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Faculty of Bioscience Engineering

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Appropriate Renewable Energy for Water Pumping in Rural Mozambique

Marie Tapiwa Bossyns

Promotor: Prof. dr. ir. J. Pieters

Master's dissertation submitted in partial fulfilment of the requirements for the degree of
Master in Bioscience Engineering: Environmental Technology

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Last but not least, I would like to thank my uncle Walter Bossyns for helping me contact local firms for price enquiries and of course the rest of my family for all their support.

CONTENT

LIST OF ABBREVIATIONS

AC	Alternating current
DC	Direct current
DNA	Direcção Nacional de Agua
DOY	Day of year
FUNAE	Fundo Nacional de Energia
mbgl	Meters below ground level
PV	Photovoltaic
W_p	Watt peak

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EXECUTIVE SUMMARY

The research question, which renewable energy application would be the best for water pumping to provide the rural population of Mozambique with drinking water in absence of an electricity net, was formulated by the project *Renewable Energy for Rural Development* by the Belgian Technical Cooperation. In the project proposal, an amount of € 500 000 was foreseen for wind energy driven water pumps without profound knowledge of the best technology for Mozambique. The objective of the study was to confirm or dismiss the hypothesis that wind energy pumping would be the most appropriate solution.

In absence of operational routine field data, the study was obliged to rely on data from general scientific literature, from international databases and best estimates of costs derived from internet or from private enterprises. Several other parameters were considered constant to keep the study realistic and specific. Three borehole depths were fixed, as well as the needed water flow at 40 $m^3\ d^{-1}$. The result is a comparative cost-effectiveness study between the different technical solutions for water pumping installations. It was divided in a technical and an economical part. The combination of the two allowed to integrate the results of the different options in a comparative life-cycle costing analysis.

The effectiveness of the photovoltaic, wind turbine and direct wind installations were compared. In the economic part, also hand pumps and diesel driven installations were included in the study.

From the results could be derived that solar driven pumping installations were most cost-effective for rural Mozambique, supposing that the initial assumptions and the estimation of certain parameters were sufficiently precise. This result was mainly influenced by the relatively high solar irradiation in Mozambique, compared with relatively low wind speed regimes. The major advantage of the solar installation was the need for only one or maximum two boreholes for the given water flow of 40 $m^3\ d^{-1}$. Secondly, the investment costs were relatively low. Due to the low wind regimes, wind turbine installations were not a realistic option because the limited yield imposed high number of wind turbines per borehole. The direct windmills were a technically feasible option, but the relatively low yield per borehole implied deploying more than one installation including more boreholes to fulfill the water supply requirements. This made the costs rise considerably. Hand pumps were most cost-effective for shallow boreholes, but the low effectiveness and high costs for deeper boreholes played again in favour of solar energy systems. Diesel pumps were relatively cheap investments, but the high running costs due to fuel consumption made it an unrealistic option as well.

As a final conclusion, PV water pumping is advised to the BTC project as the most cost-effective solution for drinking water installations in rural Mozambique. Due to the difficult rural conditions it is also recommended to support the establishment of an effective maintenance system, organized in several tiers, in order to closely monitor installation failures and to early intervene when needed.

SAMENVATTING

De onderzoeksvraag naar welke hernieuwbare technologie het beste is voor waterpompen voor drinkwatervoorziening in landelijke gebieden (zonder elektriciteitsnet) van Mozambique kwam van het project *Renewable Energy for Rural Development* van de Belgische Technische Coöperatie. In het initiële projectvoorstel werd een bedrag van € 500 000 toegekend aan windwaterpompen zonder grondige kennis van de beste technologie voor Mozambique. Het doel van deze studie was het bevestigen of ontkrachten van de hypothese dat windwaterpompen de beste oplossing zijn.

De studie, bij gebrek aan operationele data vanuit de praktijk, was verplicht zich te baseren op data vanuit wetenschappelijke literatuur, internationale databases en inschattingen van kosten via internet en communicatie met privébedrijven. Verschillende parameters werden als constant beschouwd om de analyse overzichtelijk doch specifiek te houden. Drie boorputdieptes werden geselecteerd en het beoogde debiet werd vastgelegd op 40 $m^3\ d^{-1}$. Het resultaat is een vergelijkende kost-effectiviteitsstudie tussen verschillende technologische oplossingen voor waterpompinstallaties. De studie werd onderverdeeld in een technisch deel en een economisch deel. De resultaten werden gecombineerd in een vergelijkende studie van de respectieve levenscycluskosten.

Fotovoltaïsche, wind turbine en (directe) windmolenaandrijving werden onderling vergeleken in de technische studie alsook vergeleken met de handpomp en diesel aangedreven pompen in de economische studie.

Uit de resultaten kon, onder voorbehoud dat de vooronderstellingen correct zijn evenals de gemaakte inschattingen van bepaalde parameters, besloten worden dat de waterpompinstallaties aangedreven door zonne-energie de meest kost-effectieve oplossing bieden voor Mozambique. Dit resultaat is gebaseerd op, ten eerste, de hoge zonne-instraling (en lage windsnelheden) met als grootste voordeel het beperkt aantal installaties nodig voor het bereiken van het debiet van 40 $m^3\ d^{-1}$ en ten tweede de lage investeringskosten. Door het lage algemene windsnelheidsregime was het gebruik van wind turbines onrealistisch daar het aantal nodige installaties hoog opliep voor het bereiken van de gewenste waterhoeveelheid. De directe windmolen bood een alternatief, maar de extra boorputten nodig voor iedere installatie vormden een economisch obstakel. Handpompen kwamen als meest kost-effectief uit de studie voor ondiepe boorputten, maar bij grotere diepte werd het pompen snel ineffectief en vormde de zonnepomp een sterk alternatief. De levenscycluskost van de dieselpomp was zeer hoog ten gevolge van de hoge operationele kosten veroorzaakt door het brandstofverbruik.

Het gebruik van PV waterpompen wordt daarom geadviseerd aan BTC voor het *Renewable Energy for Rural Development* project in Mozambique. Ten gevolge van de moeilijke landelijke condities wordt ook aanbevolen een piramidaal georganiseerd onderhoudsprogramma op te stellen om de correcte werking te controleren en indien nodig bij te sturen.

INTRODUCTION

This master thesis deals with an important development problem in many low income countries. Access to safe water for domestic use is unfortunately still a problem for many poor families in developing countries. The solutions are not merely technical. Technological issues must be balanced against cost, operational constraints such as maintenance issues and energy supply, climatological aspects such as wind strength, groundwater depth or solar irradiation, etc. The problem is complex and multivariate.

A development project, executed by Belgian Technical Cooperation (BTC), dealing with this problem, was the immediate opportunity to study the water supply problem for the rural poor in depth.

BTC is the execution organ for Belgian bilateral – government to government – cooperation. It formulates and executes development projects on behalf of the Directorate of the Belgian Cooperation of the Ministry of Foreign Affairs, covering a wide variety of subjects in the health, education, agricultural and infrastructure sectors.

This particular project is actually in execution in Mozambique for a total value of 18 million euros (Belgian Technical Cooperation, 2009). The underlying working hypothesis of the project is that providing renewable energy solutions for local needs in rural communities can stimulate local economic activities. The project considered initiatives as varied as hydropower as well as PV installations to provide electricity but also wind water pumping. But for the latter, the project estimated to rather start first with feasibility studies as it wanted to have more evidence-based arguments on which to base its choices. FUNAE (National Energy Fund), a national institute under the umbