercialized in recent years and are now only marginally more expensive than diesel options. Wind pump capital costs are still prohibitively high, although running and maintenance costs are low. For the Elundini municipality however, and its relatively poor wind resources, this would not be a recommended technology.

Solar powered pumps therefore, although with slightly higher capital costs than diesel pumps due to storage requirements, and the risk of theft of solar panels identified as a potential problem, are cheaper over their lifetime than both diesel and wind power as well as requiring less maintenance and being more reliable than diesel pumps and should therefore be considered the borehole pump power technology of choice for the region.

1 INTRODUCTION

"A developed country is not a place where the poor have cars. It's where the rich use public transportation" (Petro, G. 2012). This summation of what equality should look like, is directly applicable to South Africa which is rated, according to the Central Intelligence Agency (CIA) of the United States, as the second most unequal country in the world, when measured using the Gini coefficient (CIA, 2011). With the access to clean drinking water a basic human right as declared by the United Nations (UN, 2010), this is certainly an area in which equality in South Africa should be aspired to, but unfortunately is not always achieved. Most often, it is the people who can least afford to be without water, the poor, which lack access to it. This is exacerbated by the fact that poverty rates in South Africa's rural areas are almost twice that in urban areas (STATSSA, 2006) where providing access to water via conventional water supply infrastructure is made far more difficult by the distances between households. Recent statistics indicate that 92.9% of inhabitants have access to water in South Africa (STATSSA, 2010).

The massive health benefits that easy access, defined by the World Health Organisation (WHO) as distance from the home to a water source within 1000 metres, to clean drinking water has, make it an especially worthwhile and necessary pursuit (WHO, 2008), with reports that 1.8 million child deaths a year are as a result of water-borne diseases (Office of High Commission of Human Rights, 2011). The importance of correctly functioning boreholes can be highlighted by the fact that in Nigeria, the installation of a borehole led to a 50% decrease in illness (Nogier, 1998 in Short and Oldach, 2003).

1.1 The Elundini Municipality

The Elundini municipality, in the rural North Eastern region of the Eastern Cape comprising the towns of, amongst others, Maclear and Mt. Fletcher and situated on the South Western border of Lesotho, is currently struggling to provide fresh drinking water to some 50 000 of its rural inhabitants. The Energy Research Centre (ERC) of the University of Cape Town (UCT) was approached by representatives of the Elundini municipality in the hope of finding a solution to their problem, possibly via the use of renewable energy powered, water pumping technologies.

The efficacy of these technologies will be looked at when used for the extraction of water from groundwater sources, as opposed to the sourcing, storage and distribution of surface water as is common in more developed and urban areas. This is due to the fact that due to the population being sparse and widely distributed in rural areas, this type of water sourcing is the most effective and sustainable and as Macdonald et al (2008:1) in their study state: "The widespread development of groundwater is the only affordable and sustainable way of improving access to clean water and meeting the Millennium Development Goals for water supply by 2015."

Currently most of the water supplied to the rural inhabitants of Elundini is done via diesel generator powered borehole pumps extracting this groundwater, and although they can be effective and versatile, they do have several short falls including intermittent supply of diesel with fluctuating costs, and the need for regular maintenance (Oi, A. 2005).

This dissertation will seek to determine the feasibility of renewable energy powered technologies, namely solar PV and wind pumps, in providing groundwater to the rural inhabitants of the Elundini municipality. This specific type of study needs to be done due to the regional and site specific nature of renewable energy (Omer, 2008). This will be achieved firstly by studying the already existing data related to solar PV and wind pumping technology, in what climatic conditions they are most effective and how they would compare to currently used water pumping technologies (most commonly diesel generators) within the context of the Elundini municipality.

1.2 Problem Statement

The Elundini municipality, particularly the rural areas, suffer from low levels of reliable fresh water supply with some 50 000 inhabitants currently without water provision (Qotoyi, 2011). This study was therefore well supported by the municipality in order to determine whether a possible solution to this problem could be found via the use of renewable energy. The critical importance that reliable, clean water supply plays in the health, well-being and development of humanity, and the fact that this is not sufficiently provided for in the Elundini municipality, forms the motivation behind the need for this study.

1.3 Research Objectives

It is clear that the current method of water supply in the rural areas of the Elundini municipality is not adequately providing the fresh water so desperately required by the inhabitants. This is seen by the low levels of water being provided to the rural inhabitants (Sintech, 2011). Part of the reason for this may lie in the disadvantages associated with diesel powered borehole pumps, the primary form of rural water supply in the region. These disadvantages are primarily, the difficulty and associated costs, in supplying diesel to the widely dispersed locations of the borehole pumps as well as the high levels of maintenance required by the diesel generators.

Renewable energy powered options conceivably solve at least one of these problems, that being the supply of fuel, as wind and sun are freely available, location based resources. In the case of solar powered pumps, the amount of maintenance required has also been shown to be considerably less than for diesel powered ones (Ramos & Ramos, 2009), illustrated in Chapter 2. The disadvantage of renewable powered options however is that they are extremely site and situation specific and, unlike diesel, cannot simply be installed at virtually any borehole and pump effectively.

This study therefore aims to:

- Determine, based on the natural resources of wind and solar radiation, whether borehole pumps powered by these resources could be feasibly implemented within the Elundini municipality
- Analyse a sample of villages within the municipality currently being provided water through diesel powered borehole pumps and determine whether these boreholes with their respective depths and recharge rates could be serviced by renewable powered pumps and if so what size they would be
- Compare diesel powered pumps with the hypothetical renewable energy powered ones to determine whether they would provide a better alternative

1.4 Thesis Outline

Firstly a literature review is conducted in Chapter 2 which seeks to illustrate the inextricable link that exists between water and energy and how they are equally reliant upon one another. It then looks at literature specifically relevant to water provision in rural areas both broadly and with reference to South Africa and more specifically the Elundini municipality. It also examines previous studies and research into the efficacy of renewable energy technologies in supplying water, measured over a range of criteria such as cost, societal impact, efficiency and durability. As most of the sources of rural water supply investigated by the author in the Elundini municipality are groundwater (boreholes, underground streams etc.) with pumps required to supply it to residents, it is literature surrounding this water source type that will be focused on. This literature is then critically analysed regarding the potential of renewable energy options to provide an attractive alternative in the powering of water pumps in a rural context, with the Elundini Municipality being the study area. Water quality and subsequent treatment, although vitally important, falls outside the scope of this study as the type of energy used to abstract the water has little to no bearing on water quality and hence only groundwater provision itself will be investigated.

Chapter 3 outlines the method used in the determination of renewable energy's potential and efficacy in providing water through borehole pumping. This is done by designing hypothetical water supply systems based on the use of wind and solar power and then comparing these with the current diesel powered options. The comparison is made across various socio-economic criteria with the primary measure being the life cycle cost analysis of the various water supply systems.

Chapter 4 describes examples of the designs and calculations performed as well as the results for the various water supply systems designed.

Chapter 5 analyses and compares the results across various criteria, broadly being life cycle cost and practical implementation.

A summary of the findings, general conclusions and recommendations for further research in this field are then presented in Chapter 6. This is further followed by a list of references used in the study and the appendices.

2 LITERATURE REVIEW

This literature review covers a variety of previous studies and current knowledge, ranging from the crucial link that exists between water and energy and the fundamentals of wind and solar power generation to similar studies pertaining to ground water extraction using renewable energy sources.

2.1 The Water Energy Nexus

The fact that water and energy are reliant on each other and inextricably linked, although not particularly well known, is an extremely relevant and important one. Water is used to generate energy such as through hydropower, as an ingredient in processes such as cooling in coal fired power stations and as the source of the power in the case of hydropower, and similarly, energy or electricity is used in the supply of water, in the pumping, treatment and end user supply (USAID, 2001). Water is required in the production of electricity and electricity is used to supply water to the end user.

Due largely to the constraints that exist in the limited levels of supply of both of these resources, this relationship is particularly pertinent and important for South Africa, and the future of its development (Govender, 2010). The government's Integrated Resources Plan (IRP) 2010, does take the water usage of the various energy generating technologies into consideration when assessing the various development scenarios, indicating the importance placed on the conservation of this precious resource (DOE, 2011). All energy generating technologies are also not created equal regarding water usage with it varying from effectively zero for wind power up to 245 litres per MWh for Concentrated Solar Power (CSP) when looking just at the renewable energy options, with current coal powered power stations using in the region of 229.1 litres per MWh (DOE, 2011). Similarly, energy is required for the supply, transportation and treatment of water.

Recently, South Africa has received stark reminders, regarding supply levels of fresh water and electricity, by two significant events: firstly in 2008, rolling blackouts were experienced all across the country due to the state's primary energy supplier, Eskom's, supply not being able to meet the country's required demand (Eberhard, 2010). There was also an unseasonal, fairly serious drought experienced in the South Western parts of the country in 2011 where some towns even needed water to be supplied by trucks from surrounding areas. Water is obviously a requirement for human existence, and according to the United Nations (UN) access to a clean supply of it, a basic human right (UN, 2010), therefore its provision to the people of South Africa, in such a resource constrained environment, is something which needs to be carefully investigated and researched. One should seek a water and electricity supply scenario in which as much electricity is produced and as much water is supplied to the people of South Africa, with as little use of the other resource, as is practically possible.

2.2 Water Supply in the Rural Eastern Cape

The Eastern Cape is one of the poorest provinces in South Africa (Mey, 1998 in Momba et al, 2006). Momba et al (2006:715), after doing research into certain parts of rural Eastern Cape, including the Author's study area, concluded that 'water and supply facilities remain underdeveloped.' This points to the existence of a serious problem regarding water supply in the rural Eastern Cape. With regards water quality, in a rural environment, groundwater sourced water fares better than surface water as it is not exposed to the same surface contamination, with the citing of pump breakdown as one of the causes of inadequate groundwater quality (Mackintosh & Colvin, 2003). Although they do not go on to talk about supply levels explicitly, this does highlight the importance of having correctly functioning and reliable water pumping infrastructure.

That water is a necessary requirement for development is highlighted well by the fact that halving the number of people who currently don't have access to a reliable supply of safe drinking water forms part of one of the United Nations Environment Programme (UNEP)'s millennium development goals (MDG) (Kahinda et al, 2007). Other than sustaining, and improving the quality of, life, the reliable provision of water allows inhabitants to spend their time on more economically beneficial activities as opposed to the collection of water (Klasen, 2000). This is further emphasised by Blignaut & van Heerden (2009:415) who conclude after their research that "water supply constraints are therefore an issue with unparalleled economic development implications."

2.3 Rural Water Supply Technologies

Although there are several other groundwater supply technologies in existence than those dealt with in this dissertation, such as hand pumps, solar thermal and ram pumps, this study focussed only on wind and solar. It was decided to only focus on diesel, solar PV and wind pumps as they are the most commonly chosen water pumps for rural areas where large volumes of water are required, essentially enough water to provide for the needs of a small village of approximately 100 - 5000 inhabitants (Oi, 2005).

2.3.1 Pumping Theory and Pump Types

Pumps are used to move or raise fluids through the use of mechanical energy and are generally divided into two categories namely positive displacement and dynamic pumps. The study of fluids and their behaviour, hydraulics, forms the basis for pumps and their successful design and operation. Essentially, mechanical energy is transferred via the use of pumps to a fluid providing it with kinetic energy to transport the fluid.

The actual pump types vary, common types used being centrifugal pumps which use a high speed impeller to supply the incoming water with energy and then directed away from the pump and positive displacement pumps which transport defined volumes of water consecutively or “discrete packets” by a primary mover i.e. a screw or piston (Short and Thompson, 2003). Reciprocating positive displacement pumps, which are commonly used in wind pumping, displace a known quantity of liquid through each cycle of the pumping elements done by trapping the liquid between pumping element and its casing, for instance a piston and casing (Michael Smith Engineers, 2006). Each of these pump types has their own advantages and disadvantages and the choice between each being highly dependent on the application i.e. head and flow required (Meah et al, 2006).

Regarding the extraction of groundwater using pumps, the two main criteria that need to be assessed when designing an effective pumping system, regardless of technology type, are the head (essentially the height to which water is transported from the level of the underground water source to the top of the water level in the container vessel or discharge point), as well as the volume of water required to be pumped. The energy required to ‘lift’ this water from source to point of use measured in kWh is referred to as the hydraulic energy (E*w*) and is calculated by multiplying the density of water (ρ=1000 Kg/m^3), gravitational acceleration (g=9.81m/s^2), flow rate of water (Q) and the head it is to be pumped to (h=metres) together; i.e. Ew = ρgQh which gives the energy value in joules. Using the above constants and converting into kWh by dividing by 3 600 000 gives the hydraulic energy (E_w) in terms of head and water flow rate, as:

E_w=0.002725QH **Equation 2.1**

(Markvart, 2000). The volume of water needed is usually calculated on a daily basis and therefore the total energy required is determined for a daily provision of water, hence kWh/day.Diesel Powered Water Pumps

In the case of diesel pumps, they are typically comprised of four elements; an engine used to power a pump which in turn lifts the water, a discharge head fitted to the top of the borehole and a rising main centred down the borehole. Diesel pumps, although covering a wide range of pumping requirements with differing heads and water volume requirements (Ramos and Ramos, 2009) are characterised by the need for regular maintenance of the generator; 250 hours per minor service, and 500-1000 hours per major service (Emcon, 2006). They are however not limited by natural conditions; amount of sun shining and wind blowing, as solar and wind pumps are. They are however reliant on a reliable and consistent supply of fuel which is a continuing cost that needs to be financed and can often be problematic and difficult to supply, particularly in rural areas such as those of the study area (Omer, 2000).

2.3.2 Photo Voltaic Water Pumps

The essence of solar photo voltaic water pumps involves the conversion of the sun's radiation energy into useful pumping energy to either provide water with kinetic energy, or potential energy when being stored in a reservoir or similar storage medium. This technology, not unlike wind and diesel power, can only be seen as an appropriate technology if it can be implemented in such a way as that it is sustainable by the community and aids in the development of that community (Short & Oldach, 2003).

In sparsely distributed, rural environments where access to the grid is difficult and not cost-effective, stand-alone systems such as those designed around solar power energy provide a good and viable option for water provision and hence are investigated further (Meah et al, 2008). However Kou et al (1998) in Odeh et al (2006) have concluded that in certain instances, even when connection to the grid is easily implementable, that the use of PV pumps is a more viable option.

A typical photo voltaic pump (PVP) system, similarly to that illustrated in Figure 2.1, consists of a solar array which converts sunlight into usable electricity, a controller to regulate operation to provide energy to an electric motor which in turn powers a pump that lifts the water from the water source to the surface. The makeup of these systems can vary greatly and either a Direct Current (DC) or Alternating Current (AC) inverter is required to convert the incoming DC power from the solar panels into AC power, as used by typical electric pumps, or a DC powered pump can be used, utilizing the DC power from the panels directly (Ramos & Ramos, 2009). In terms of the motors powered by the panels, various types, as mentioned, with different variations exist and in terms of DC powered; brushed and brushless options are available, with brushless often being preferred for PVP application due to better power matching with the PV panels, as well as lower friction and therefore lower required start up power; brushed motors also require regular brush replacement, thereby increasing maintenance cost and requirements (Short & Oldach, 2003).

Another important fact regarding PVP systems that needs to be considered in their design is the fact that each of the components of the system do not necessarily match the others well i.e. the power output from the PV panel sized for the system doesn't necessarily match that required by the pump (Shot & Oldach, 2003). Although this can be remedied by some degree though the use of a maximum power point tracker (MPPT), described in more detail in Section 2.3.4, careful consideration needs to be made regarding the combination of individual components and the use of components which are each individually efficient, does not necessarily result in an overall efficient system.

The actual pumps themselves can also vary with the most common types used for ground water abstraction in PVP applications being: submerged multistage centrifugal pumps (**Error! Reference source not found.**) which are common for village water supply and are characterised by simple installation and equipment protection due to being submerged-pumps and can be AC or DC; submerged pumps with surface mounted motors (**Error! Reference source not found.**) which give easy access for maintenance but are generally being replaced by fully submerged such as those in **Error! Reference source not found.**; reciprocating positive displacement pumps (**Error! Reference source not found.**) which are highly suited to high-head, low flow applications, which is common for rural villages, they do however require robust above ground components as well as power controllers for impedance matching (Markvart, 2006; Ramos & Ramos, 2009).

The success of a PVP system is highly reliant on its correct sizing and design as an oversized system (larger PV array than what is required for the desired water flow and subsequent pump size) although pumping will occur throughout the day, will be overpriced. Similarly if an array is chosen which is undersized, pumping may only occur during midday sun and therefore miss out on several pumping hours each day (Omer, 2001). The main aim therefore when designing a PVP system is that the required pumping power be generated by as few PV panels as possible to make the system cost effective (Yesilata & Firatoglu, 2008).

Not unlike other renewable energy powered systems, storage becomes an issue, as the sun is not always shining, however water is always needed. Unlike diesel powered pumps which can be switched on and off as is needed, PVP's require sunshine to operate. It is for this reason that either the energy to power the pumps needs to be stored, for instance in batteries, or the water pumped during times of sunshine needs to be stored for access later when the sun is not shining. For this study, due to higher reliability of the system, less theft and overall lower costs (Ramos, 2009), only PVP systems designed utilising water storage, and not batteries, will be considered.

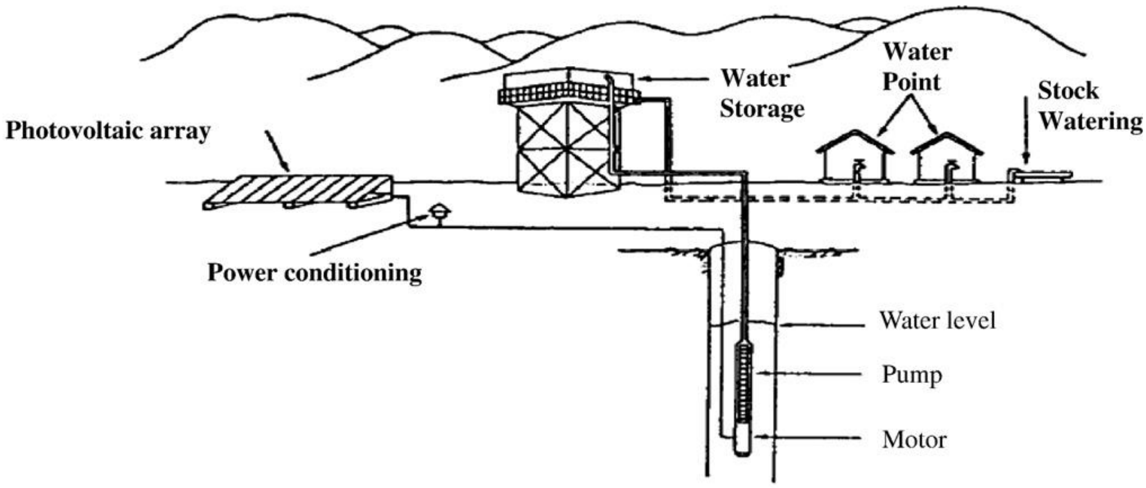

Figure 2.1 Typical PV water pumping scheme with water storage (Ramos & Ramos, 2009)

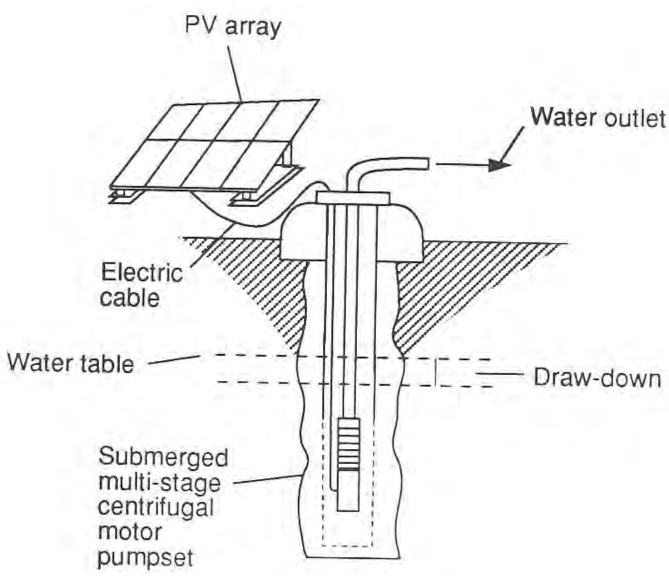

Figure 2.2 Submerged multistage centrifugal pump design (Practical Action, 2012)

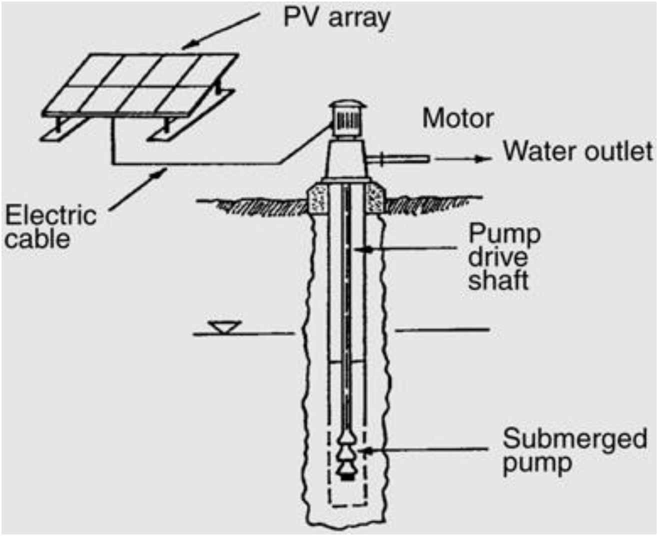

Figure 2.3 Submerged Pump with surface mounted motor (Practical Action, 2012)

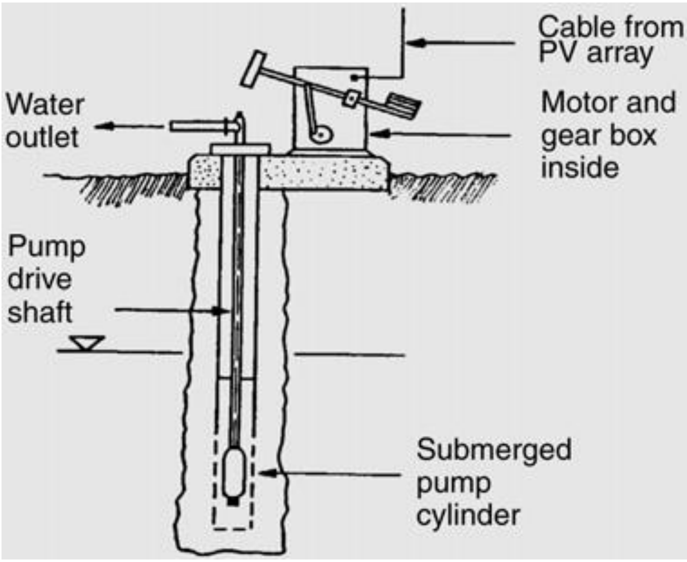

Figure 2.4 Reciprocating positive displacement pump (Markvart, 2006)

2.3.3 Wind Pumps

With regards wind pumps, they can be broadly separated into two categories; Mechanical Wind Pumping Systems (MWPS) where the blade turning kinetic energy of the windmill is used directly, via either a crank shaft or gears, to pump water and Wind Energy Converting Systems (WECS) where the wind mill is used to generate electricity and then used to power an electric powered water pump (Badran, 2003). For the purposes of this study and due to the simpler technology, and therefore more applicable in rural environments, as well as requiring lower maintenance than diesel powered pumps, only

MWPS will be investigated. The primary advantages of wind power over traditional fossil fuels, similar to those for solar power, are the fact that wind is freely available, non-polluting, and relatively easily implementable in rural off-grid applications (Jagadeesh, 2000).

MWPS are essentially comprised of three elements: the rotor (windmill blades) situated at the top of the structure which rotates as the wind blows over them; this horizontal rotation creates a torque which then turns a crank shaft or gear set; this crank shaft or gear set in turn operates a, usually, positive displacement piston pump which is usually a cylinder type system where water fills a piston case, submerged in water, on its down stroke and is then forced up the pipe on the up stroke through the pipe into a storage unit (Omer, 2000).

Essentially two forces cause the horizontal rotation of the rotors; drag and or lift. Drag is caused by the direct force of the wind and acts in the same direction as the wind, lift is caused by the pressure differential caused by the turbine blades “stopping” the wind in front of the rotor thereby increasing the pressure in front of the rotor, and this force acts perpendicular to the wind direction (Smulders, 1976). This is highlighted in more detail in Figure 2.5 with F_D being drag force, F_L being lift force with F_N, F_T and F_R being the subsequent tangential, normal and resultant forces of the rotor. V1 is the wind velocity.

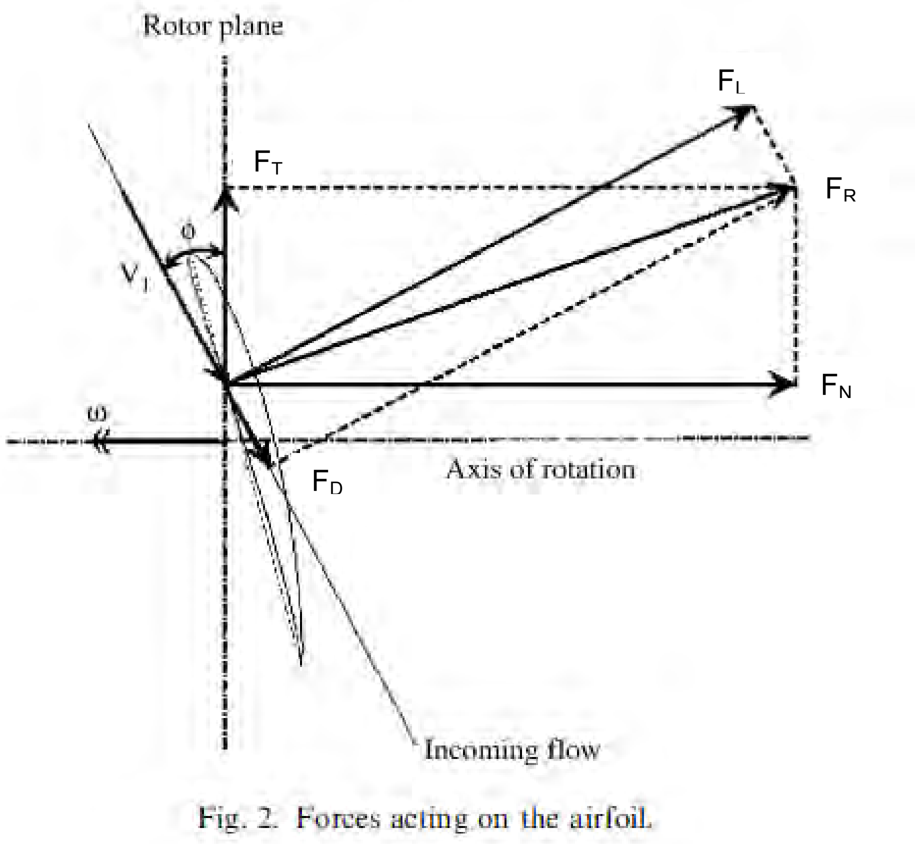

Figure 2.5 Image indicating resultant forces acting on a windmill blade (Lanzafame & Messina, 2007)

The power of a MWPS is proportional to the square of the rotor diameter and the cube of the wind speed perpendicular to the rotor (Harries, 2002). The theoretically available power can be derived as follows:

Using the kinetic energy formula

KE(v) = 0.5mv2 **Equation 2.2**

where m is mass of the wind acting on the rotor and V its speed and therefore the power in terms of v as

$P(v) = 0.5mv^2$ **Equation 2.3**

And mass flow rate of the wind

$m_w = \rho Av$ **Equation 2.4**

(Kahwaji, 2012) where ρ is the density of the air.

Combining these two equations results in

$P_w = 0.5\ \rho A v^3$ **Equation 2.5**

For wind to continue flowing however, conserving the conservation of momentum equation, the wind speed cannot be reduced to 0 on the leeward side of the rotor as there would then be no flow of air and subsequently no power generated. If we make inlet velocity = V_i and output velocity = V_o, the mass flow rate is approximately

= $\rho A V_{ave}$ where

average velocity, $V_{ave} = V_i + V_o / 2$ **Equation 2.6**

and the power recovered = rate of change in the kinetic energy:

$P_{out} = m_W (V_i^2 - V_o^2)/2 = (\rho A/4)(V_i + V_o)(V_i^2 - V_o^2) = (P_w/2)(1+x-x^2-x^3)$ **Equation 2.7**

where $x = V_o / V_i$. Differentiating P with respect to x and setting it to 0 in order to determine optimum value of x for maximum power output:

$dp/dx = 0 = 1-2x-3x^2$ **Equation 2.8**

and solving results in x or $V_o / V_i = 1/3$. Substituting this into Equation 2.7 results in 16/27 P_w (Bansal et al, 2001). This value, 16/27,is referred to as the Betz efficiency and applies to any type of wind power (Omer, 2008). The total actual power produced by the windmill will diminish dependant on the turbine efficiency of the system used, usually denoted as $A\eta$ (Da Rosa, 2009).

Pump power is relative only to the effective, or swept, area of the rotor blades, i.e. the area covered by the rotor blades during a rotation and not the area of actual blade material. The ratio of the material area to the swept area is referred to as solidity. This is important as the greater area of blade material results in a larger torque being created, but at a lower speed, which is better suited to MWPS as the torque is used directly by the reciprocating pump and can assist in the lift of water (Da Rosa, 2009). This can be illustrated using the blade element momentum (BEM) theory and experimental data from different turbine types illustrated in Figure 2.5. This figure compares a high solidity turbine, such as those used for water pumping, A with a typical electricity generation one B with

$\lambda = \Omega r/v$ and $\Omega = 2\pi n$ where Ω = angular velocity and n = shaft frequency, r the radius and v the velocity.

Using a base case of wind velocity = 10 m/s and rotor radius of 5m:

In the case of high solidity rotor A where for a torque co-efficient, Cm of 0.15, λ ≈ 1.8 with subsequent shaft frequency = 0.57 s^{-1}

In the case of the lower solidity rotor C where for a Cm of 0.15, λ ≈ 2.2 with subsequent shaft frequency = 0.7 s^{-1}

The theoretical power of both of these turbines

= 16/27 x 0.5 x 78.5m^2 1.25 kg/m^3 x 10^3 m/s **Equation 2.9**

= 29 074 watts

This therefore illustrates how for the same power and at the same wind speed, a higher solidity rotor such as those used for water pumping, produces a higher torque at lower speeds and is therefore ideally suited for MWPS.

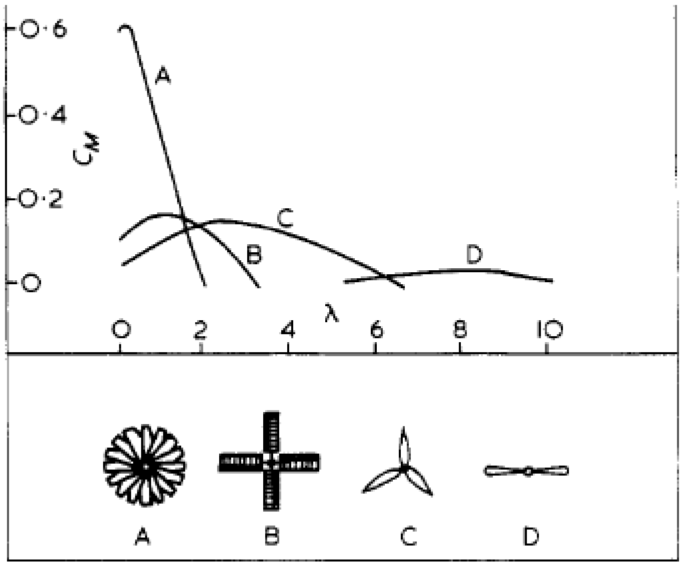

Figure 2.6 Illustration of the relationship between tip-speed ratio λ and torque co-efficient Cm (Smulders, 1976)

An option other than the use of the conventional crank and positive displacement piston design is to use roto-dynamic pumps which instead of driving a reciprocating piston directly, uses a series of gears to power a centrifugal pump. This results in better matching of the power provided by the rotor (proportional to the cube of the wind speed) to the linear increase in power associated with an increase in rotor speed for a reciprocating type pump system. The increase in efficiencies have been shown to be appreciable with more than double the amount of water volume being pumped by roto-dynamic pumps over reciprocating pumps when pumping at low heads (Mathew and Pandey, 2003). However, the increase in complexity with associated increased costs and needs for maintenance associated with roto-dynamic pumps makes them infeasible for use in rural Elundini and will not be considered in the analyses.

2.3.4 Maximum Power Point Tracker (MPPT)

A MPPT essentially matches the electrical power generated by a source, i.e. solar panels, with the power required by the actual pumping system (Odeh et al, 2005). As the wind pumping technologies looked at in this study will only be mechanical and not involve conversion into electricity, MPPT will only be considered for the use with solar PV pumping. The variability in the amount of energy available from renewable energy sources, in this case insolation levels, often results in a scenario where the particular power output from the solar panels does not match those required by the pump sized for the task (Markvart, 2000). This results either in the pump not even operating during times of low insolation (morning and evenings or cloudier days) as the power generated during these times is incapable of powering the pump motor as the power supplied cannot overcome the static friction of the motor (Short and Mueller, 2002). This maximum power point tracking is usually done via a DC-DC converter which absorbs power from the PV array at a fixed voltage and current and then outputs this at an optimal voltage that matches that of the pump system (Skretas et al, 2007; Ramos and Ramos, 2009; Oi, 2005). As Markvart (2000) illustrates,

$$V_R = \sqrt{P_{max}R} \qquad \textbf{Equation 2.10}$$

where V_R is the voltage of the resistive load, R of the pump motor in this case.

Oi (2005) in his study of the subject concluded that the use of a DC-DC MPPT, due to increased system efficiency as well as increased pumping times, resulted in an overall system performance increase (in terms of total volume of water pumped) of 67% when using a 90% efficient DC-DC MPPT. However, Firatoglu and Yesilata (2004) suggest that the use of an MPPT is not advantageous over a directly coupled system (where PV panel is connected directly to the pump with no MPPT) as the use of an MPPT introduces a further electronic device that may be subject to malfunction and require subsequent repair and maintenance. They suggest rather that the system be designed using very site specific and complex calculations, as well as changing the tilt of angle of the solar array, if not through automatic means, at least manually on a monthly basis in order to design an efficient solar PV pumping system (Firatoglu and Yesilata, 2004).

Although Short and Oldach (2003) in their study cite several reliability problems with MPPT's, predominantly attributable to ill-prepared design and implementation for developing world rural regions (heat and moisture, insect damage as well as inadequate lightning protection) and quoting failure rates in the region of 18%, the use of a MPPTs is generally recommended and seen as beneficial to the overall efficiency and efficacy of the PVP systems. This is especially true for systems with arrays of 1kWp and larger, primarily due to their simplicity and negligible increase in capital cost to the system (Ramos and Ramos, 2009; Oi, 2005; Markvart, 2000). This difference in perceptions and respective conclusions of studies could be attributable to advancements in technology in recent years. It must also be noted that instead of an MPPT, a battery can be used to regulate the I-V characteristics of the system and also ensure maximum power is delivered to the pump, this will also have the added benefit of an energy source for simple electrification and lighting in a village (Short and Oldach, 2003). This will however not be looked at in this study, as only PVP systems utilizing water and not battery storage, as discussed in Section 2.3.2 will be considered.

2.4 Natural Resource Potential of the Elundini Municipality in the Powering of Water Pumping Technology

The potential of any renewable energy technology is obviously highly dependent on the natural energy resource that is to be used, in this case wind and sun. Regardless of how efficient or easily implementable a given technology may be, the strength/availability of the natural resource (essentially the fuel) will have a significant impact on the cost-effectiveness and efficacy of the given technology (Odeh et al, 2006). Nestled in the foothills of the Southern Drakensberg and border of Lesotho, the Elundini region is situated on South Africa’s escarpment and therefore has climatic conditions consistent with predominantly the cold and to a lesser extent, the temperate interior. The region experiences large temperature fluctuations between average winter maximums of 11^{0}C to average summer maximums of 42^{0}C, an average of 150 frost days in the year with winter snow in the higher lying areas and Maclear. Average rainfall in the area is between 600 and 800 mm per year (Elundini Integrated Development Plan, 2011).

2.4.1 Wind Power Potential in the Elundini Municipality

“The successful exploitation of wind energy is highly site specific and largely depends on the wind resources of the area being exploited” (Harries, 2002:1). This important fact regarding, not only for wind energy but renewable energy in general, forms one of the major objectives of this research as a new water pumping technology cannot be recommended for a location, regardless of its efficiency and effectiveness, if it cannot be implemented due to unfavourable natural conditions.

Wind pumps can operate from wind speeds as low as 2 m/s although generally 3 m/s is required to be effective (Karekezi & Ranja, 1997). The South African national energy development institute (SANEDI) in collaboration with the South African weather service (SAWS), UCT and Riso DTU have recently published a numerical wind atlas for South Africa. Using 10 wind measurement masts covering the Western, South Western and South Eastern Cape coastlines extending up to almost 300 kilometres inland in places, a mesoscale map indicating average wind speeds at 10 metres above ground level has been created. Although there are not enough wind atlas measurement points across the Elundini municipality to determine accurate wind speeds, there are points within 5km of some of the selected boreholes, with indications that these sites receive average wind speeds in excess of 3m/s. There is also strong evidence from other sources such as Diabi's wind atlas for South Africa (Diabi, 1995 as quoted by Szewczuk, 2010) as well as Hageman's wind atlas (Hageman, 2009) that indicate wind speeds of around 4 m/s for the region. Although further investigation will need to be done, this makes them potentially viable locations for effective wind pump implementation and justifies further investigation.

Average or mean wind speeds, although a good guide and indicator of a wind pump's potential are not sufficient to accurately calculate the power potential of a site for wind pumping. This is due to the fact that the potential power of a wind pump is relative to the cube of the wind speed, as discussed in Section 2.3.3. For instance a site which over a 10 day period has a constant wind speed of 10m/s i.e. mean wind speed of 10m/s carries wind energy proportional to 10^3 = 1 000 which over 10 days is 10 000. A site where over a 10 day period the wind only blows every second day but at 20 m/s also has an average wind speed of 10 m/s over the same period, the energy however is proportional to 20^3 = 8 000 X 5 days = 40 000 (Da Rosa, 2009). Most wind pump manufacturers however specify their systems based on average wind speeds for a location; having used assumptions with regards maximum wind speeds and duration (Southern Cross, 2013).

Another important consideration to be taken into account regarding wind resource evaluation when using wind atlases and general wind data for an area is the topography of the land, which may have a marked effect on wind speeds for the specific site location (Badran, 2003). Topographical features which may cause increased localised wind speeds include: gaps, passes and gorges in areas of frequent strong pressure gradients; long valleys extending down from mountain ranges; plains and plateaus at high elevations; plains and valleys with persistent down slope winds associated with strong pressure gradients; exposed ridges and mountain summits in areas of strong upper-air winds; exposed coastal sites in areas of strong upper-air winds or strong thermal pressure gradients (Omer, 2008). Omer (2008) also notes features which may cause lower speeds to include: valleys perpendicular to the prevailing wind; sheltered basins; short and/or narrow valleys and canyons; areas of high surface roughness (e.g., forested hilly terrain). The surface roughness effect of the terrain on wind speeds is often negated, at least to some extent, by the rotor placement of wind turbines being high off the ground (Harries, 2002).

When assessing the wind power potential of a certain site, it is also vital to establish the frequency distribution of wind speed due to the fact, as mentioned in Section 2.3.3, that even if the average wind speed for a location is sufficient, wind pumps have cut-in and cut-out wind speeds below and above which they will not operate (Mathew & Pandey, 2003). The total time that the wind is blowing at a speed between these two speeds is therefore the amount of time available for operation of the wind pump. In order to determine this, one needs to analyse the wind-speed frequency distribution for the site under consideration. One of the most commonly used statistical methods for wind data analysis is the Weibull distribution function illustrated in Equation 2.11 (Bansal et al, 2002)

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp - \left[\left(\frac{V}{c}\right)^{k}\right]$$ **Equation 2.11**

where V is the wind speed, k is the Weibull shape factor and c is the Weibull scale factor (Mathew et al, 2002).

In order to determine k and c, long periods of wind data measurements are required. If only the average wind speed for a site is known, the Weibull distribution can be estimated by using a shape factor of 2, which is known as the Rayleigh distribution and has shown to estimate actual wind-speed frequency distributions for the site fairly accurately (Seguro & Lambert, 2000).

An effective means in determining the wind power potential of a particular site using a specific wind turbine is through the use of wind power curves which illustrate what power can be derived from a turbine for a specific wind speed, as well as the cut-in and cut-out wind speed for the turbine. This is illustrated in **Error! Reference source not found.**.

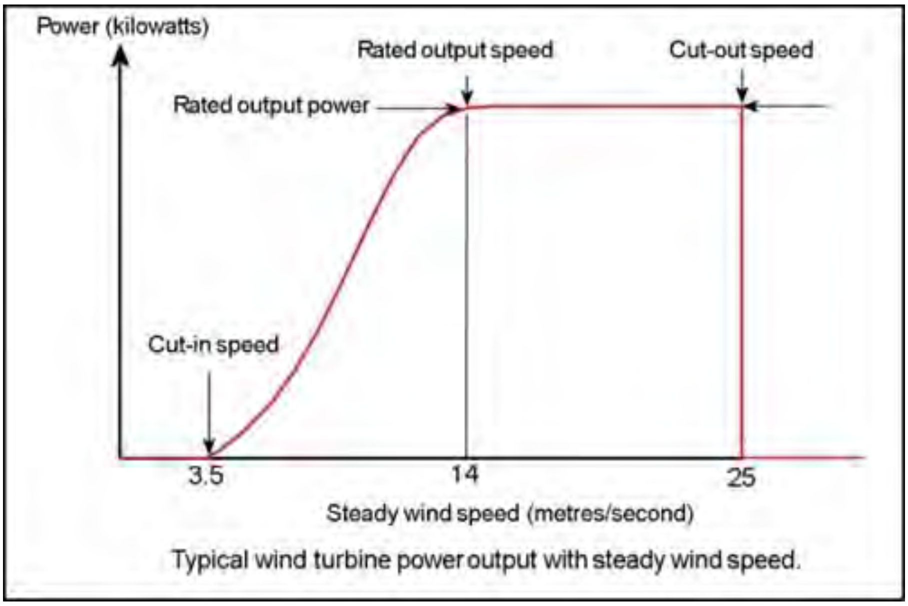

Figure 2.7 Example of a wind power curve (Pelaflow Consulting, 2011)

2.4.2 Solar Power

The amount of energy provided by the sun, the solar radiation or insolation, is made up of two components; Direct Normal Insolation (DNI) which is solar radiation received from the sun without having been scattered by the atmosphere and Diffuse Horizontal Insolation (DHI) which is the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere (Duffie & Beckman, 2006). On clear days the largest proportion of the total insolation or Global Horizontal Insolation (GHI), which effectively is the total insolation received by any horizontal surface, is provided by DNI and on cloudier days by DHI (SECO, 2012). The DNI levels striking the panel are proportional to the cosine of the angle between the sun's rays and the orientation of the panel, hence larger levels of total insolation is captured by the panel the more directly the panel faces the sun. In order to gain maximum efficiency, panels are therefore orientated, as far as is practically possible, directly facing the sun. This can be achieved by using solar tracking devices that change the angle of the panel to track the position of the sun's rays throughout the day. The increase in insolation levels relative to the cost of the trackers however, may not make their use feasible for small scale installations, such as those proposed for Elundini, due to increased cost and the usage of moving parts which would be subject to malfunction and the need for servicing and repair (Oi, 2005). Alternatively the panels can be fixed facing the equator (i.e. North or South dependant on hemisphere) at an angle approximately equal to their latitude. This ensures that they attain the maximum amount of DNI possible over the year when fixed. The solar radiation levels used for the rest of this study will be those received by a surface tilted towards the equator, as it is assumed that installations in Elundini would be done in this way. These radiation levels are referred to as global tilt insolation (GTI) levels and in the Elundini municipality would refer to a tilt angle of approximately 31^0 facing North. These concepts are further illustrated by Figure 2.8.

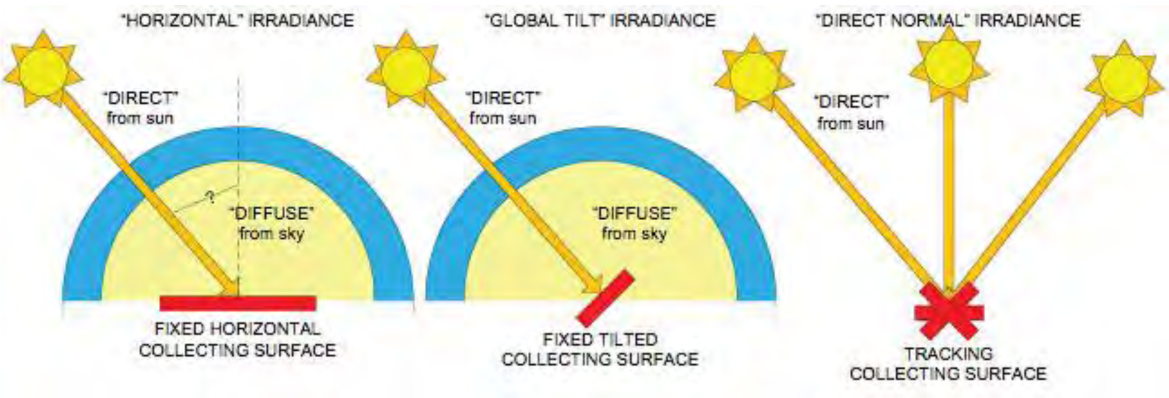

Figure 2.8 Graphic illustrating Horizontal, Direct normal and Global tilt irradiance levels (SECO, 2012).

PVP systems have been seen to be cost effective (dependent on water demand, comparative fuel costs etc.) at solar radiation levels as low as 10.08 MJ/m2, but generally around 15 MJ/m2 with very good results from areas with insolation levels of 21.6 MJ/m^2 (Odeh et al, 2006). As can be seen from the solar map in **Error! Reference source not found.**, solar radiation levels across the Elundini municipality range from 17.35 to 19.14 MJ/m^2 (Geomodel Solar, 2011) making this area potentially viable for the use of PVP systems. This is further supported by the National Renewable Energy Labs (NREL) solar radiation map for South Africa, indicating solar radiation levels of up to 21.6 MJ/m2 per day (NREL, 2012).

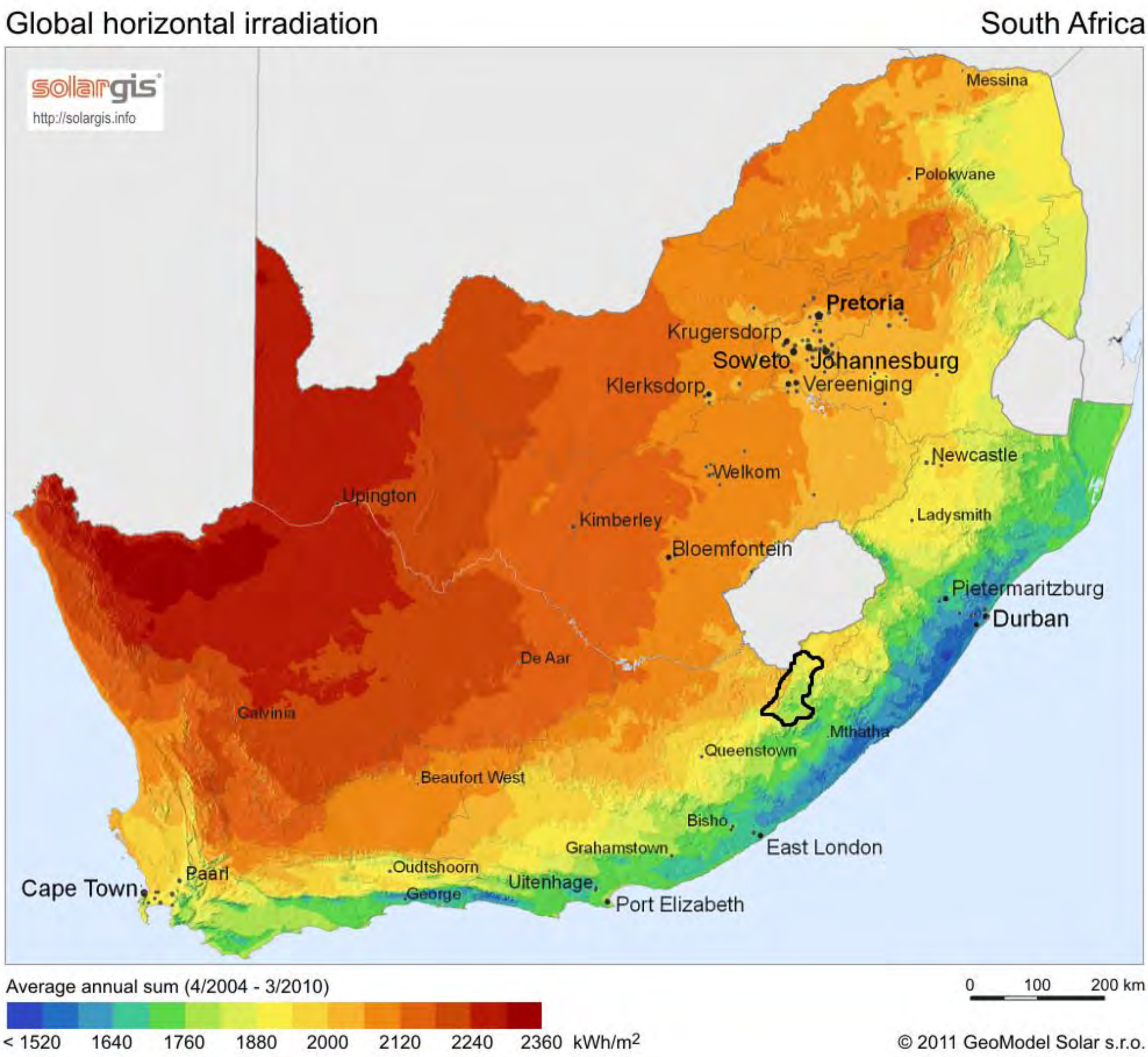

Figure 2.9 South Africa solar map with Elundini municipality illustrated.

2.5 Technology Costs

The capital, maintenance and fuel costs for each of the supply technologies from previous studies are presented below.

2.5.1 Capital costs

Regarding the cost of purchasing the various power generating equipment options available, diesel generators have a clear advantage, and likely why they have been the preferred option for so long. This point is illustrated by the Solar Electric Light Fund (SELF, 2008) who in their study compared diesel powered pumps with a cost of USD 2 000 with an SPV powered option costing USD 12 300. Similarly Karekezi & Ranja (1997) compared a diesel generator with a cost of USD 6 000 and a wind pump with a cost USD 10 000. Although it is not clear exactly what the pump types for each technology were used in these studies, the comparisons were done between pumping systems with a similar water supply potential. Although not comprehensive, these two studies, both supporting the use of renewable energy options, highlight well the fact that in terms of capital costs, diesel generators are cheaper. For example, in 2006 Rands, a diesel powered pump required to pump water at a rate of 12m^3/day to a head of 60m costs R39 604 compared to a PVP equivalent which would cost R76 487 (Emcon, 2006).

The high capital costs associated with SPV pumps is extremely well documented (Ghonheim, 2006; Odeh et al, 2006; Ramos and Ramos, 2009; Skretas and Papadopoulos, 2008) with the actual SPV panels themselves making up 50-75% of the total system costs (Meah et al, 2008). This is obviously hugely inhibiting for poor, rural communities such as those in the Elundini municipality and one of the major reasons why these kinds of systems have not been rolled out on a large scale (Karekezi and Khityoma, 2002). This again highlights the need for correct system sizing when designing a PVP.

Further evidence of the high initial capital costs associated with wind pumps, compared with their diesel counterparts is illustrated by the studies of, amongst others; Jagadeesh (2000), Badran (2003) and Harries (2002). This is largely due to the amount of extra material required with a wind pump, i.e. windmill blades, support structure and mechanical pumping mechanism, costs which cannot be avoided. These costs can be lowered however via the use of locally manufactured materials, thereby avoiding import duties and exchange rate discrepancies from developed countries where most of their manufacture occurs (Badran, 2003).

2.5.2 Maintenance costs

SELF (2009) have derived a maintenance cost for diesel generators of USD 4 854 and for solar pumps of USD 335 per year, thus highlighting one of the major benefits of solar PV pumps i.e. low maintenance costs. In the case of wind pumps, Karekezi & Ranja (1997) compare an annual maintenance cost of USD 250 for diesel generators with USD 100 for wind pumps, likewise illustrating renewable energy's advantage in this area. Odeh et al (2006) in their study of the subject determine differences in maintenance costs of between USD 600 – USD 900 per year for existing PV systems and USD 5 250 – USD 5 480 per year for equivalent sized diesel powered pumping systems based on actual prices in Jordan.

2.5.3 Fuel costs

Although estimations of total fuel cost/usage for diesel powered generators vary considerably, depending on type of generator, size, head and quantity of water pumped as well as the loading of the pump, the fuel costs of both SPV and wind pumps is zero. This naturally gives renewables a large economic advantage over diesel. Along with no fuel cost, the other benefit of using wind and the sun as a fuel source is that, particularly if sites are designed correctly, one is not subject to the price fluctuations and unreliable fuel supply associated with fossil fuels such as diesel (Odeh et al, 2006). This essentially takes a guess element out of life cycle system costing for renewable options. One cannot accurately predict what diesel fuel prices will be in the future, although they will more than likely increase (Meah et al, 2008), however the majority of the costs associated with solar and wind powered pumps lie with the initial costs (Oi, 2005) and hence one can budget more accurately and not run into surprise costs at a later stage which may potentially hinder the effective operation of the project. Not only is the cost a potential inhibiter, but the mere sourcing and supply of the fuel in the future cannot be certain for many developing nations, highlighted by the fact that Rwanda has experienced 3 nationwide fuel shortages within an 18 month period in the past 5 years (SELF, 2008). A further cost regarding fuel is the cost of transporting it to the site, which can be an appreciable factor in sparsely populated rural environments such as that of Elundini (Emcon, 2006). At the time of writing, the cost of diesel in the Elundini municipality was R14.11 (DOE, 2014).

2.6 Previous Studies of Life Cycle Costs

As part of the determination of the most appropriate technology to be used for water pumping in the Elundini municipality, a life cycle cost analysis was performed and analysed in the method and results section of this paper respectively, using appropriate costs applicable to South Africa and more specifically Elundini. There are several studies currently available however that have completed life cycle cost assessments between diesel and wind as well as diesel and solar highlighted in Table 2-1 and Table 2-2.

Table 2-1: Cost comparison between wind and diesel pumps in Sudan (Omer, 2008)

Cost comparison of diesel and wind pumps in Sudanese Dinar (S.D.)		
Specification	Diesel pump	Wind pump
Cost of borehole deep well	182,400	114,000
Cost of the system (purchased or fabricated in Sudan)	93,600	440,000
Cost of storage tank	—	420,000
Cost of annual fuel consumption	343,700	—
Cost of maintenance and repair	120,000	110,000
Total annual cost	1,582,100	1,084,000
Specific water pumping cost/S.D.	79/m3	54/m3

1 US$ = S.D. 250 (Sudanese Dinar), in January 2001.

Annual output 15,000–20,000m3 of water.

Annual fuel consumption: 490 gal (1 imperial gallon = 4.55 l) at price S.D. 475/gallon.

The cost comparison in Table 2-1 was done between a 35-40m deep borehole operated by a 13.3 kW diesel powered pump and a 25-30m deep borehole powered by a CED 5000 wind pump with a 5m diameter rotor (Omer, 2008).

Table 2-2: Cost comparison between Diesel and Solar PV pumps (Odeh et al, 2006)

Scenarios	**Systems**			
	Cost (US$/1 000 m^4)		**Change over base case (%)**	
	PV	**Diesel**	**PV**	**Diesel**
Case A (base)	4.18	7.51	0.0	0.0
Case B at +50%	5.57	7.97	+33.25	+6.13
Case C at -50%	3.14	7.04	-24.88	-6.26
Case D at +50%	2.79	5.0	-33.25	-33.42
Case E at -50%	8.36	15.02	+100	+100
Case F at +100%	4.70	7.65	+12.44	+1.86
Case G at -100%	3.27	7.37	-21.77	-1.86
Case H at +50%	4.68	10.78	+11.96	+43.54
Case I at -50%	3.69	4.23	-11.72	-43.68

In Table 2-2, an existing 4.5 kW PV pumping system in Jordan was analysed and compared against an equivalent notional diesel pumping option with several different cases illustrating sensitivity to changes to the systems' capital costs (B+C), system productivity of SPV (D+E), interest rate (F+G) and operating costs. In all these cases, the solar PV systems display a lower cost per m^4 (volume X head) pumped. It is stated however that this result is very sensitive to the head pumped and is also site specific (Odeh et al, 2006).

There are several other studies such as these showing very similar results, i.e. that over its lifetime, a solar PV system is more economical than a similar sized diesel one but that it is highly dependent on pumping head, insolation and size of the system - generally under 10kW (Ghonheim, 2006; Ramos & Ramos, 2009; Emcon, 2006).

2.7 Maintenance

There are several studies attesting to diesel powered pumps' needs for continuing servicing and maintenance, as well their subsequent high failure rates in rural environments (Mahmoud, 1990; Oi, 2005; Omer, 2001; Meah et al, 2008). Firstly, diesel generators require someone to turn them on and off each day and are only recommended to run for 8 hours at a time (Ghonheim, 2006) and according to Meah et al (2008) diesel generators require constant re-fuelling and daily checking whereas SPV pumps only require to be inspected once a week and even then do not require any appreciable levels of maintenance unless something has malfunctioned. This is further reinforced by the study done by the SELF (2008) who discuss the difficulty in diesel generator maintenance finding that "diesel engines lie rusting and unused by the thousands and solar pumps sometimes run for years without anyone touching them" (SELF, 2008:1).

Although diesel generators offer a lower capital cost, they require regular, skilled maintenance, attention and refuelling which can often not be sufficiently provided in isolated, rural, poor areas, such as those found in the Elundini municipality (Omer, 2001). This often results in their eventual failings, leading to under or non-supply of water to the villages in which they have been installed.

Traditional wind powered water pumping systems, such as the steel ones common on many farms in South Africa, are also often found to malfunction due to lack of maintenance and servicing due to the many mechanical and specialised parts required for their effective operation (Oi, 2005). Modern and simpler designs however seem to be a lot more reliable and require less maintenance and have higher reliability than similarly sized diesel options with claims that with good maintenance they can operate largely unaffected for 40 years (Badran, 2003). Harries (2002) in their study also highlight this advantage that wind powered pumps have over their diesel counterparts for implementation in rural Kenya. Difficulties with supply and transportation of fuel to diesel generators is also cited as a disadvantage that this technology has when compared with wind.

PVP's are characterised by low levels of maintenance due to fewer moving parts and a simpler design with maintenance intervals ranging from one to five years (Emcon, 2006). There are also several other studies attesting to the simplicity and reliability of SPV systems with their subsequent low levels of required maintenance such as the studies by Mahmoud (1990) and Odeh et al (2006) to name a few. These low levels of maintenance and high reliability, when compared with diesel pumps, is attributable to their simplistic design and currently mature technology with Ramos and Ramos (2009) citing maintenance intervals of only 3-5 years for PV pumps. This is an appreciably better scenario than that for diesel powered pumps which require monthly maintenance (Emcon, 2006). Although several reports of solar PV pump failures have been documented, the most common cause of these malfunctions have been with the actual pumps and not the solar system itself, essentially inferring that the malfunction would have occurred regardless of the power source (Meah et al, 2006).

Although the above literature has dealt with maintenance periods and subsequent costs in depth, another factor regarding maintenance that needs to be carefully considered is the type of maintenance and the practicality of it in a rural environment where spare parts may be difficult to source and transport to site and necessary skills to undertake the maintenance may be scarce. From the literature researched, it is apparent that the most skilled and specialist maintenance needs lie with diesel generators (Harries, 2002; Practical Action, 2010; Ramos, 2009).

Wind pumps, although not requiring the same regular maintenance that diesel pumps do, older technology windmills did have complex pumping systems requiring some specialist knowledge and replacement parts (Ziter, 2009). New wind pump designs however utilize a direct shaft system negating the need for gears and simplifying repairs and subsequent skill levels (Badran, 2003). An added hindrance of wind power however is the need to ascend 12+ metres when attending to the rotor which not every repairman or village inhabitant is willing to do (Harries, 2002).

SPV repairs and maintenance, through several sources claim to require a low level of skill for the majority of repairs, with most of the required skills easily transferrable onto the local inhabitants of the village containing the pump (Meah et al, 2008; Ramos, 2009). This raises another important consideration for the implementation of any new technology into a community, that being the human element.

2.8 Societal Integration

As with so many interventions involving the deployment of a new technology or project aimed at improving peoples' lives in a community; ownership, involvement and acceptance by the inhabitants is imperative to its success (Short and Thompson, 2006). There are countless cases of installed infrastructure found non-operational after implementation with the most common reason for this being a lack of community ownership, without which, maintenance requirements will be ignored and the systems will ultimately fail (Short and Oldach, 2003). Successful implementation and sustainability of a technology requires a high degree of village level operation and maintenance which

Tyndale-Briscoe and McMurdie (2000) suggest relies heavily on ease of use and maintenance, durability and the cost and availability of spare parts.

One of the major problems associated with the dissemination of solar powered technology in rural, generally poorer, areas is theft, primarily of the panels but also of batteries where they form part of the installed system (Ramos & Ramos, 2009; Emcon, 2006). This can be a problem whether ownership of the systems has been successfully imbued onto village inhabitants or not and in its mitigation, several initiatives can be pursued, such as guarding or fencing of the systems. These measures all however add to overall system costs and to the operation and maintenance of the systems (Meah et al, 2008).

Although vitally important, one cannot only look at the technological aspects of a system-ensuring optimal operation at a reduced cost and expect it to work, which is a very developed world mind-set (Short and Thompson, 2003). Of equally, if not greater importance, is the acceptance of a technology by the inhabitants it is supposed to be benefitting and its subsequent impact on the various sociological aspects (Short & Oldach, 2003).

2.9 Preliminary Conclusions

From various studies, from regions similar to those in the rural areas of the Elundini Municipality (Badran, 2003; Odeh et al, 2006; Emcon, 2006), it is clear that renewable powered options can offer an attractive option when it comes to the supply of water in rural environments (Badran, 2003; Odeh et al, 2006; Emcon, 2006.) This is for several reasons; the maintenance costs are greatly reduced when comparing wind and solar to diesel, as illustrated in 2.5.2 above, there is no concern with regards security of energy supply (provided the system is correctly sized and designed for the prevailing weather and solar radiation conditions of the area) and the subsequent lifecycle costs associated with them are lower (Emcon, 2006 and Badran, 2003). In terms of their impacts on inhabitants and the environment in general, renewables also tend to have an advantage in that they cause less noise and air pollution, contribute less to climate change and are inherently more reliable than the diesel alternatives, which all helps contribute to sustainable rural development (Ramos & Ramos, 2009).

The fact that diesel powered pumps are more widely used in Elundini is likely due to the lower up-front costs of diesel when compared to renewable options, the making a choice of technology based on this fact is not particularly wise if it results in the choice of a technology which cannot be maintained due to a lack of funds to keep up maintenance and fuel costs and therefore more expensive and more poorly maintained over their lifetime (Mahmoud, 1990). These systems have also been in operation in the area for some time and when chosen may have been appreciably cheaper and better understood than SPV's as these would not yet have been a mature technology.

From this preliminary research it can be seen that in terms of ground source water pumping (such as from boreholes) the renewable energy options of wind and solar PV powered pumps can, and do, offer a cheaper (over their lifetime), more reliable alternative to their diesel counterparts. This is however largely dependent on the local climatic conditions and supply requirements such pumping head and water volume, and therefore requires further, site-specific investigation (Argaw et al, 2003).

3 METHOD

The method outlined below aims to illustrate how the potential of each of the respective pumping technologies, namely diesel, wind and solar, in providing water for rural villages in Elundini will be assessed. It covers topics ranging from the research design and instruments used, to the limitations of this chosen methodology and the ethical issues taken into consideration.

3.1 Introduction

In order to determine the applicability of using renewable energy, such as solar and wind power, in providing water to the rural inhabitants of the Elundini municipality, over and above a review of relevant literature of what had been done previously, it was also necessary to conduct specific research into the study area. The methodology outlined below aims to determine the theoretical suitability of using renewable energy powered water pumps to provide water to several different rural villages in the study area. Essentially, water pumping systems using renewable energy (wind and solar) was designed for a sample of villages and their suitability compared to diesel pump systems across a range of criteria, namely: technical, economic and social. This range of criteria required a wide range of data capturing techniques and included interviews, calculations and secondary data review.

Currently, most of the water supplied to rural inhabitants in the Elundini municipality is ground sourced and pumped using diesel powered generators (Ngceba, 2011). This has been the case for many years now and seems to be the status quo for the region. It was not apparent from the author's site visit why this was the case with negligible use of wind, and no PV pumps in operation. However, the length of time they had existed and a lack of knowledge of other available technologies and higher up-front costs of them appeared to be the most likely reason. With regards to pumping groundwater from boreholes, underground springs and the like in rural regions with little or no access to grid-tied electricity, such as that of the Elundini municipality; the options generally are fossil fuel (diesel) powered, solar PV powered and wind pumps. Hand pumps and "play" pumps can also be used, although not investigated here due to the autonomy they lack, as one of the benefits of an improved water supply system is that inhabitants will spend less time sourcing water for survival and can rather use this time for more economically beneficial tasks instead.

In order to compare these technologies and determine the efficacy of renewable energy options, this study critically analysed each of these against a range of criteria. A range of criteria, covering social, economic and technical aspects was considered; as projects such as these involving the introduction of a new technology into an environment which has changed very little in recent years cannot be looked at purely from an isolated, technical perspective. There are several factors such as the sociological and economic needs of the end user that have been overlooked in previous projects disseminating renewable energy powered technologies, which although technically feasible, have failed due to this oversight (Short & Thompson, 2003). Having said this, first and foremost, a technology must work effectively before one can even consider its roll-out, as a water pump which doesn't pump water effectively, helps no-one.

3.2 Village Sample

In order to make an assessment of renewable energy potential on the ground, a sample of villages was chosen in order to test theoretical applicability of renewable energy options as an alternative to diesel powered ones. Although a representative sample was desired for the assessment, taking into account the widespread nature of the villages, a lack of reliable available data ultimately determined which villages and boreholes formed the sample. The final sample analysed did cover a large portion of the villages over a wide range of the conditions relevant to the design of the systems (water depth, population and topography). Of the approximately 100 rural villages within the study area that are currently provided water through diesel powered pumps, 27 had sufficient information to be assessed and represented a wide range of conditions. The sample of villages and their distribution is shown in Figure 3.1 with the details of each of the assessed villages presented in Table 3-1.

Although only 27 villages were ultimately chosen, based on those with the most available data and representing a wide range of conditions, during the analysis using the GMS toolkit, described in Section 3.5.1.1, all the village borehole data that was available (approximately 60 boreholes) with their respective estimated abstraction rates, were used in the modelling to determine drawdown. This was done as the modelling tool takes into consideration any abstraction occurring in the vicinity of the focus area in order to determine more accurate water availability and subsequent draw down values.

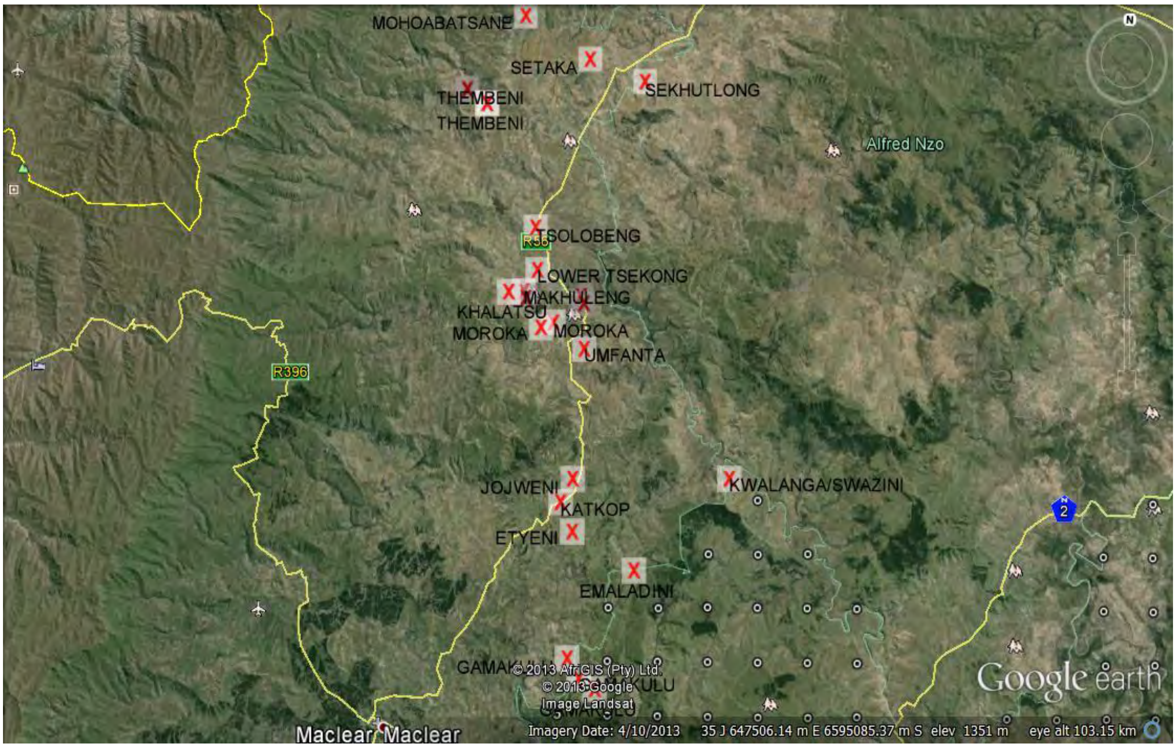

Figure 3.1 Distribution of village sample (Google Earth, 2013)

Table 3-1: Details of village sample used in study (Sintech, 2012).

VILLAGE NO	WARD NO.	NAME	LOCATION		Diesel/m³ water pumped	Current Water pppd (l)	POPULATION	LENGTH OF PIPES (m)
			Lat	Long				
265	7	Mgcantsi	-30.828590	29.603370			90	7 645
258	7	Gamakulu	-31.006690	28.541670			186	3 405
308	8	Kwalanga	-30.846667	28.697222			228	3 944
318	7	Jojweni	-30.857840	28.533580			300	2800
200	11	Gobo	-30.533950	28.390910	0.33	22.91	396	2 133
253	7	Emaladini	-30.929440	28.604170			414	3 390
190	12	Polokoe	-30.519667	28.536667	0.51	17.12	516	5 135
40	12	Tabatlala	-30.514222	28.521000	0.23	9.30	576	3 185
257	16	Jojoweni	-30.857840	28.533580	1.41	2.13	630	3288
101	12	Moleko	-30.489566	28.537972	0.43	7.03	648	3 735
242	5	Hopedale	-31.170611	28.479500	0.69	15.48	750	7 413
153	8	Makhuleng	-30.703500	28.467380	0.63	5.22	786	2 512
210	12	Mohoabatsana A	-30.464950	28.446800			792	1 500
172	8	Makhalong	-30.747111	28.560472	0.53	21.20	822	1 779
39	16	Katkop	-30.878020	28.522800	0.48	6.59	864	5095
274-01	6	Upper Sinxako	-31.132250	28.593583		3.45	918	4 250
56	8	Khalatsu	-30.705110	28.451780	0.25	10.76	996	4 137
167	8	Umfanta	-30.748000	28.535500			1086	959
246	5	St Augustins	-31.229450	28.575550			1110	9 869
78	12	Setaka	-30.498050	28.518880	0.31	15.37	1128	2 450
274	6	Lower Sinxako	-31.126110	28.622770		2.32	1338	4 992
105	8	Sekoteng	-30.709380	28.531590			1410	4 470
104	8	Moroka	-30.732800	28.488320	0.37	4.56	1680	2 851
156	11	Thembeni	-30.544444	28.413056	0.43	3.91	1794	4 585
250-01	7	Etyeni	-30.901660	28.537220			1884	2684
189	10	Tsolobeng	-30.647830	28.474610	0.31	1.00	5226	2 554

3.3 System Design

First and foremost, the technical efficacy of renewable energy powered water pumping systems was compared with their diesel powered counterparts. This was done by analysing the sample of boreholes currently used to supply villages with water. The solar and wind powered systems, respectively, were designed to maintain minimum supply levels, prescribed as 25l per person per day as described in South Africa's department of water affairs and forestry (DWAF)'s white paper (DWAF, 2002), and then compared with equivalent sized diesel powered options. Currently the supply of water to the villages, according to the provided data, is generally erratic and overall far lower than this 25l per person per day (Sintech, 2012).

3.3.1 Minor system losses and friction head

Minor system losses are losses in the pressure/energy of the system due to various minor obstructions to flow such as bends in pipes, as well as orifices for exit and entry out of and into different parts of the system. These losses are caused due to eddy formation generated in the fluid and are generally calculated using the equation:

$$h_L = k_L V^2/2g \qquad \textbf{Equation 3.1}$$

where h_L is the local head loss and k_L is a constant for a specific fitting and often derived experimentally (Chadwick et al, 2004). As these losses make up a proportionately small part of the overall head requirements of the system in large pipe networks such as those for water supply schemes and are difficult to calculate for each and every particular bend in the pipes or orifice, they are estimated based on the total length of pipe in the water supply network of the system. The estimates for these local head losses are based proportionately from a study done by Ziter (2009) which presents K factors for a 1km long water supply pipe network and are presented in Table 3-2**Error! Reference source not found.** as follows:

Table 3-2: Summary of losses for 1km long water supply network (Ziter, 2009).

Loss	K
Sharp entrance	0.5
Open globe valve	5.7
90° bend	0.25
Screwed 90° elbow	0.64
Open gate valve	0.11
Sharp exit	1

ΣK =	**8.2**

Entrance and exit losses as well as those for the globe and gate valve will only be considered once for each system, however those for the bends will be multiplied by each kilometre of pipe used in the network.

Friction losses,

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$ **Equation 3.2**

were calculated by using a Moody diagram and the particular Reynolds number for the pipes based on their material and diameter to determine f , the friction factor. Firstly, two dimensionless quantities need to be determined, namely the relative roughness $\frac{\in}{D}$ with $\in$ representing the absolute roughness of the material and D the diameter of the pipe (both in millimetres). The second dimensionless quantity is Reynolds number,

$$\mathbf{R} = \frac{VD}{v}$$ **Equation 3.3**

with v being the coefficient of kinematic viscosity of the fluid (in this case water) in m^2/s, V being the velocity of the fluid and D the diameter of the pipe. Once these quantities have been determined, a Moody diagram, such as the one shown in Figure 3.2**Error! Reference source not found.** is used in order to determine the value of f . L and D are the length and diameter, respectively, of the pipe network utilised in the water supply system. V refers to the velocity of the water flowing through the pipes and is determined by the equation

$$V = \frac{Q}{A}$$ **Equation 3.4**

with Q being the volume of water supplied (in m^3/s) and A being the cross sectional area of the pipe. Q is, as described in Section 4.1, the volume of water required by the village per day. In the friction loss equation, g is the gravity constant and taken as being equal to $9.81m^2/s$. (Chadwick et al, 2004). For the systems designed in the Elundini municipality, pipe characteristics similar to those currently present, namely 90mm galvanised steel pipes will be used.

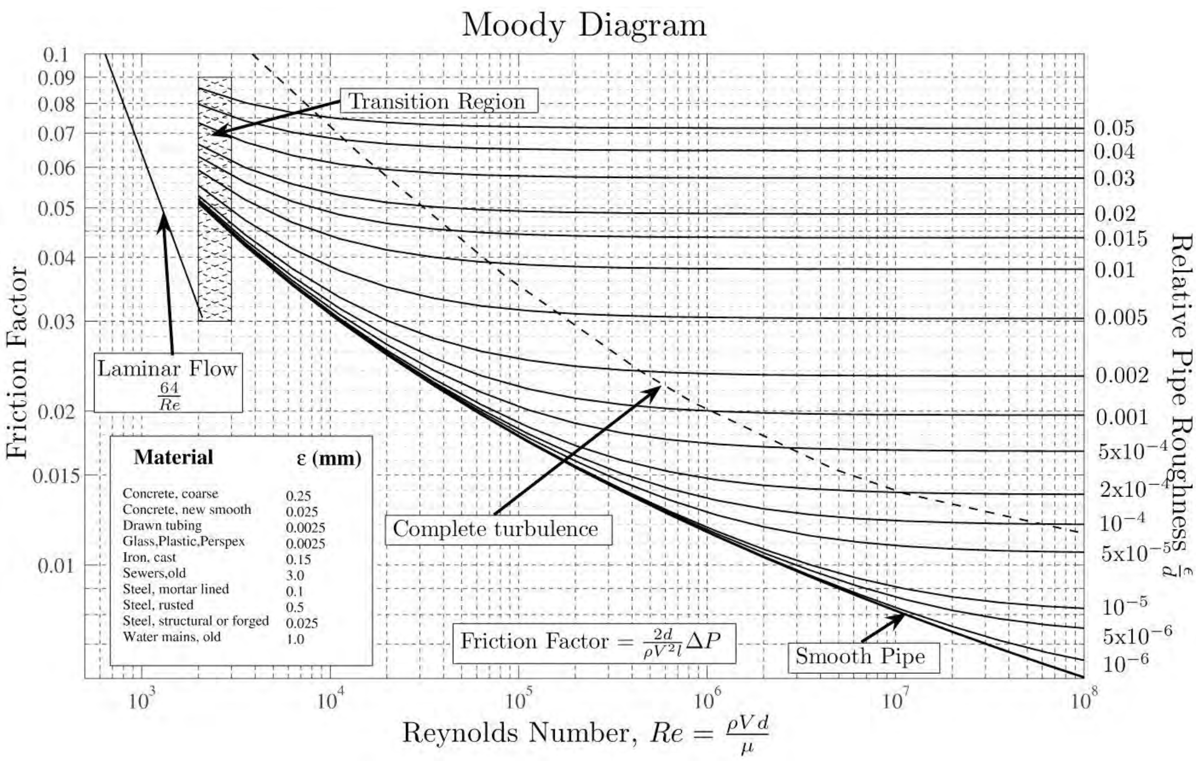

Figure 3.2 Moody Diagram (Chadwick et al, 2004)

3.4 Research Design

This took the form of interviews with several public and private individuals who had relevant experience regarding ground water provision in rural areas, an assessment of Elundini's natural resources (insolation and wind) as well as the availability of ground water, both generally and for specific sites.

It was hoped that through these investigations, and subsequent data analysis, that a conclusion would be reached regarding the potential of renewable energy in providing ground water to rural villages. The interviews with relevant people will provide insight and highlight certain problems and areas of study in which to focus on. The analysis of the ground water availability of the sites, combined with the use of the available renewable energy resources, will indicate if and to what degree wind and solar powered pumps are suitable for rural ground water provision.

3.4.1 Interviews

Interviews with relevant people, both within the municipality and within the field of renewable energy powered water pumps as well as rural groundwater supply itself was performed in this study. Interviews with people directly involved in these fields provide a means of gaining immediate access to information that is required for this particular study that otherwise may not have been publicly available or easily attainable due to the specific focus of the study area. Inherent problems with interviews however are the human element as actual facts may in certain cases be swayed by opinion or alternative agendas. This was mitigated by verifying any information gained through previous peer-reviewed studies of a similar nature, largely addressed in the literature review. Although interviews and contact with relevant industry professionals and members of the community was used primarily for data collection, certain interviews also aided in the acquisition of knowledge into certain processes and procedures required for further analysis of the data.

3.4.2 Process Simulation and Life Cycle Cost Analysis

Once the necessary and relevant data for the village was sourced, namely the head and volume of water needed to be pumped from boreholes, a simulation design was used in order to determine the theoretical potential of implementing solar and wind pumps against their diesel counterparts. This simulated design was done in order to gain a clearer picture of the technical efficacy of renewable energy powered options as opposed to merely a high level indication of whether wind and solar pumps may theoretically operate in the study area. It has already been shown in the literature review of this study that there is indeed potential for their implementation. A life cycle cost analysis was performed as a measure to help in the comparison between the different technologies as in a relatively poor area; cost will be a major consideration in the ultimate choice of a technology (Ramos & Ramos, 2009). A life cycle cost analysis is helpful in that it is a useful way in comparing what a certain technology will cost the owner over its lifetime as opposed to merely its initial up-front cost. Drawbacks to this type of analysis is that it is extremely difficult to predict what fuel costs, inflation and discount rates will be over the lifetime of an installed system and requires informed estimations (Meah et al, 2006).

3.5 Research Method

The methodology used for this study began with an overview of the Elundini municipality, an analysis of the general natural resources with an appropriate solar and wind powered pump and storage system designed for selected sites. The practicality and cost of such a system was then assessed and compared with currently used diesel powered options. This was done through a life cycle cost (LCC) comparison, as well as an assessment of the social impacts associated with each of the technologies.

3.5.1 Research Instruments

This chapter will outline the various research instruments and tools, such as the Groundwater Model Suite (GMS) described in Section 3.5.1.1, used in helping to source the relevant data required to accurately design water supply systems for the sample of villages.

3.5.1.1 GMS Toolkit

Designed by a group of specialist consultants and commissioned by the water research commission (WRC), this toolkit was developed to help municipalities and decision makers on the potential of groundwater, and its supply, to provide for their water requirements. This toolkit is limited to the main Karoo basin in South Africa as shown in Figure 3.3 and covers some 560 000 km^2 (Murray et al, 2012). The Elundini municipality area under consideration is located within the GMS toolkit's study area and was therefore used to determine the water level below ground, and subsequent drawdown, for the chosen village borehole sample.

"The project aimed to identify favourable groundwater potential areas for bulk municipal water supplies, to provide a method to quantify them, and to package the information so that it is assessable for planning purposes" (Murray et al, 2012: i). The tool encompasses several maps of South Africa such as groundwater quality, electrical conductivity and transmissivity maps. These maps are combined together in the electronic software and through a user interface can be used to determine specific characteristics about a potential borehole site, such as the drawdown and the potential water yields. The aquifer firm yield model (AFYM) is used to define a critical management water yield for a specific location, taking into account water recharge, evapotranspiration and pumping that occurs in the given area and relevant aquifers (Murray et al, 2012). The Wellfield model is used to determine the effects of what a proposed borehole pump, or series of pumps, will have on the affected aquifer, and subsequently what the drawdown level will be at the proposed boreholes as a result of the imposed abstractions and for this toolkit was based on the Cooper-Jacob approximation of the Theis groundwater flow equation and aptly named the Cooper-Jacob Wellfield Model (C-J Wellfield) (Murray et al, 2012).

For this study, the AFYM was used to gain a good idea of the yield potential of the general area, however the C-J Wellfield model was used to determine drawdown values for the sample of boreholes, and subsequently used in the calculations of borehole pumping heads for the relevant sample of boreholes.

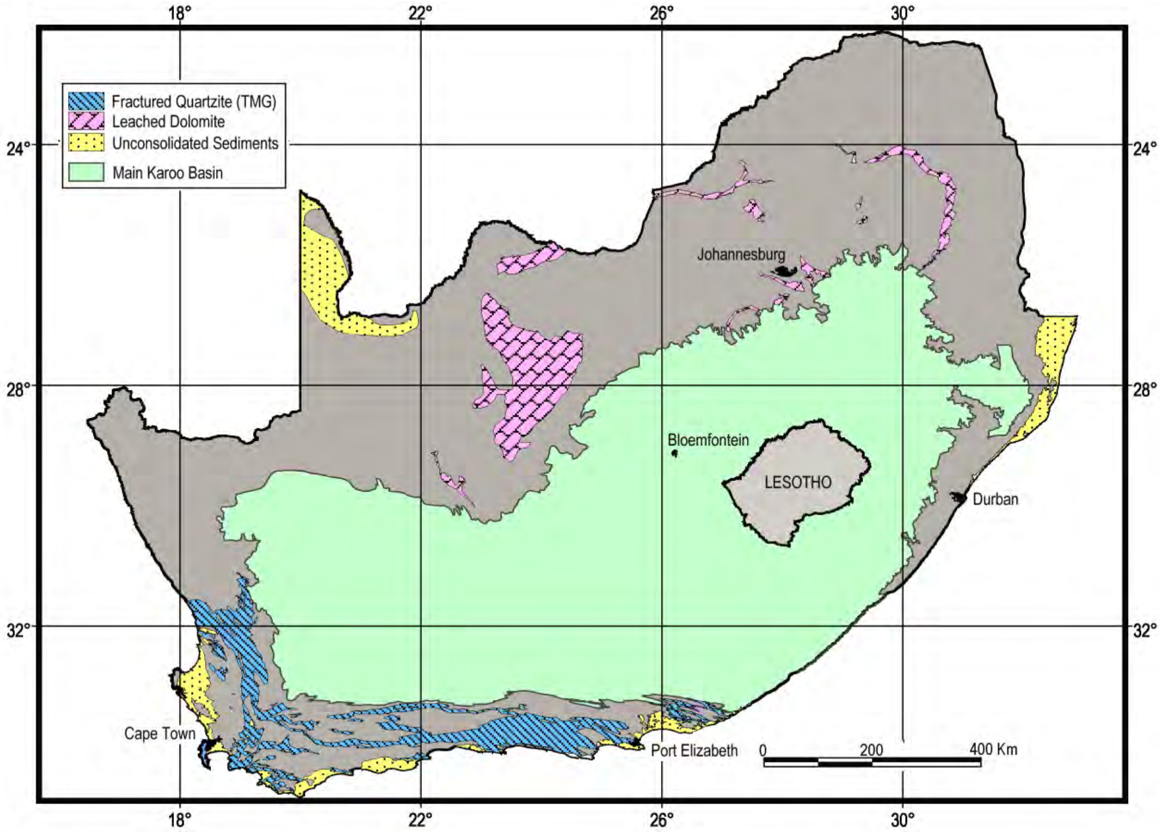

Figure 3.3 GMS study area, Main Karoo Basin.

3.5.1.2 Wind analysis and application programme (WAsP)

WAsP is a Danish developed wind analysis computer programme which is used to derive data provided by the wind atlas of South Africa (WASA). WAsP uses the wind atlas methodology which forms generalised wind climate data from measured data points from a wind atlas, then uses a flow model to represent terrain effects on the generalised wind climate for the point of interest thereby determining the predicted wind climate for that point, the location of the wind turbine/pump (WAsP, 2014).

The wind atlas, although not having points near enough to the village and borehole locations to use exclusively to source wind speed and power values, did have data for a reasonably close point (within 5 kms) and was used to help verify primary data sourced for the area and deductions of power available in the wind regime.

3.5.1.3 Emcon Solar and Diesel Water Pumping Tool

This excel based toolkit compares life cycle costs of diesel and solar powered pumps and was developed by Emcon (2006). This tool was used in order to source operation, maintenance and replacement costs for some of the designed water pumping systems.

3.5.2 Data

Primary data used in this study, which mainly consists of information relating to the villages which includes their GPS co-ordinates, current water and diesel supply levels, as well as population numbers, was sourced through the local Elundini municipality, as well as private companies and individuals employed by the municipality such as Sintech. This data was acquired through a combination of face to face meetings, telephonic conversations and emails.

Data about the groundwater such as the depth to water level as well as draw-down and recharge rates were sourced through the use of the GMS toolkit described in Section 3.5.1.1. This data was verified against actual pumping test data done at a few of the sites which was sourced from AGES geohydrologists. The data primarily used for the assessment of the villages' renewable energy potential was Surface Meteorology and Solar Energy (SSE) satellite data sourced from the National Aeronautics and Space Administration (NASA). This is climate and meteorological data recorded and modelled over the past 22 years by NASA and made available to the public for the support of renewable energy proliferation (NASA, 2013). Other data used to verify and compare with the results given by this data was supplied by the wind association of South Africa (WASA)'s wind atlas for South Africa, as well as recorded data from the South African Weather Service (SAWS) from a nearby weather station.

Due to a lack of long term measured hourly wind data for the sites in the study area, a frequency distribution of wind from Barkly East was analysed in order to give an indication of what the wind patterns in Elundini would be like.

3.6 Analysis and Cost Comparison

The primary data required for the analysis in this study was related to conditions on the ground within the study area. This ranges from the potential natural energy resources to the water requirements of the villages, the estimated costs of current diesel, wind and solar powered pumps, and the depth of boreholes. A comparative analysis was then performed between the status quo regarding water supply in the study area and the hypothetical use of renewable energy powered water supply systems. The efficacy of the systems relative to one another being determined by several parameters such as life cycle cost, practical implementation and maintenance as well societal impact.

Due to the fact that these systems are expected to operate in excess of 20 years (Odeh et al, 2006) it is also not sufficient to only compare initial capital costs of the various systems. A cost comparison was then performed comparing not only capital costs of the systems but also the lifetime costs associated with the operation, maintenance, fuel costs and expected parts replacement costs over their expected 20 year life spans. The lifecycle cost of the various systems was then determined by adding all the costs associated with a designed system over its lifetime. This entailed the discounting of future costs which will be incurred by a system including replacement, operating and maintenance costs, to today's values and then adding these to the total capital cost of the system. In this way, a more comprehensive idea of what the system will cost the municipality over its lifetime was determined in order for better decisions on technology choice to be made.

It was primarily through the review of secondary data, presented in the literature review, as well as interviews with relevant people that will inform conclusions on the practical implementation, maintenance and societal acceptance of a water pumping system.

Although only 27 villages were chosen, they covered a wide range of borehole depths and population sizes spread out across the region and gave a good indication of the range of power and water pumping requirements across the municipality.

Assisting in the choice of which type of rural water supply system is most suitable for implementation in the Elundini municipality, a cost comparison between the systems was performed. This forms a major decision making criterion for the municipality due to the poverty associated with it (STATSSA, 2006 and Qotoyi, 2011). The results and analysis of these costs are discussed in Chapter 5.

3.6.1 Present worth analysis

In order to compare the systems "like for like" the net present value (NPV), over 20 years, of each of the systems was calculated by adding the current capital costs as well as the future expected recurring costs by discounting them to today's value. These future values were discounted by using Equation 3.5:

$$p = f\frac{1}{(1+i)^n}$$ **Equation 3.5**

Where: p = present value

f = future value

i = discount rate

n = year in which payment is made

(IAEA, 1984)

3.6.2 Discount rate

The discount rate, defined by the IAEA as "the rate of interest reflecting the time value of money that is used to convert benefits and costs occurring at different times to equivalent values at a common time" (IAEA, 1984:133). A discount rate is chosen to take into account the time value of money which is essentially the changing value of money with time. The value of money changes for a variety of reasons such as inflation/deflation and the investment growth potential of money were one to invest the money with a financial institution. When comparing different systems with differing recurring future costs, it is necessary to equate the values to one common point in time in order to make a likewise comparison of the options (IAEA, 1984). For this study, due to the fact that the municipality is essentially a government institution with access to reasonably affordable capital, the discount rate was taken as 5%, the same as the bank repo rate at the time of writing (South African Reserve Bank, 2013). It must be noted that for simplicity, constant monetary values were used in this analysis and therefore inflation was not taken into account in the calculations.

The capital costs associated with the various systems used in the analyses, was limited only to the borehole pump/generator as well as the storage costs as other capital costs such as piping, valves etc. would be similar for all the systems and it is assumed much of the water supply infrastructure would already be in place from the existing borehole pump systems.

3.6.3 Diesel Pump system and storage capital costs

Costs for diesel systems were sourced from secondary data by Odeh et al (2006) and Emcon (2006) which both provided comprehensive data related to both capital and recurring costs for diesel systems. The advantage of using this data is that it is cost data specifically related to diesel powered pumps for borehole water abstraction.

3.6.4 Solar PV system and storage capital costs

There are a wide range of solar PVP manufacturers in South Africa offering various sized pumps. For this research the pump prices used were Lorentz pumps, being a well-regarded and established pumping brand, as well as those pumps described in Odeh et al (2006) as there is comprehensive information on their life time costs. Water storage will also be considered for PVP systems and therefore additional capital costs. The storage tanks are designed to be circular concrete reservoirs and costed accordingly. This storage option was used as opposed to Jo-Jo type plastic tanks, which is common for off-grid storage systems, as the water volumes were generally large and would require several tanks with a subsequent increase in total costs.

3.6.5 Wind Pump system and storage capital costs

Although there are several wind pump manufacturers available in South Africa (Turbex, Southern cross industries) Kijito wind pumps had the most available technical data and were chosen for the assessment. They have also been used successfully across sub-Saharan Africa, so is a proven technology (Harries, 2002). Storage would also be required for days of little or no wind and similarly to the design of solar systems, reservoirs would be designed as circular, concrete reservoirs and costed accordingly.

3.6.6 Operation, replacement and maintenance costs

Information related to operation and maintenance was not readily available for commercial systems, although price lists for various replacement parts could be sourced. For diesel and PVP systems, costs were taken from Odeh et al (2006) as well as Emcon (2006), with the replacement and maintenance costs for the Lorentz systems calculated proportionately from their capital costs, based on the Emcon and Odeh values. For the wind pumps, information was available from Kijito (2013).

3.7 Research Limitations

In this section, the limitations associated with the chosen methodology will be highlighted and discussed.

3.7.1 GMS Toolkit

Although the GMS toolkit is based on empirical data and is a well-researched and accurate modelling programme, it is still based on modelling and simplifying a hugely complex subject i.e. groundwater. There is always a chance of human error, both in the creation of the programme, as well as in the use of the programme that could affect the answers obtained from it. There is no substitute for expertise in the field of groundwater and the on-site testing of existing or potential boreholes, which should be done prior to the construction of any new borehole or implementation of a new water abstraction technology. The programme also determines the amount of water available for abstraction by taking into consideration what is presently being abstracted based on gathered information. It is of course possible that changes between the time the abstraction database was formulated for the tool, and what is presently the case, have occurred. This increase or decrease in the amount of water being abstracted from the area would therefore have a bearing on the calculated results. It must therefore be reiterated that the results are calculated estimates.

3.7.2 Wind data

Although the wind atlas of South Africa (WASA) and data obtained from NASA do provide accurate estimates of average wind speeds and duration, they are still modelled from empirical data from a few locations. There will always be inherent errors in data that is sourced through modelling and extrapolation and hence, if highly accurate data is required, one would need to do on-site measurements for at least a period of one year. This is due to the site variability associated with wind speeds, as explained in Section 2.4.1. For this relatively simplistic and inexpensive technology however, with its low efficiency levels, when compared with large scale wind farms, the sourcing of more accurate data would not justify the expense involved. Although wind values obtained in this study for each of the assessed sites may not be as accurate as could be obtained through the use of on-site monitoring, it was felt that for this study that the modelled wind data used would be sufficient for potential implementation of the wind pumps were it deemed to be appropriate. The fact that there were no modelled points from the WASA at the villages researched, could also lead to potential discrepancies between modelled values and actual values.

The Weibull statistical analysis was performed on wind data from nearby Barkly East, approximately 100 km from the assessed villages, and not on measured wind data from the actual site. Although this would give an indication of the wind regime for Elundini, measured on-site data would be required in order to make an accurate assessment of the wind characteristics and subsequent power available in the wind for the area.

3.7.3 Village water use

In the assessment done and subsequent system design for each of the villages in the sample, it presumed that only the 25 litres per person will be used daily. 20 to 25 litres per person per day is considered the bare minimum required by people to survive according to the WHO (2010) and it is possible that inhabitants will try use more than this if it is available. The analysis assumes that only this 25 litres per person per day (pppd) will be used. In reality this may be difficult to implement but some kind of rationing system could be employed to ensure this. The systems have been conservatively designed however and in most cases will provide more than this 25 litres pppd. Several of the villages also have access to other water sources such as springs and rivers, and conservatively, these were not considered in adding to the total available supply of water to the inhabitants.

3.7.4 Wind pump blade design

The number of blades used on a windmill rotor, or its solidity, despite not affecting its overall power output does affect the way it pumps, with a higher solidity rotor (more blades) resulting in a windmill with higher torque compared with a lower solidity one. As described in Section 2.3.3, for MWPS it is beneficial to have higher solidity rotors (Da Rosa, 2009) like the Kijito models used in the analysis. The actual calculations and optimisation of solidity and subsequent torque relating to starting power were not performed in this study as it was felt unnecessary due to the fact that commercial systems were being used with standard rotor solidity; however in a detailed assessment or optimisation of wind pumps for the area it is something that could be explored further. This is also taken into account by the systems with their rated cut-in and cut-out wind speeds illustrating when they will essentially generate enough torque and begin driving their pump mechanism.

3.7.5 Number of water sources

The analysis performed for the boreholes only considered the use of one borehole per village as this was the most common situation in the villages visited by the author. This can lead to the need for large pump systems to extract all the village's water needs from just one source. It is possible that the use of two or more smaller pumps, especially in the case of PVP's, could result in lower lifetime costs of the system for larger villages due to the decreased overall running costs. This was however not considered and only re-fitment of the old borehole with a new system, as this would be the most likely form that replacement of existing borehole pumps would occur as it negates the need for the siting and sinking of new boreholes, was considered. Several villages also have access to more than one borehole however, for simplicity of comparison, only single borehole systems were used in the analysis.

3.7.6 Height of villages above boreholes

With publicly available GIS data for the area only provided with contour intervals greater than 10 metres, google earth as an alternative was thought to provide an accurate enough estimation of the height difference between the location of the boreholes and the height of the villages, i.e. the pumping head. As the distance between the two points was also not large, it was felt that any errors in the altitudes would be negligible as it was only the difference in altitude and ultimately the height difference that was of importance and not absolute altitude. Although absolute attitude (metres above sea level) which for Elundini is over a thousand metres may not be accurate using google earth, when looking at two locations in close proximity to one another, any error would be carried by both points so the difference in height between them would still be relatively accurate. In a detailed design however it would be beneficial to perform a thorough site assessment and through a detailed survey, determine the actual pumping head of the system.

3.8 Ethical Considerations

The major ethical issues identified in this research were the facts that human subjects were a source of information and that the outcome of the research may have some bearing on the provision of services to a community, namely the Elundini municipality. Appendix D, being the ethical clearance granted for this study, is evidence of the mitigation measures taken in the study to protect the municipality and its inhabitants. Essentially with regards the fact that people will be a source of data; the people were not part of any vulnerable group, the research did not discriminate against any population groups, none of the data collected would be of a confidential nature, there was no foreseeable risk of harm to the participants due to the conducted research and the research involved no payment to the participants involved. Regarding the impacts on the community, no economic or social process was foreseen to be terminated due to the outcome of the research or lead to services being provided at a level below generally accepted standards. Although the community could make a decision based on the outcomes of the research, the decision would be made by responsible leaders in the community with only informed decisions that are in the best interests of the community being made.

3.9 Conclusion

The methodology above, outlines essentially how the investigation and analysis of renewable energy powered pumping options for villages compares with current diesel powered ones was conducted. The research findings, Chapter 4, did this comparison by firstly selecting a representative sample of villages currently sourcing their water from diesel powered borehole pumps, determining how much water each village needed, to what height it needed to be pumped, the size pump/system required to provide for this, including storage for the renewable powered options. Each of the three options (diesel, wind and solar) were then compared against each other through a life cycle cost analysis, as well as their foreseen impacts from a social and practical implementation and operation perspective.

The limitations of this methodology highlighted in Section 3.7, are not foreseen to have a major impact on the objectives of the study which are essentially to determine, through a high level analysis, whether renewable powered water pumping options offer an attractive alternative to diesel powered pumps.

4 RESEARCH FINDINGS

The research findings regarding the design of different water supply systems and their efficacy are presented below. Of the sample of villages, Jojweni is used to illustrate how each system was designed as it has characteristics well representative of the village sample. The results of the system design for each village is then presented.

4.1 Water requirements

The amount of water required by each of the villages was calculated by multiplying the total population size by the minimum water requirements per person, namely 25l per day. An example of this simple calculation for Hopedale is:

750 x 25 = 18 750 l/day **Equation 4.1**

This was then converted to m^3/day by dividing by 1 000 to give 18.75 m^3/day. Although this would be the design volume for a pump powered by diesel, were it always available to pump, the design of solar and wind systems, due to the erratic nature of solar and wind power availability, would need to have this value increased to take storage into account and provide for some days of autonomy. From the author's site investigation, water storage for the diesel powered systems did not appear to be common place.

4.1.1 Total Dynamic Head

One of the critical factors in determining the power required by a borehole pump is the head that it needs to pump to. This is essentially the difference in height between the lowest existing water level and the point of water delivery, as well as the added friction head caused by the resistance of the pipes on the flow of water through them. Bernoulli's equation is used to determine this, and numerically is defined as:

$$h_p + \frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f + \Sigma h_m \qquad \textbf{Equation 4.2}$$

where: hp is the required pumping head,

hf is the head loss caused by friction,

hm are the minor losses throughout the system,

ρ, p, V and z are density, pressure, velocity and elevation respectively

Subscripts 1 and 2 represent the well and storage tank locations respectively

As both the borehole and storage tank will be at atmospheric pressure i.e. p1 = p2 and the velocities at each point V1 and V2 will be equal and approximately = 0, the pumping head is therefore equal only to the change in elevation and losses in the system. These losses can be calculated using:

$$hf + \Sigma h_m = \frac{V^2}{2g}\left(\frac{fl}{d} + \sum K\right) \qquad \textbf{Equation 4.3}$$

where: V is the water velocity through the pipes

g is the gravity (9.81 m/s2)

f is the friction factor

l and *d* are the pipe length and diameter, respectively,

K represents the various minor loss coefficients throughout the system

4.1.2 Pumping Head hp

For boreholes, one firstly has to determine the depth below ground level that water is naturally present, and then how much this water level will drop once an abstraction is applied to it, termed drawdown which is indicated in Figure 4.1. This is determined most accurately through on-site borehole testing, usually performed by specialist groundwater consultancies. Results of such testing was extremely limited for the study area, although some tests for 4 boreholes in the author's study area were found, having been performed by AGES hydrogeologist consultants. The four sites with test results were all located within close proximity of each other and concentrated in the Northern part of the author's study area and sample of boreholes. This limited range of borehole information was of course inadequate to make informed, generalised conclusions regarding the borehole depths of the chosen sample of boreholes. This problem of limited information regarding availability of groundwater resources in South Africa is a common, long standing one (Cobbing, 2013), and as such there has been much research into it. The largest studies on the matter being Groundwater Resource Assessment I and Groundwater Resource Assessment II (GRAI and GRAII) respectively. These studies developed estimations of storage, recharge, base flow and the impact of current groundwater use on available groundwater, across South Africa (Witthuser et al, 2009).

Values for the depth of water below ground, and the subsequent maximum drawdown level, were therefore derived using the GMS toolkit, described in Section 3.5.1.1. This required plotting of the relevant borehole's location onto the groundwater map, and entering a pumping rate for the proposed borehole which was determined by the water requirements for each of the villages. A value for the borehole's transmissivity and storativity, estimated from the transmissivity and storativity maps supplied with GMS toolkit. Values used in this analysis were 5 m^2/day and 0.0003 respectively.

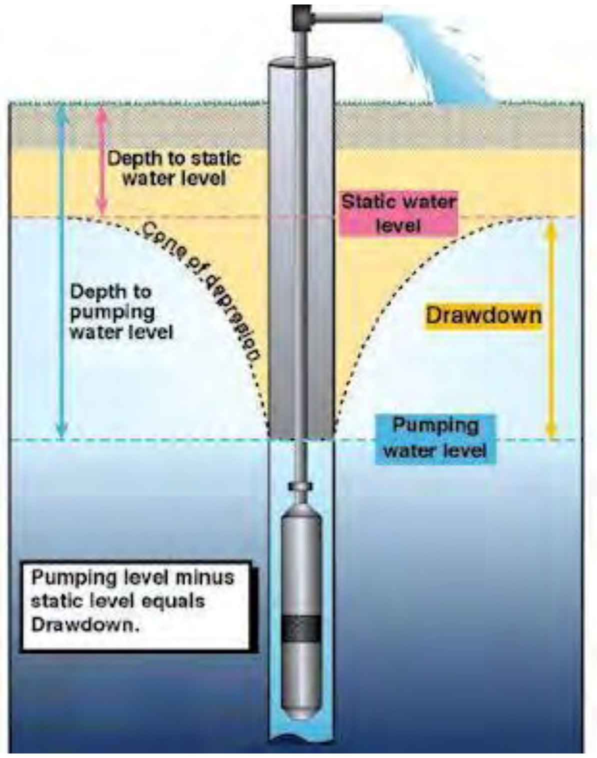

Figure 4.1 Image indicating static water level and drawdown caused by pumping (TND Drilling, 2014)

Table 4-1: Maximum depth of water drop below ground level due to pumping per village

Village	Water Drawdown (m)
Mgcantsi	16
Gamakulu	16
Kwalanga	16
Jojweni	19.1
Gobo	20.9
Emaladini	16.4
Polokoe	8.45
Tabatlala	3.05
Jojoweni	19.1
Moleko	2.22
Hopedale	18.5
Makhuleng	25.2
Mohoabatsana A	16.8
Makhalong	20.8
Katkop	20.5
Upper Sinxako	18.4
Khalatsu	25
Umfanta	22.4
St Augustins	17.1
Setaka	17.6
Lower Sinxako	18.8
Sekoteng	21.7
Moroka	23.5
Thembeni	20.8
Etyeni	18.5
Tsolobeng	19.9

The values presented in Table 4-1 are the results of the GMS toolkit modelling performed on the village sample. The maximum depth below ground level that the water will drop is modelled here based on the transmissivity, which is illustrated in Figure 4.2, and storativity of the aquifers; the amount of abstraction taking place in the vicinity and the current groundwater levels.

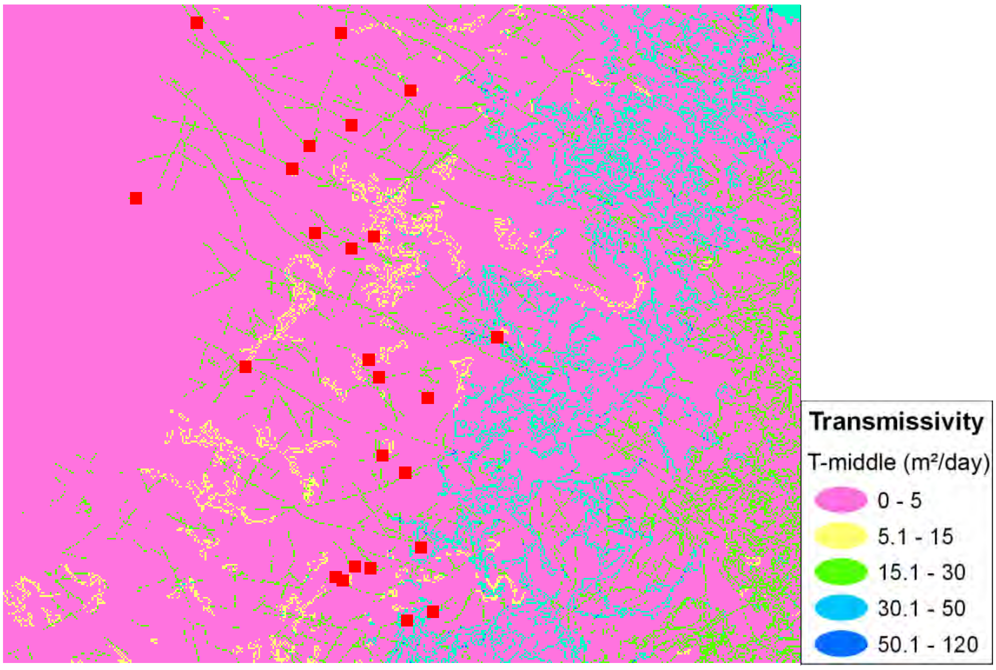

Figure 4.2 Transmissivity Map of Elundini Municipality with village boreholes indicated by the small red blocks (GMS, 2012)

4.2 System design for Solar PV with water storage

For the renewable energy pump options, the systems were designed to be as efficient as possible i.e. as small as possible to maintain desired service levels, as this optimises the cost of installation. This entails taking into consideration the renewable energy resources present (average solar insolation during the least sunny month), as well as necessary water storage for a particular village's water volume needs and head (Omer, 2001). The amount of water storage necessary (enough so as inhabitants are not without their daily prescribed levels of water provision) was calculated by ensuring the pumping system had enough capacity to not only provide the primary daily needs of the inhabitants but also fill a storage medium that will supplement inhabitants' needs for a length of time equivalent to the maximum time that no sun is forecast to shine. Although it is common practice to design small solar storage systems by simply multiplying the daily required flow by the number of storage days required, which is generally the number of days the sun is not expected to shine or 'no-sun' days (Bakelli et al, 2011), for village sized systems where often water is provided for 500 or more people, this is not feasible due to resultant unnecessarily large sized reservoir and pump. If systems were designed in this way, for seven days of autonomy one would have a system almost seven times the size it needs to be.

Information regarding the number of days without sunshine is available from NASA's 22 year historical satellite data (NASA, 2012). For the Elundini municipality, this was equivalent to 7 days within a twelve month period, as can be seen in Table 4-2**Error! Reference source not found.**. The storage volume required is equal to 7 times the village's daily water requirement. The amount of extra solar pumping capacity required to supplement this storage, whilst still providing primary water provision, was calculated by firstly dividing the storage size by days in the month i.e. 30 in September (lowest month of insolation), adding this figure to the daily water needs and then dividing this number by the minimum percentage of solar insolation expected for that month. Numerically, for the month of September where there are a maximum of 7 'no-sun' days, a storage unit needs to be designed that can provide for 7 days of no sun. The amount of daily flow required is equal to 30/23, which is equal to 1.3 multiplied by the daily water requirement of the village. i.e:

Daily water required (m^3) = no. inhabitants x 0.02 m^3 x 1.3 **Equation 4.4**

A storage unit is then sized that will be able to supply the village for 7 days of no sun, i.e. seven times the total daily water requirement of the village. This tank, pumping at the rate calculated above, is able to be filled up within a month of average pumping in the worst case scenario month i.e. September. This ensures that in any month of operation, by the end of that month, whilst supplying the daily water requirements of the village, enough storage will be made available to supply the village autonomously for the maximum "no-sun" period. This of course assumes that the system begins operating outside of a no sun period so the system has a few days of pumping to fill the reservoir before any "black" days.

Table 4-2: Equivalent Number Of NO-SUN or BLACK Days (NASA, 2012)

Lat -31.4 Lon 28.21	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 day	0.93	0.84	0.76	0.93	0.86	0.87	0.89	0.82	0.87	0.84	0.90	0.93
3 day	1.98	2.21	2.07	1.78	1.83	2.07	2.20	1.98	2.42	2.09	2.07	1.95
7 day	2.98	4.53	3.42	2.29	2.63	3.44	3.56	3.56	4.88	3.94	2.89	2.48
14 day	4.15	6.40	3.93	3.35	2.68	3.51	4.31	4.33	5.33	5.37	4.60	3.75
21 day	3.98	5.29	4.02	4.45	2.83	3.80	4.73	4.87	4.81	5.58	5.63	4.36
Month	3.25	5.51	4.22	4.15	2.04	4.17	3.92	5.42	7.02	5.32	5.12	4.52

The daily energy required to supply water, based on mass flow rate and referred to as hydraulic energy, is calculated using Equation 4.5:

E (kWh/day) =$\mathrm{VH}\rho\mathrm{g}$/3.6 MJ = 0.002725(HV) **Equation 4.5**

Where: V = Daily volume of water (m^3), H = Head (m), ρ = density of water (1000kg/m^3), g = gravity (9.8ms^{-2}). (Markvart, 2000)

Once simplified, this equation essentially multiplies metres by m^3 resulting in m^4 which although not a standard unit of measurement, will be used to illustrate hydraulic energy required by the pumping systems before being converted into electrical energy (kWh/day).

The power supplied to the pump by the panels is illustrated by equation 6:

$$\frac{\mathrm{P_E}}{\textit{Average daily solar irradiation}\left(\frac{kWh}{m^2}\right) \mathrm{x\ F\ x\ E}}$$ **Equation 4.6**

Where: F = array mismatch factor, E = sub-system efficiency (between 0.25 and 0.4) (Markvart, 2000)

4.2.1 Solar PV system design for Jojweni village

To illustrate complete SPV system design, the calculations done for Jojweni are presented below:

Population = 300

Minimum water requirements = 25l pppd

Therefore Q = 300 x 25 = 7 500 l/day = 7.5m^3/day

Including extra pumping required for water storage = 30/23 x 7.5m^3/day = 9.8m^3/day

Depth of drawdown water level derived from GMS toolkit = 19.1m

Altitude difference between village and borehole estimated from Google Earth = 36m

Friction Head:

Velocity of water in pipes = 9.8m^3 / 8 hours daily pumping time = 1.225m3/hour / 3 600

= 0.00034m^3/s / pipe cross-sectional area (0.0064m^2) = 0.053m/s

Re (Reynolds Number) Re = $\frac{\rho Vd}{\mu}$ = 1000 x 0.0534 x 0.09 / 0.001002

= 4 796

Relative pipe roughness, using = $\frac{\epsilon}{D}$ = 0.025/90 (using ϵ = 0.025 for steel pipes)

= 0.000278

Friction Factor = 0.043 (read from Moody's diagram)

Friction losses: $h_f = f\frac{L}{D}\frac{V^2}{2g}$

With L = 2800m, V= 0.053m/s, D=0.09m, g=9.81m^2/s

h_f = 1.985 m

Total minor losses: based on Table 4-3 but adjusted for 2.8km network

Table 4-3: Total minor losses for Jojweni

Loss	K
Sharp entrance	0.5
Open globe valve	5.7
90° bend	0.7
Screwed 90° elbow	1.8
Open gate valve	0.11
Sharp exit	1
ΣK =	**9.81**

Total minor losses therefore = $\Sigma h_m = \frac{V^2}{2g}\left(\sum K\right)$ using the same values for V & g

= 0.0014m

Total system losses therefore ≈ 2m

Total dynamic head of system = 19.1 + 36 + 2

= 57.1m

Therefore hydraulic energy = 9.8m^3/day x 60m

= $588m^4$/day

Substituting into Equation 4.5 = 1.52 kWh

Substituting this into Equation 4.6, using an insolation value of 5.3kWh/m^2, a mis-match factor of 0.85 and a sub-system efficiency factor of 0.3

= 0.84 kW PV Array

Storage volume, as discussed in Section 4.2:

= $7.5m^3$/day x 7 days = 52.5 m^3

4.3 System Design for Wind Pump with Water Storage

In the design of wind powered water pumping systems, the design process is not as simple as for wind powered electricity generation systems; this is because the selection of the design wind speed in the case of electricity generation is based purely on the wind speed corresponding to the maximum amount of potential energy. The design process is more complicated for water pumping wind mills as the pump type has a direct bearing on the design, highlighted by Mathew et al who state that “in the case of water pumping wind mills with positive displacement piston pumps, selection of design wind speed is greatly influenced by the pump characteristics” (Mathew et al, 2002:10). This was however not looked at as the systems used are standard commercial ones where these considerations have been taken into account by their cut-in, cut-out and rated wind speeds. Further complications inherent with water pumping wind systems is the need to supply water storage during times of little or no wind, further affecting the design considerations of the system.

Although the villages analysed were not sufficiently covered by the wind atlas of South Africa (WASA) to use the data exclusively for the wind analysis, several data points exist within 5 kilometres of some of the villages. The nearby WASA data points were used as well as NASA satellite data in order to confirm the wind potential of the villages and act as a comparison for verification purposes.

The power required by the wind pumps was calculated in much the same way as for solar pumps and was effectively a factor of pumping head and the daily water required by the village. This energy value, in kWh, was then divided by the number of pumping hours available in the day (hours that the wind is blowing at a sufficient speed to pump) in order to determine the power of the pump required. Although sufficient wind speed blowing hours is a good indication of pumping availability, more specifically, it is the amount of power that is available from the wind each day that is of actual concern. As was explained in Section 2.3.3, power derived from the wind is relative to the cube of the wind speed; hence it is the average total amount of power available from the wind each day that is of interest in the wind pump design. Data from the WASA once analysed with WAsP has already taken this into consideration and simply provides a power value in W/m^2 for direct design of the pump. For the NASA data however, a wind speed frequency, and associated power, distribution was required in order to estimate the average amount of power available for pumping.

The hydraulic energy required is calculated in the same way as for the PVP system i.e. using Equation 4.5.

The basic calculation for a simplistic estimation of power available in the wind based purely on average wind speed is shown in $P(U) = 0.5\ \rho AU^3$

Equation 4.7

$$P(U) = 0.5\ \rho AU^3 \qquad \textbf{Equation 4.7}$$

Where: ρ is air density, A is the swept area of the rotor, U is the instantaneous wind speed.

4.3.1 Average wind speed

The average wind speed, sourced from NASA, for the village sample was acquired using the online toolkit by inputting the co-ordinates of the area. A central location in the middle of the sample was chosen. As the NASA data is at a resolution of only 1° (NASA, 2013) it was felt that it was unnecessary to source data for each and every location's exact co-ordinates as all the villages fell comfortably within a 1° grid block. From the raw data acquired, the actual average wind speed value had to be chosen based on several site and system specific factors, namely the height above ground that the rotor of the wind turbine would be when built of 10 metres, as well as an indication of the surrounding ground conditions, defined as the surface roughness. It is assumed that the siting of the wind turbines will be done in such a way that there will be no topographical features causing either marked increase or decrease in the wind speeds and that topographical effects will be limited only to the surface roughness. From the author's site investigation, a surface roughness class of between 1 and 2, resulting in a roughness length of between 0.03 and 0.1m, would be an accurate description of the general layout of the land. From the author's limited site investigation, the roughness class was generally representative of class 1 and was chosen for determination of the average wind speed and power from the WASA data. This corresponded to an average wind speed of 2.93m/s and power of 55

W/m^2. Descriptions of terrain and their associated roughness class are presented in Table 4-4.

Table 4-4: Terrain descriptions and associated roughness class for wind calculations (WAsP, 2012)

Physical z_0 [m]	Terrain surface characteristics	Roughness Class	z_0 specified in WAsP [m]
1.5		**4** (1.5 m)	1.5
> 1	tall forest		> 1
1.00	city		1.00
0.80	forest		0.80
0.50	suburbs		0.50
0.40		**3** (0.40 m)	0.40
0.30	shelter belts		0.30
0.20	many trees and/or bushes		0.20
0.10	farmland with closed appearance	**2** (0.10 m)	0.10
0.05	farmland with open appearance		0.05
0.03	farmland with very few buildings/trees	**1** (0.03 m)	0.03
0.02	airport areas with buildings and trees		0.02
0.01	airport runway areas		0.01
0.008	mown grass		0.008
0.005	bare soil (smooth)		0.005
0.001	snow surfaces (smooth)		0.003
0.0003	sand surfaces (smooth)		0.003
0.0002	(used for water surfaces in the Atlas)	**0** (0.0002 m)	0.0
0.0001	water areas (lakes, fjords, open sea)		0.0

Although the NASA data does not use surface roughness classes as such to define the different wind regimes, a range of descriptions of the surrounding surface is provided for the user to choose the most applicable one and subsequently the average wind speed corresponding to this. From the site investigation, the most applicable description of surrounding conditions was defined by the NASA data as “Tundra: 0.6-m trees/shrubs (variable %) & groundcover” (NASA, 2013) with a corresponding wind speed of 3.36m/s indicated in Table 4-5.

Table 4-5: Selection of surface descriptions and associated wind speeds for the Elundini municipality (NASA, 2012)

Monthly Averaged Wind Speed For Several Vegetation And Surface Types (m/s) Height 10 meters													
Lat -30.5 Lon 28.5	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
0.6-m perennial groundcover (100%)	3.23	3.04	3.02	3.05	3.25	3.58	3.58	3.65	3.74	3.58	3.38	3.15	3.36
0.5-m broadleaf shrubs (variable %) & groundcover	3.23	3.04	3.02	3.05	3.25	3.58	3.58	3.65	3.74	3.58	3.38	3.15	3.36
0.5-m broadleaf shrubs (10%) with bare soil	3.23	3.04	3.02	3.05	3.25	3.58	3.58	3.65	3.74	3.58	3.38	3.15	3.36
Tundra: 0.6-m trees/shrubs (variable %) & groundcover	3.23	3.04	3.02	3.05	3.25	3.58	3.58	3.65	3.74	3.58	3.38	3.15	3.36
Rough bare soil	3.50	3.30	3.27	3.31	3.52	3.88	3.88	3.95	4.06	3.88	3.66	3.41	3.64
Open water	4.25	4.00	3.97	4.01	4.27	4.70	4.71	4.80	4.92	4.70	4.44	4.14	4.41
"Airport": flat rough grass	3.92	3.69	3.66	3.70	3.94	4.34	4.35	4.43	4.54	4.34	4.10	3.82	4.07

4.3.2 Speed frequency distribution

The results from the Weibull analysis of the hourly data measured over two years, at a height of 10 m were as follows:

Scale parameter c = 4.3 m/s and shape factor k = 1.55. These were determined using

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\frac{1}{n}\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(vi)}{n} \right)^{-1}$$ Equation 4.8

and $c = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^k \right)^{1/k}$ Equation 4.9

respectively and with the help of Microsoft excel to analyse and assimilate the large quantities of data.

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\frac{1}{n}\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(vi)}{n} \right)^{-1}$$ **Equation 4.8**

c = $\left(\frac{1}{n}\sum_{i=1}^{n} v_i^k \right)^{1/k}$ **Equation 4.9**

Where v_i is the wind speed value at time step i and n is the number of non-zero wind speed data points (Seguro and Lambert, 2000). Here, k is determined iteratively, with an initial guess of 2 and then c determined explicitly once k is calculated.

The average wind speed used in the analysis however was sourced from the NASA data for Elundini's co-ordinates i.e. 3.36 m/s.

In order to calculate average power in the available wind, Equation 4.10 was used.

$$\overline{P}w = \frac{\rho A \bar{v}^3 \Gamma(1+3/k)}{2[\Gamma(1+1/k)]^3}$$ **Equation 4.10**

Where Γ represents the gamma function applied to the data (Lu et al, 2002)

For a wind speed of 3.36 m/s this resulted in a value of 54.8 W/m^2, almost exactly that provided by the WAsP analysis of the WASA point located in the vicinity. This value however had to be adjusted to take into consideration storage required for periods of little wind. Using the data from NASA and more specifically, the variations from the average wind speed during various months, illustrated in Table 4-6, the largest monthly decrease from the average wind speed, of 12%, occurs in May. As power in the wind is relative to the cube root of the wind speed, by using equation 10 again and now substituting in a wind speed 12% lower than the average wind speed, i.e. 2.96 m/s, the resultant wind power would be 37.5 W/m^2. The wind pumps for each village were then sized based on this amount of available wind power.

Table 4-6: Percentage Difference from Monthly Averaged Wind Speed at 50 m (NASA, 2012)

Lat -30.5 Lon 28.5	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Minimum	-11	-10	-9	-8	-12	-10	-7	-6	-7	-9	-9	-5	-9
Maximum	8	14	11	11	15	8	13	7	5	9	10	7	10

In order to determine the size of the storage tank required, in the absence of long term data for the region, the amount of water that would result from the greatest expected increase from the average wind speed was used, also the month of May with an increase of 15%. The amount of water that would be pumped at each specific village using the wind pump based on the lower wind speed, but utilizing the higher wind power was calculated, with the difference between this value and the amount of water used by the village, determining the required water tank storage volume.

In order to determine the total energy that could be provided during a typical day of pumping, one had to multiply the power available in the wind by the forecast operating hours of the wind pump. In order to achieve this, wind pump characteristics, such as the cut-in and cut-out wind speeds, were required. The characteristics of Kijito wind pumps, which have been disseminated successfully across Sub-Saharan Africa were used for the analysis. The characteristics of the Kijito Wind pump are as follows:

Cut-in wind speed = 2.5 m/s

Rated Wind Speed = 7 m/s

Cut-out wind speed = 9.33 m/s

Using these values, an average wind speed of 3.36 m/s, as well as k and c values of 1.55 and 4.3 respectively, the resultant wind availability was calculated to be 61.4% which, for a 24 hour day, equates to 14.74 hours of wind available per day.

4.3.3 Wind powered system design for Jojweni village

Using the same village as was used in the solar PV design, the typical design of a wind powered water pumping system is illustrated below.

The daily energy required to lift the required water volume, overcoming gravity, head and friction losses calculated using Equation 4.5, with H=60 and Q=7.5 resulted in 1.23 kWh.

With 14.4 hours of available useful wind per day, the power required to lift this volume of water from the borehole is equal to

1.23kWh/14.74h = 0.083 kW or 83 Watts **Equation 4.11**

Using a minimum wind power available, as calculated in 4.3.1 of 37.5 W/m^2, the resultant wind-pump size, using a wind pump performance co-efficient of 0.25:

83W = 0.25 A 37.5 W/m^2

Therefore, wind swept area = 9.1 m^2

Diameter is therefore = 3.4m which is equivalent to 11.15 feet.

From the commercially available systems, it was decided that a Kijito 12 foot model be used for this installation.

In order to calculate the amount of water requiring storage to maintain service levels, a worst case scenario of wind unavailability days all occurring consecutively in a given month was used. Therefore with wind availability of 61.4%, 38.6% of days not being able to pump water consecutively will result in approximately 11 days within a typical 30 day month which for Jojweni results in a storage volume of

300 inhabitants x 25l pppd x 11 days = 82 500 litres i.e. 82.5 m^3

To determine whether the chosen windmill will be able to provide this extra volume of water, 61.4% availability was applied for the preceding days, i.e. 19 days experiencing average expected wind conditions.

Therefore, the amount of water pumped in preceding 19 days with average wind speed:

19 days of pumping using the 12 foot Kijito with wind power of 54.8 W/m2:

Energy generated =

0.25 x 54.8 W/m2 x 10.52m2 x 14.74 hours/day x 19 days **Equation 4.12**

= 40.36 kWh

Substituting this into $\mathbf{E_w=0.002725QH}$

Equation 2.1:

40.36 kWh = 0.002725HQ

And using the fixed value for H of 57.1m

Therefore Q = 40.36/ 0.002725*57.1

= 259.4 m^3

Storage volume available month = total water available during month – water used during the = 259.4 m^3 – (300inhabitants x 25litres x 19 days) = 142.5m^3

Therefore = 259.4 m^3– 142.5 m^3 = 116.9 m^3 excess water available for storage.

4.4 Comparison between Systems

Table 4-7, summarises the calculations performed for each of the assessed villages. Firstly, the hydraulic energy (m^4) required for each village's borehole is presented followed by the required size of diesel, PV and wind pump required to supply the village with its water requirements. In the case of wind and solar, extra pumping capacity is included for water storage as well. These values are what the optimum size system will be, however in reality there is only a limited range of products and hence a suitably sized one for each of the technologies needed to be chosen in order to make a realistic comparison of typical installed systems. It is only the diesel use which was dependent on the actual required energy and not purely on the chosen diesel powered pump size, as a slightly larger system will be chosen to ensure reliable water supply.

Table 4-7: Comparison of each technology's theoretical power (in kW) rating for each village

Name	Proposed Water pppd (l)	Population	Water required per day (m^3)	Total Dynamic Head (m)	m^4 Required per day	Total Daily Energy Required (kWh)	Diesel Pump and Generator (kW)	Solar PV Pump (kW)	Wind Pump (kW)*
Mgcantsi	25	90	2.3	16.5	37.1	0.101	0.093	0.073	0.007
Gamakulu	25	186	4.7	104.5	485.8	1.324	1.222	0.958	0.092
Kwalanga	25	228	5.7	16.7	95.1	0.259	0.239	0.188	0.018
Jojweni	25	300	7.5	57.1	428.1	1.167	1.077	0.844	0.081
Gobo	25	396	9.9	56.7	561.2	1.529	1.412	1.107	0.106
Emaladini	25	414	10.4	75.6	782.3	2.132	1.968	1.543	0.148
Polokoe	25	516	12.9	50.6	653.0	1.779	1.643	1.288	0.124
Tabatlala	25	576	14.4	30.7	442.7	1.206	1.113	0.873	0.084
Jojoweni	25	630	15.8	57.0	898.3	2.448	2.260	1.772	0.170
Moleko	25	648	16.2	101.4	1643.1	4.478	4.133	3.241	0.311
Hopedale	25	750	18.8	66.1	1238.6	3.375	3.116	2.443	0.234
Makhuleng	25	786	19.7	90.4	1775.4	4.838	4.466	3.502	0.336
Mohoabatsana A	25	792	19.8	18.4	364.7	0.994	0.917	0.719	0.069
Makhalong	25	822	20.6	67.7	1390.6	3.790	3.498	2.743	0.263
Katkop	25	864	21.6	29.5	637.1	1.736	1.602	1.257	0.121
Upper Sinxako	25	918	23.0	99.2	2276.0	6.202	5.725	4.489	0.431
Khalatsu	25	996	24.9	55.1	1372.3	3.739	3.452	2.707	0.260
Umfanta	25	1086	27.2	110.6	3003.4	8.184	7.555	5.924	0.568
St Augustins	25	1110	27.8	101.2	2809.4	7.656	7.067	5.541	0.532
Setaka	25	1128	28.2	73.1	2062.3	5.620	5.187	4.068	0.390
Lower Sinxako	25	1338	33.5	86.7	2900.0	7.903	7.295	5.720	0.549
Sekoteng	25	1410	35.3	55.6	1959.5	5.340	4.929	3.865	0.371
Moroka	25	1680	42.0	72.4	3041.1	8.287	7.649	5.998	0.575
Thembeni	25	1794	44.9	102.6	4601.0	12.538	11.573	9.075	0.871
Etyeni	25	1884	47.1	87.5	4122.1	11.233	10.369	8.131	0.780
Tsolobeng	25	5226	130.7	777.1	101529.6	276.668	255.386	200.262	19.213

*For wind pumps, due to the square relationship between windmill size and power, only the net power required is presented, i.e. without system efficiencies considered. These are taken into account when calculating the power provided by a proposed wind pump.

Table 4-8 indicates commercially available systems that were chosen for each of the villages as well as the storage requirements of each system. Although there is a wide range of locally available systems for solar and wind, those chosen were based firstly on the closest match to the optimum designed system size and secondly those with the most available cost data in order that a comprehensive comparison could be made. In the case of diesel, the range of commercially available, long-life pump sizes was found to be limited as it is relatively easy to adjust output from an engine by increasing or decreasing pump time as well as being able to provide for a larger range of pumping loads. The impact of upfront costs of diesel pumps is also relatively small compared with operating costs and hence it is less critical to match pump size to load exactly. Although for diesel engines, smaller systems are available, for ones that were of a good quality with long life expectancy and able to provide reliable water supply, as is required for village water supply, the smallest size found was a 3 kW engine. It is for these reasons that the range of sizes for the diesel engines is limited and doesn't vary much between similarly sized systems.

Although the range of sizes for the diesel powered pumps was limited, when calculating the future maintenance and operating costs for the diesel systems, the operating hours were optimised for each village. This was done by adjusting the running hours per day to bring the operating power of the pumps as close to their rated power and thereby increasing their efficiency. This results in lowering overall operation and maintenance costs as with the pump operating as close to its maximum efficiency, the maximum amount of power is extracted from the pump from a shorter run time, thereby reducing the number of services, parts replacement and fuel required.

Table 4-8: Comparison between size of designed systems and commercially available ones

Name	Diesel Pump (kW)	Diesel Pump Design (kW)	Commercial Diesel (kW)*	Solar PV Pump Design (kW)	Commercial Solar PV (kW)	Wind Pump Design (kW)*	Commercial Wind (kW)
Mgcantsi	0.063	0.063	3.000	0.073	0.091	0.007	0.044
Gamakulu	0.827	0.827	3.000	0.958	0.968	0.092	0.099
Kwalanga	0.162	0.162	3.000	0.188	0.227	0.018	0.044
Jojweni	0.729	0.729	3.000	0.844	0.925	0.081	0.099
Gobo	0.956	0.956	3.000	1.107	1.51	0.106	0.175
Emaladini	1.332	1.332	3.000	1.543	2.12	0.148	0.175
Polokoe	1.112	1.112	3.000	1.288	1.51	0.124	0.175
Tabatlala	0.754	0.754	3.000	0.873	0.925	0.084	0.099
Jojoweni	1.530	1.530	3.000	1.772	2.12	0.170	0.175
Moleko	2.798	2.798	3.000	3.241	4.5	0.311	0.394
Hopedale	2.110	2.110	3.000	2.443	2.843	0.234	0.274
Makhuleng	3.024	3.024	3.500	3.502	4.5	0.336	0.394
Mohoabatsana A	0.621	0.621	3.000	0.719	0.756	0.069	0.099
Makhalong	2.368	2.368	3.000	2.743	2.843	0.263	0.274
Katkop	1.085	1.085	3.000	1.257	1.51	0.121	0.175
Upper Sinxako	3.876	3.876	4.500	4.489	4.5	0.431	0.462
Khalatsu	2.337	2.337	4.500	2.707	2.843	0.260	0.274
Umfanta	5.115	5.115	10.000	5.924	6.3	0.568	n/a
St Augustins	4.785	4.785	10.000	5.541	6.3	0.532	n/a
Setaka	3.512	3.512	6.300	4.068	5.172	0.390	0.394
Lower Sinxako	4.939	4.939	10.000	5.720	6.3	0.549	n/a
Sekoteng	3.337	3.337	5.500	3.865	4.5	0.371	0.394
Moroka	5.179	5.179	10.000	5.998	6.3	0.575	n/a
Thembeni	7.836	7.836	15.000	9.075	10.888	0.871	n/a
Etyeni	7.020	7.020	15.000	8.131	10.888	0.780	n/a
Tsolobeng	172.918	172.918	n/a	200.262	n/a	19.213	n/a

4.5 Cost comparison for Jojweni village

An example of how a life cycle cost was determined for each technology in Jojweni will be presented below in order to illustrate the process used for all the villages.

4.5.1 Diesel

From Section 4.4, size of commercial sized diesel pump and generator = 3 kW

Capital cost = R23 755 (2006 Rands) (Emcon, 2006)

Therefore in 2013 Rands, using an average inflation rate of 6% = R23 755 x 1.06^7 = R35 719

Replacement costs: Minor service = R 2 000 (2006 Rands) x $1{,}06^7$ = R 3 007 (2013 Rands) total annual value of 4 services per year

Major service = R4 384 (2006 Rands) x $1{,}06^7$ = R 6 592 (2013 Rands) performed once a year

Overhaul = R 9 234 (2006 Rands) x $1{,}06^7$ = R 13 885 (2013 Rands) every 13 years

Pump and pipes = R 10 548 (2006 Rands) x 1.06^7 = R 15 860 (2013 Rands) replaced every 5 years

NPV of recurring costs, using Equation 3.5:

Annual services = R 9 599 / $(1.05)^1$ + R 9 599/ $(1.05)^2$ …. + R 9 599 / $(1.05)^{20}$
= R119 625

Overhaul = R 13 884 / $(1.05)^{13}$ = R 7 364

Pump and pipes = R15 860/ $(1.05)^5$ + R15 860/ $(1.05)^{10}$ + R15 860/ $(1.05)^{15}$ = R 29 792

Fuel = 854 litres pa (derived from Emcon, 2006) x R14.11 = R 12 050 pa, diesel price conservatively assumed to increase at the same rate as discount rate, i.e. 5% therefore total fuel cost = R12 050 x 20 = R 241 000

Therefore NPV of diesel system for Jojweni

= **R 433 500**

Table 4-9: Projected Cash Flow for Diesel Powered Borehole Pump

Year	Capex	Maintenance costs	Fuel costs	Overhaul	Replacement costs	Total
0	R 35 719	R 0	R 0	R 0	R 0	**R 35 719**
1		R 9 142	R 12 050	R 0	R 0	**R 56 911**
2		R 8 707	R 12 050	R 0	R 0	**R 77 667**
3		R 8 292	R 12 050	R 0	R 0	**R 98 009**
4		R 7 897	R 12 050	R 0	R 0	**R 117 957**
5		R 7 521	R 12 050	R 0	R 12 427	**R 149 954**
6		R 7 163	R 12 050	R 0	R 0	**R 169 167**
7		R 6 822	R 12 050	R 0	R 0	**R 188 039**
8		R 6 497	R 12 050	R 0	R 0	**R 206 586**
9		R 6 188	R 12 050	R 0	R 0	**R 224 824**
10		R 5 893	R 12 050	R 0	R 9 737	**R 252 503**
11		R 5 612	R 12 050	R 0	R 0	**R 270 166**
12		R 5 345	R 12 050	R 0	R 0	**R 287 561**
13		R 5 091	R 12 050	R 7 364	R 0	**R 312 065**
14		R 4 848	R 12 050	R 0	R 0	**R 328 963**
15		R 4 617	R 12 050	R 0	R 7 629	**R 353 259**
16		R 4 397	R 12 050	R 0	R 0	**R 369 707**
17		R 4 188	R 12 050	R 0	R 0	**R 385 945**
18		R 3 989	R 12 050	R 0	R 0	**R 401 983**
19		R 3 799	R 12 050	R 0	R 0	**R 417 832**
20		R 3 618	R 12 050	R 0	R 0	**R 433 500**

4.5.2 Solar PVP

Using Lorentz system 9 costing R46 000 (2013 Rands) (Quote from KG electric, 2013) + installation and PV structure = R18 092, therefore total

= R64 092

Cost of storage, using storage volume from Section 4.2.1 of 52.5m^3 and a circular tank of 1 metre high results in area = 8.2m diameter

and therefore 26m perimeter, using a wall thickness of 300mm and total tank height of 1.2metres (200mm freeboard) gives a concrete volume of 26 x 0.3 x 1.2

= 9.4m^3

Using a concrete cost of R2 500/m^3 (SLR, 2013) results in a capital cost of R23 500 + a 300mm base slab = 0.3 x 52.5m^2

= 15.75m^3 x R2 500

= R39 375

Total storage tank cost = R62 875

Therefore total capital costs for PVP system

= R126 967

Recurring costs in 2013 Rands:

Annual service and maintenance = R938

Replacement of main components = R18 589 every 7 years

Service of PVP = R5 188 every 3 years

NPV of replacement costs, using Equation 3.5 again

$= R5\ 188 / (1.05)^3 + R5\ 188 / (1.05)^6 + R18\ 589 / (1.05)^7 + R5\ 188 / (1.05)^9 + R5\ 188 / (1.05)^{12} + R5\ 188 / (1.05)^{15} + R18\ 589 / (1.05)^{14} + R5\ 188 / (1.05)^{18}$

= R41 836

NPV of annual service and maintenance = $R938 + R938 / (1.05)^2 \ldots.. + R938 / (1.05)^{20}$

= R11 690

Therefore total NPV of all costs for PVP system

= **R180 493**

Table 4-10: Projected Cash Flow for Solar Powered Pumping System

Year	Capex	Maintenance costs	Replacement costs	Total
0	R 126 967	R 0		**R 126 967**
1		R 893	R 0	**R 127 860**
2		R 851	R 0	**R 128 711**
3		R 810	R 4 482	**R 134 003**
4		R 772	R 0	**R 134 775**
5		R 735	R 0	**R 135 510**
6		R 700	R 3 871	**R 140 081**
7		R 667	R 13 211	**R 153 958**
8		R 635	R 0	**R 154 593**
9		R 605	R 3 344	**R 158 542**
10		R 576	R 0	**R 159 118**
11		R 548	R 0	**R 159 666**
12		R 522	R 2 889	**R 163 078**
13		R 497	R 0	**R 163 575**
14		R 474	R 9 389	**R 173 438**
15		R 451	R 2 496	**R 176 384**
16		R 430	R 0	**R 176 814**
17		R 409	R 0	**R 177 223**
18		R 390	R 2 156	**R 179 769**
19		R 371	R 0	**R 180 140**
20		R 354	R 0	**R 180 493**

4.5.3 Wind system

Kijito 12 foot windmill capital cost = R185 140

Cost of storage, using volume of storage from Section 4.3.3 of 82.5m^3 and again using a circular concrete reservoir with 1m high walls results in a tank diameter of 10.25m and perimeter of 32.2m. Again using 300mm thick walls, and 300mm thick concrete base results in a total concrete volume of

300mm x (32.2m^2+82.5m^2) = 34.4m^3 at a cost of R2 500/m^3

= R86 000

Therefore total capital cost in year 0 = R271 140

Recurring costs: Operation and maintenance = R5 963 pa

NPV of recurring cost = R5 963 / $(1.05)^1$ + R5 963 / $(1.05)^2$ …. + R5 963 / $(1.05)^{20}$

= R 74 312

Therefore total NPV cost for wind pumping system

= **R345 452**

Table 4-11: Projected Cash Flow for Wind Powered Pumping System

Year	Capex	Maintenance and Replacement costs	Total
0	R 271 140	R 0	**R 271 140**
1		R 5 679	**R 276 819**
2		R 5 409	**R 282 228**
3		R 5 151	**R 287 379**
4		R 4 906	**R 292 285**
5		R 4 672	**R 296 957**
6		R 4 450	**R 301 406**
7		R 4 238	**R 305 644**
8		R 4 036	**R 309 680**
9		R 3 844	**R 313 524**
10		R 3 661	**R 317 185**
11		R 3 486	**R 320 671**
12		R 3 320	**R 323 992**
13		R 3 162	**R 327 154**
14		R 3 012	**R 330 166**
15		R 2 868	**R 333 034**
16		R 2 732	**R 335 766**
17		R 2 602	**R 338 367**
18		R 2 478	**R 340 845**
19		R 2 360	**R 343 205**
20		R 2 247	**R 345 452**

5 ANALYSIS AND COMPARISON OF FINDINGS

This chapter will critically analyse the results presented in Chapter 4 of the different water supply technologies across various criteria, broadly being cost and practical implementation and operation in the unique setting of rural Elundini. Results for life cycle cost analyses, as demonstrated in Chapter 4, for the entire village sample, are presented in **Error! Reference source not found.**.

5.1 Capital Cost Comparison

Generally, as illustrated in **Error! Reference source not found.**, diesel powered pumps have the lowest upfront costs. As discussed in Chapter 4, however one needs to look at the life cycle cost in order to truly determine how expensive a given technology is over its lifetime.

Table 5-1: Comparison of capital costs between different technologies

Village	Diesel (Rands)	Solar PV (Rands)	Wind (Rands)
Mgcantsi	R 35 719	R 54 992	R 112 871
Gamakulu	R 35 719	R 116 152	R 238 848
Kwalanga	R 35 719	R 91 972	R 152 719
Jojweni	R 35 719	R 127 092	R 271 765
Gobo	R 35 719	R 158 252	R 353 736
Emaladini	R 35 719	R 192 032	R 358 933
Polokoe	R 35 719	R 183 452	R 388 386
Tabatlala	R 35 719	R 174 052	R 351 460
Jojoweni	R 35 719	R 196 392	R 421 303
Moleko	R 35 719	R 370 080	R 483 941
Hopedale	R 35 719	R 294 592	R 492 342
Makhuleng	R 28 900	R 399 060	R 523 788
Mohoabatsana A	R 35 719	R 224 412	R 413 830
Makhalong	R 35 719	R 309 712	R 513 132
Katkop	R 35 719	R 256 532	R 488 871
Upper Sinxako	R 35 699	R 426 780	R 586 753
Khalatsu	R 35 699	R 346 252	R 563 375
Umfanta	R 66 500	R 554 260	N/A
St Augustins	R 66 500	R 559 300	N/A
Setaka	R 46 003	R 419 972	R 622 541
Lower Sinxako	R 66 500	R 607 180	N/A
Sekoteng	R 41 866	R 530 100	R 703 968
Moroka	R 66 500	R 679 000	N/A
Thembeni	R 83 700	R 679 832	N/A
Etyeni	R 83 700	R 698 732	N/A
Tsolobeng	R 250 000	N/A	N/A

N/A refers to systems for which no large enough commercially available sized wind or solar powered system could be sourced.

5.2 Life Cycle Cost Analysis

More critical than merely the upfront cost of a technology is the total cost the technology will incur over its lifetime. The results of the cost analyses performed in Chapter 4 are summarised in **Error! Reference source not found.**. The lower life cycle costs associated with solar powered systems, due primarily to their lack of fuel costs and relatively low capital costs, illustrates clearly their cost advantage over their diesel and wind counterparts. Although the high capital costs of wind are recovered through its lifetime due to the lack of fuel costs and lower maintenance costs than diesel, it never reaches parity with solar. These findings are consistent with what was preliminarily concluded in the literature review from previous similar investigations.

Table 5-2: Comparison of net present value between different technology choices for each village

Village	Annual Hydraulic Energy Requirements (m^4)	Diesel NPV (Rands)	Solar NPV (Rands)	Wind NPV (Rands)
Mgcantsi	17 675	R 159 093.71	R 108 517.11	R 187 183.25
Gamakulu	231 333	R 472 254.52	R 169 677.11	R 313 159.74
Kwalanga	45 323	R 229 957.55	R 145 497.11	R 227 030.75
Jojweni	203 882	R 433 500.61	R 180 617.11	R 346 077.24
Gobo	267 230	R 473 414.05	R 211 777.11	R 428 048.03
Emaladini	372 531	R 593 139.75	R 245 557.11	R 433 245.53
Polokoe	310 973	R 588 520.12	R 236 977.11	R 462 698.03
Tabatlala	210 843	R 466 512.30	R 227 577.11	R 425 772.24
Jojoweni	427 792	R 715 240.78	R 249 917.11	R 495 615.53
Moleko	782 380	R 971 331.69	R 489 613.57	R 558 252.90
Hopedale	589 811	R 1 098 426.10	R 348 117.11	R 566 654.41
Makhuleng	845 381	R 1 017 709.27	R 518 593.57	R 598 100.40
Mohoabatsana A	173 771	R 465 326.01	R 277 937.11	R 488 142.24
Makhalong	662 207	R 1 000 706.72	R 363 237.11	R 587 444.41
Katkop	303 440	R 650 494.83	R 310 057.11	R 563 183.03
Upper Sinxako	1 083 705	R 1 120 263.28	R 546 313.57	R 661 064.98
Khalatsu	653 491	R 782 068.46	R 399 777.11	R 637 686.91
Umfanta	1 430 060	R 1 359 230.32	R 727 512.30	N/A
St Augustins	1 337 720	R 1 286 640.81	R 732 552.30	N/A
Setaka	982 021	R 969 084.58	R 473 497.11	N/A
Lower Sinxako	1 380 885	R 1 320 541.83	R 780 432.30	N/A
Sekoteng	933 133	R 1 060 693.93	R 649 633.57	R 778 280.40
Moroka	1 448 089	R 1 500 795.68	R 852 252.30	N/A
Thembeni	2 190 753	R 2 298 497.43	R 733 357.11	N/A
Etyeni	1 962 769	R 2 119 270.55	R 752 257.11	N/A
Tsolobeng	48 337 797	R 44 161 873.82	N/A	N/A

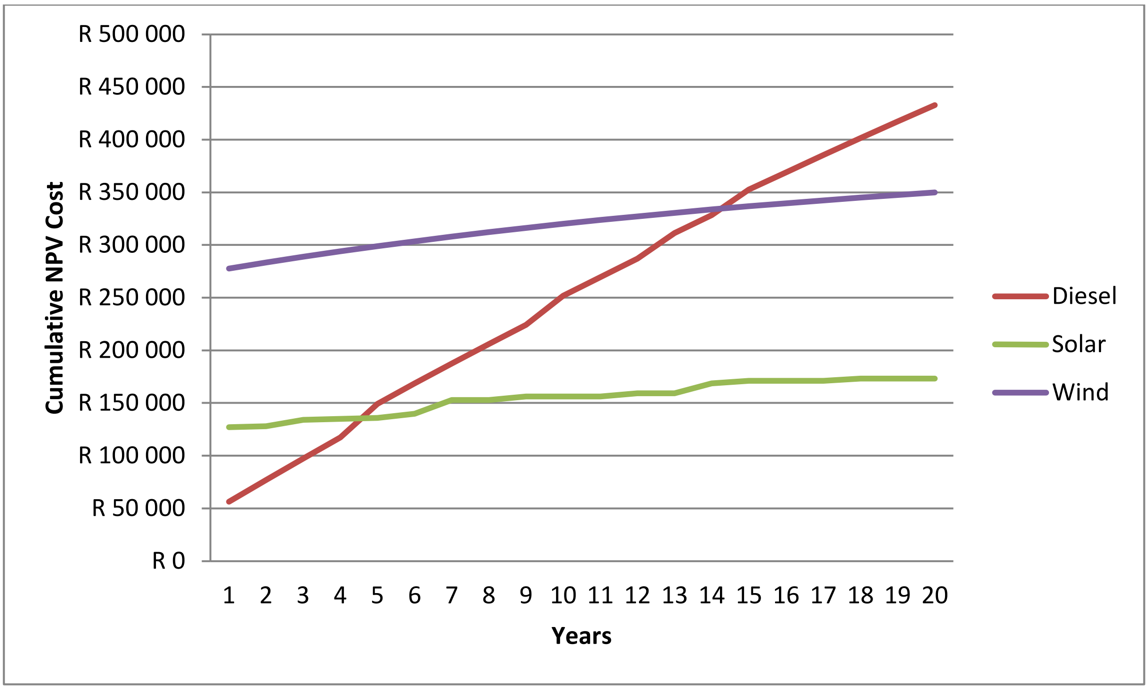

Figure 5.1 Chart illustrating comparison between cumulative NPV costs of different technologies for Jojweni village.

5.3 Societal Integration

As mentioned previously and discussed in Section 2.8, one cannot determine the potential success of a new technology by looking only at the technical and financial aspects but needs to consider how it might integrate with the society in which it is to be implemented. This section outlines some of the main societal considerations identified for the Elundini municipality.

5.3.1 Theft

Throughout the author's study, a common problem that kept arising regarding the dissemination of new water pumping alternatives, particularly solar powered pumps, to diesel powered borehole pumping was the issue of theft of solar panels (Zietsman, 2012; Short & Thompson, 2003). This was further reinforced by several similar studies such as those quoted in the literature review. This is obviously a potentially debilitating problem as without solar panels, and therefore a power source, the pumps will not operate and therefore village inhabitants will be without water. Although this is, to a certain extent, mitigated by having water storage as part of the solar pumping system, providing for at least some autonomy, replacement panels would need to be delivered before the water tank empties.

Theft is not seen to be as much of an issue with the other technologies as windmills are large structures with no specific parts particularly valuable and worth stealing, although it would be recommended that no copper piping or elements be used due to their black market value. Diesel powered pumps and generators are also usually stored within secured buildings near the boreholes and also lack any specific, valuable and easy to steal elements. This obviously puts SPVP's at a considerable disadvantage over their wind and diesel counterparts. Although measures can, and must if SPVP's are implemented, be taken to minimise the risk of theft, no measure is fool-proof and the issue of theft must be considered when making a decision of which technology to utilise.

5.3.2 Employment and Skills Transfer

Employment around the selection of a certain water pumping technology is a contentious issue as the technologies requiring less maintenance, and therefore which are more reliable, are also the ones which offer less opportunity for employment creation. Although the South African government has identified renewable energy and the "green-economy" as a way of generating more employment (UNEP, 2013), in the case of water pumping however this is not exactly the case. Although on a country wide scale, it may be argued that with the increased deployment of SPV and wind powered pumps, especially if manufacturing is done in South Africa, that overall levels of employment would increase. Determining this however falls outside the scope of this study. Only potential direct employment as a result of particular water pumping technology implementation will be considered.

The fact that diesel powered pumps require regular maintenance (monthly), as illustrated in Section 2.7, creates the need for employment of someone in the community to perform this maintenance. This maintenance does however require someone who is relatively well-skilled (SELF, 2008) and therefore may be out of reach for the employment of a local village inhabitant. Wind pumps do not require as much maintenance, with the skill levels to do so also not as high as those required for diesel maintenance and hence someone from within the community could be up-skilled to carry out this maintenance (Harries, 2002). Solar powered pumps tend to require the least amount of maintenance (once every 3-5 years) with most repairs and maintenance requiring little specialist skills (Odeh et al, 2006). This makes it easy to up skill almost anyone from within the community to do and therefore relatively easily creates new employment, albeit not on a large scale.

5.3.3 Level of service

Through several studies on the choice of water pumping technology covered in the literature review, in the situation of rural water supply where fuel is required to be transported long distances and easy access to maintenance is not always available, solar and wind powered options tend to provide higher levels of service with fewer malfunctions and break downs. This of course has a large bearing on the choice of a technology, especially the acceptance by a community of a new technology. A new technology which will provide a more reliable supply of water is more likely to be accepted over its predecessor (Short & Thompson, 2003). As highlighted by Harries (2002), industries themselves, arguably corrupt ones, often form around certain aspects of a given water supply technology such as the delivery of diesel to the pump generators. In the greater Joe Gqabi district municipality, there are similar instances where the supply of water through the use of water tankers has prevented the commissioning of formal water supply systems which have already been constructed (author's interview with community members, 2011). Although it is the inhabitants that ultimately suffer in these situations, and the implementation of a better suited technology/infrastructure would undoubtedly benefit them, it is not a simple case of entering into the community and disseminating the technically more beneficial technology.

In the accepting of a new technology, there exist various potential hurdles to its successful implementation. Although diesel powered pumps may require regular maintenance and replacement spares, the fact that they have been operating for some time means that an established supply chain has been established so that when repairs or replacement parts are required, they are relatively easily attainable. Solar and wind pumps however are not well-established in the region for village level water provision and therefore should maintenance or spare parts be required, they may not currently be as easily accessible.

Wind pumps are however used sporadically in the region, primarily on farms and there is an established industry in South Africa for wind pumps, hence as long as adequate service providers could be sourced prior to their implementation, wind pump maintenance shouldn't pose a major obstacle to their potential implementation. PVP's, historically being the least established, but by no means non-existent, water supply technology industry on a large scale in South Africa; pose the highest relative risk with regards lack of maintenance. This however in recent years has largely been nullified by the establishment of several major international technology providers locally such as Lorentz and Grundfos providing complete life cycle solutions from item purchase to parts and servicing. Local manufacturers have also established themselves in the market, such as Watermax, and with suitable agreements being made with service providers prior to implementing their products, it is foreseen that part sourcing and maintenance would not be a problem.

5.3.4 Technology choice

Looking at the choice of a technology for groundwater provision to a rural village or community purely from a sociological perspective (ignoring costs), there are several variables that need to be looked at when making this decision. Whereas the use of a technology such as diesel will result in the creation of a few skilled jobs, for which there will be regular work due to the constant maintenance requirements, the choice of this technology runs the risk of not providing as reliable a level of water supply service as other options such as PVPs. PVP's on the other hand, although more reliable than their diesel counterparts, would result in the creation of little employment. As each technology type comes with its own sociological advantages and disadvantages, the primary needs and requirements of the community in which the borehole pumps are to be installed therefore needs to be assessed as this will determine, at least from a sociological point of view, which technology is most suitable.

In the case of the Elundini municipality, when UCT and the author were approached by their representatives, their primary need was for the reliable, cost-effective provision of water to the inhabitants of the municipality. It can also be argued that job creation and economics wise, even if no direct employment is created by a certain water supply technology, the fact that the inhabitants have a more reliable water supply because of it, means that they have more time to pursue more productive and economically beneficial activities such as studying and job searching as opposed to spending time collecting water. It is within this context then, that sociological impacts of the various groundwater providing technologies was assessed; with SPV systems shown to provide the most reliable supply of water for the region.

6 CONCLUSION

This study has drawn several important conclusions through the literature reviewed and the analyses and comparisons of the various designed systems for villages within the Elundini municipality. These are summarised and presented below with firstly a summary of the findings, conclusions drawn from these, a summary of the contributions of this study to the field and recommendations for future research.

6.1 Summary of Findings

This study has illustrated well that there is indeed scope for the effective use of renewable energy, particularly solar, powered borehole pumps within the Elundini local municipality. Wind powered pumps, although feasible and generally cheaper over their lifetime than diesel pumps, are not appreciably cheaper than diesel and their high capital costs could make them unattractive to the local municipality. A major reason for their marginal effectiveness is the relatively poor wind conditions of the regions. Solar powered pumps however, are far more attractive than their diesel counterparts over their lifetime from both a cost and operational perspective, and although several other socio-economic factors need to be considered when making a choice of technology such as the risk of theft; for the Elundini municipality they make the most attractive choice from a technical, practical and financial perspective.

6.2 Conclusions

The Joe Gqabi district municipality, not unlike the rest of South Africa, is beset with a unique eco-social situation with the decision on the best type of technology implementation to help solve a problem, not a straight-forward one. There are a large number of social and political forces at play that need to be addressed before one can simply install a new technology deemed to be technically and economically the best choice by the service provider.

From a purely technical and economical point of view however, and if one can implement the systems in such a way that theft can be minimised and ownership can be successfully bestowed onto the local inhabitants, for the Elundini municipality solar photovoltaic powered pumping systems do offer an improved alternative to current diesel powered options. Although a general conclusion, due to the varying nature of groundwater supply conditions and requirements, each potential site of implementation would need to be thoroughly investigated prior to the installation of a new system.

It is of the author's opinion that a potentially effective way of mitigating theft as well as addressing problems of regular maintenance of the systems is by creating ownership within the community as opposed to merely just supplying the systems, or the aid approach as has historically been used. This is illustrated in Mabuze et al (2007)'s study on the transfer of energy technologies in developing countries who cite creating ownership, amongst other findings, as one of the keys to the successful implementation of a new technology within a developing world context.

This study has also illustrated well the importance of assessing the natural energy resources of an area prior to installation of a new technology. This can be seen by the large technical and cost advantages that the designed solar systems have over their wind counterparts in a region with appreciably better solar resources than wind. Another critical aspect that this study has highlighted is the importance of calculating the life time costs of a technology as opposed to merely considering up-front costs. For instance, if the diesel pumps had been chosen for Jojweni village based purely on the fact that their initial cost was approximately R50 000 as opposed to approximately R130 000 for the solar option; this difference would be made up for by the solar pump's lower operating costs within 5 years and over the pump's life time the solar option would save in excess of R250 000.

6.3 Summary of Contributions

This study has highlighted well the cost effectiveness of solar powered water supply systems for groundwater abstraction in the Elundini municipality when studied over their lifetime. It has also illustrated that, although technically feasible, wind power is not a favourable and cost effective technology choice, when compared to the likes of solar for the region due to the relatively poor wind resources. It has also highlighted, as several other similar studies do, the complexities inherent with installing a new technology and how these need to be considered when assessing their suitability in a region such as the Elundini municipality.

6.4 Suggestions for Future Research

If further research is conducted into the applicability of renewable energy for water pumping from boreholes in any rural environment, the most crucial aspect to consider improving on is the sourcing of more precise wind, groundwater and solar data. It is felt that although the method used in this study is adequate in order to inform decision makers on the best groundwater abstraction systems for their municipality, and the data used does give a good estimation, in order to confidently approach funding organisations to roll out new technology, one should attempt to use as accurate information as is possible. The systems designed in this study, due to the relatively uncertain nature of the data, were done conservatively as a way to mitigate against possibly inaccurate data being used. In a situation where more accurate data is attained, one could size systems a lot closer to what the actual pumping requirements and available resources permit which would make them more cost effective.

It is recommended that for future studies in this field, one attempt to combine the wind and solar resource maps of South Africa with the groundwater potential of South Africa. This could then be presented similarly to, or combined with, an assessment tool such as the GMS modelling tool that was used for groundwater resource assessment in this study. This would then provide a relatively simple way for decision makers within rural municipalities in South Africa to assess the most appropriate choice of groundwater abstraction technology, if at all, based on their unique natural resource potential, as well as socio-economic priorities. If sufficient funding could be sourced, it would also be beneficial to install a pilot system in order to test the veracity of conclusions drawn by this study.

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APPENDICES

A. Discussions and Interviews

A.1 Telephonic conversation between author (GK) and Subject 1 of AGES

GK: Where would the best place be to find information relating to specific heads that pumps are pumping to?

Subject 1: The Elundini hydro census and infrastructure survey may show this but a lot of the time the information lies with private consultants who are not keen on sharing out this information as the handing and out and paying of work appointments is complicated.

GK: Who are the main private consultants who have been involved with this work?

Subject 1:: Sintech and Aurecon. The Joe Gqabi district municipality, if they have their act together, should have all this information available through their GIS department. If I were you I would then use the GIS and borehole depth information to determine the total heads that the boreholes are pumping to. To get the specific information for each borehole otherwise will be very difficualt.

GK: You have obviously been involved in this are for a while, what do you think about using solar powered borehole pumps?

Subject 1:: There have been private companies approach the municipality before to install solar pumps and technically they are extremely feasible and would be a great option, however theft is a major problem and very seldom do they last long without being stolen.

GK: Yes, that does seem to be a common problem, I am also going to look at wind pumps, perhaps these would be a better option.

Subject 1:: Yes, that would be very interesting to see, there are one or two installations around and I would like to see what you discover. When you write a paper on your research I think you should come and present it at the groundwater conference to be held in Durban in September.

GK: That definitely sounds like something I would like to aim for. Thank you so much for your invaluable help.

A.2 Initial discussion between Jude Cobbing and Author

Mr Cobbing gave a brief overview of the state of affairs regarding ground water provision in South Africa applicable to my research, citing several wide ranging studies on the subject for South Africa including the GRA 1 and GRA 2. Further to this a study/working tool has been completed by Rick Murray in the Western Cape covering all regions of South Africa in the Karoo basin. This tool essentially provides information regarding a particular area's groundwater provision potential including median yields and water depths etc.

In Mr Cobbing's research into ground water provision in South Africa, operation and maintenance of infrastructure once it has been installed is cited as the biggest hindrance to sustainable ground water provision. This bodes well for the introduction of systems requiring less maintenance than traditional diesel powered options.

A.3 Second discussion between author and Jude Cobbing

Jude gave a background as to how groundwater data and potential yields for South Africa have been determined in the past and what the current GRA2, and Ricky Murray's subsequent model, are based on. Also mentioned topography that could be made available by Theo Roussow if unavailable freely, much information on Ricky Murray's data already on the server.

Pertinent points:

- GRA based on KM2 models
- Ricky Murray tool adapted to quaternary catchments
- Need separate software from WRC

B. GMS Toolkit Outputs

SiteName	X	Y	Z(mamsl)	T(m²/d)	S	Q(l/s)	Time(d)	Drawdown(mbgl)
NGCELE	28.52505	-31.1608	0	5	0.0003	1	365	29.5
HOPEDALE	28.4795	-31.1706	0	5	0.0003	0.85	365	25.1
STAUGUSTINE	28.61143	-31.2178	0	5	0.0003	1.26	365	37.2

ETYENI	28.53722	-30.9017	0	5	0.0003	2.13	365	63.2
GAMAKULU	28.54167	-31.0067	0	5	0.0003	0.21	365	6.2
MGCANTSI	29.60337	-30.8286	0	5	0.0003	0.1	365	3
LOWERTSEKONGMHLOTSHENI	28.29035	-30.4196	0	5	0.0003	0	365	0
SEKOTING	28.53159	-30.7094	0	5	0.0003	1.6	365	47.2
MOROKA	28.50124	-30.7276	0	5	0.0003	1.9	365	56.1
KHALATSU	28.45178	-30.7051	0	5	0.0003	1.13	365	37.7
SIKHEPENI	28.69722	-30.8467	0	5	0.0003	0.58	365	17.1
FAIRVIEWMVUMANE	28.50086	-30.5604	0	5	0.0003	0.54	365	15.9
FLETCHERVILLE	28.42081	-30.6173	0	5	0.0003	0	365	0
LAHLANGUBOLUGCADWENI	28.44448	-30.5876	0	5	0.0003	0.84	365	24.8
THAKASO	28.3575	-30.8858	0	5	0.0003	1	365	31.2
MATSHELENG	28.57905	-30.5136	0	5	0.0003	1	365	29.5
MATSHATA	28.48588	-30.4354	0	5	0.0003	1	365	29.5
LENGEULUNDI	28.20834	-30.6594	0	5	0.0003	1	365	29.5
KATKOP	28.5228	-30.878	0	5	0.0003	0.98	365	30.7
NGCELE	28.52505	-31.1608	0	5	0.0003	1	365	29.5
HOPEDALE	28.4795	-31.1706	0	5	0.0003	0.85	365	25.1
STAUGUUSTINE	28.57555	-31.2295	0	5	0.0003	1	365	29.5
UPPERSINXAKO	28.59358	-31.13	0	5	0.0003	1.04	365	31.1

		23						
GAMAKULU	28.54167	-31.0067	0	5	0.0003	0.21	365	6.2
EMALADINI	28.60417	-30.9294	0	5	0.0003	0.47	365	13.9
LOWERTSEKONG	28.47573	-30.6862	0	5	0.0003	1	365	32.1
MAKHULENG	28.46738	-30.7035	0	5	0.0003	0.89	365	31.4
SEKOTING	28.53159	-30.7094	0	5	0.0003	1.6	365	47.2
MOROKA	28.50124	-30.7276	0	5	0.0003	1.9	365	56.1
KWALANGASWAZINI	28.69722	-30.8467	0	5	0.0003	0.26	365	7.7
SIKHEPENI	28.69722	-30.8467	0	5	0.0003	0.58	365	17.1
FAIRVIEWMVUMANE	28.50086	-30.5604	0	5	0.0003	0.54	365	15.9
GOBO	28.39091	-30.534	0	5	0.0003	0.45	365	17
THEMBENI	28.41306	-30.5444	0	5	0.0003	2.03	365	60.7
RAMAFOLE	28.54692	-30.5607	0	5	0.0003	1	365	29.5
SETAKA	28.51888	-30.4981	0	5	0.0003	1.28	365	37.8
MOHOABATSANE	28.4468	-30.465	0	5	0.0003	0.9	365	26.6
LOWERNXOTSHANA	28.3485	-30.5557	0	5	0.0003	0.41	365	12.7
JOJWENI	28.53358	-30.8578	0	5	0.0003	0.71	365	21.8
BOREHOLE	27.87917	-31.5639	0	5	0.0003	1	365	29.5
UPPERTSITSANA	28.36944	-30.8989	0	5	0.0003	1	365	31.2
NGCELE	28.52505	-31.1608	0	5	0.0003	1	365	29.5

SOMERVILLE	28.65099	-31.1952	0	5	0.0003	0.48	365	14.2
LOWERSINXAKO	28.62277	-31.1261	0	5	0.0003	1	365	30
SI QUNGWINI								
GAMAKULU	28.54167	-31.0067	0	5	0.0003	0.21	365	6.2
EMALADINI	28.60417	-30.9294	0	5	0.0003	0.47	365	13.9
LOWERTSEKONG	28.47573	-30.6862	0	5	0.0003	1	365	32.1
MAKHULENG	28.46738	-30.7035	0	5	0.0003	0.89	365	31.4
MOKHALONG	28.56042	-30.7472	0	5	0.0003	1	365	30.7
UMFANTA	28.5355	-30.748	0	5	0.0003	1.23	365	37.2
MABHELENI	28.69722	-30.8467	0	5	0.0003	0.8	365	23.6
TSOLOBENG	28.47461	-30.6478	0	5	0.0003	5.92	365	174.7
FLETCHERVILLE	28.42081	-30.6173	0	5	0.0003	0	365	0
GOBO	28.39091	-30.534	0	5	0.0003	0.45	365	17
THEMBENI	28.41306	-30.5444	0	5	0.0003	2.03	365	60.7
SEKHUTLONG	28.57905	-30.5136	0	5	0.0003	1	365	29.5
KINIGAPOORT	28.53722	-30.9017	0	5	0.0003	1	365	29.9
ZWELITSHA	28.36655	-30.5749	0	5	0.0003	1	365	29.7
ZWELITSHALUZIE	28.55001	-30.7864	0	5	0.0003	1	365	29.5

C. WAsP WASA Calculation Outputs

'SAWASA_05_28.578E_32.219S_7.4_5' wind atlas

Produced on 2014/03/06 at 07:23:27 AM by licenced user: Unlicensed using WAsP version: 10.02.0010.

Reference conditions

The wind atlas contains data for 4 reference roughness lengths (0.000 m, 0.030 m, 0.100 m, 0.400 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) above ground level. The roses of Weibull parameters have 12 sectors each.

Table C-1: Regional wind climate summary for Elundini (WASA, 2012)

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m
10.0 m	Weibull A [m/s]	4.8	3.2	2.8	2.2
	Weibull k	1.48	1.27	1.28	1.27
	Mean speed [m/s]	4.37	2.93	2.56	2.00
	Power density [W/m²]	142	55	36	18
25.0 m	Weibull A [m/s]	5.2	3.9	3.4	2.8
	Weibull k	1.49	1.41	1.34	1.31
	Mean speed [m/s]	4.67	3.54	3.11	2.57
	Power density [W/m²]	172	81	60	35
50.0 m	Weibull A [m/s]	5.6	4.5	4.0	3.3
	Weibull k	1.51	1.42	1.38	1.29
	Mean speed [m/s]	5.05	4.07	3.67	3.07
	Power density [W/m²]	211	122	94	62
100.0 m	Weibull A [m/s]	5.7	5.2	4.9	4.2

	Weibull k	1.34	1.44	1.51	1.44
	Mean speed [m/s]	5.22	4.70	4.44	3.79
	Power density [W/m²]	282	185	144	97
200.0 m	Weibull A [m/s]	6.3	6.2	5.8	5.1
	Weibull k	1.47	1.53	1.56	1.55
	Mean speed [m/s]	5.74	5.58	5.17	4.58
	Power density [W/m²]	325	280	218	153

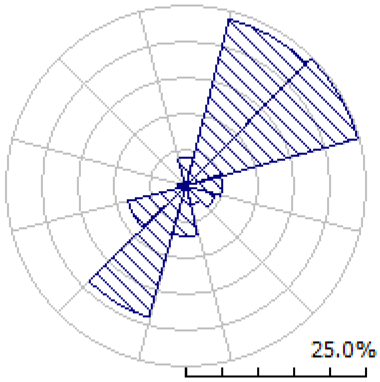

Figure C.1: Wind rose for roughness length 0.00 m for Elundini Municipality (WASA, 2012)

Table C-2: Sector frequencies for roughness length 0.00 m

i	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
[°]	0	30	60	90	120	150	180	210	240	270	300	330
f [%]	3.9	23.8	24.6	5.0	4.2	2.7	6.9	19.0	8.2	1.2	0.5	0.1

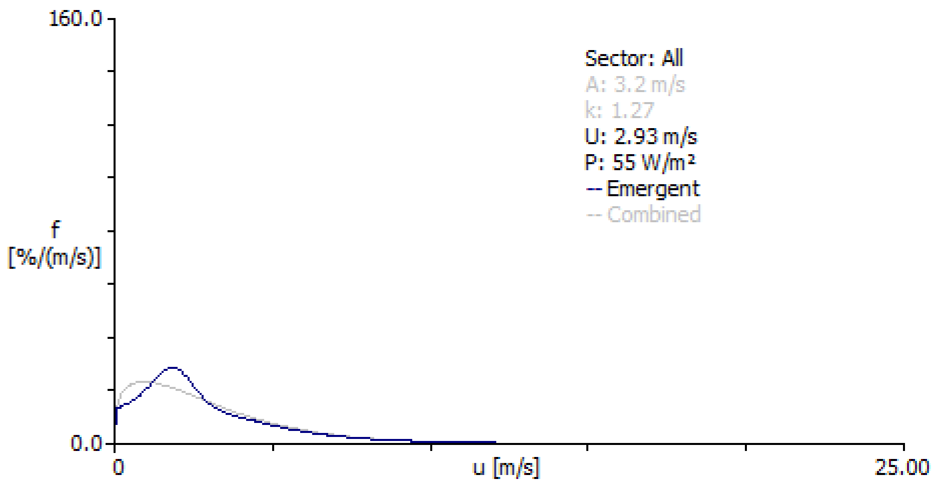

Figure C.3: Wind Speed distribution curve for Elundini (WASA, 2012)

Table C-2: Sector-wise Weibull distributions for roughness length 0.00 m

H	i °	1 0	2 30	3 60	4 90	5 120	6 150	7 180	8 210	9 240	10 270	11 300	12 330
10.0	A k U E	3.0 15.63 2.94 16	2.9 3.37 2.63 15	5.8 2.92 5.19 122	5.1 2.60 4.57 89	1.9 1.12 1.82 17	2.5 1.44 2.24 20	2.7 1.49 2.42 24	5.4 1.95 4.74 128	10.5 2.55 9.31 769	11.3 2.74 10.09 932	7.9 2.00 7.02 404	4.2 10.24 3.99 40
25.0	A k U E	3.9 11.38 3.69 32	3.4 3.71 3.10 23	6.1 2.83 5.39 139	4.1 1.60 3.67 75	1.9 1.06 1.90 22	2.5 1.37 2.26 22	3.0 1.55 2.69 31	5.6 1.99 4.96 144	11.6 2.77 10.32 990	12.2 4.12 11.11 102	8.5 1.66 7.57 629	5.5 15.10 5.33 95

											7		
50.0	A k U E	4.6 10.60 4.34 52	4.1 4.01 3.71 38	6.6 2.98 5.91 178	3.9 1.41 3.56 82	1.9 0.99 1.94 27	2.8 1.39 2.52 30	3.1 1.46 2.80 38	6.0 1.92 5.32 184	11.3 2.19 10.04 1087	13.5 2.77 12.03 1571	9.1 1.56 8.21 872	6.4 4.87 5.90 146
100.0	A k U E	4.3 2.16 3.83 61	4.5 2.62 3.98 59	6.2 1.87 5.48 206	3.9 1.29 3.60 100	2.6 1.08 2.49 48	1.8 0.98 1.80 23	3.1 1.34 2.87 47	6.3 1.81 5.57 224	13.4 2.62 11.92 1583	14.6 2.45 12.92 2117	11.5 1.95 10.21 1279	7.0 10.18 6.64 186
200.0	A k U E	3.0 1.28 2.80 47	4.6 2.80 4.10 62	7.3 2.85 6.48 241	5.0 1.94 4.46 107	3.2 1.33 2.93 51	2.6 1.39 2.39 26	3.5 1.71 3.08 40	6.7 2.14 5.94 230	14.6 3.45 13.15 1825	15.9 2.14 14.04 3035	13.2 2.20 11.66 1700	7.6 8.67 7.18 239

D. Ethical Clearance

EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).
NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination

This form must only be completed once the most recent revision EBE EiR Handbook has been read.

Name of Principal Researcher/Student: **Gordon Kernick** Department: Energy research Centre

Preferred email address of the applicant: **gordon.kernick@gmail.com**

If a Student: Degree: **MscEng** Supervisor: Prof K Bennett

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Effectiveness of rurally located solar and wind powered borehole pumps

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?		NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.		NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EiR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	Gordon Kernick	23/01/2012
This application is approved by:		
Supervisor (if applicable):	PROF KF BENNETT	
HOD (or delegated nominee): *Final authority for all assessments with NO to all questions and for all undergraduate research.*	Ken Bennett	25.01.2013
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	[signature]	11 . 07 . 2011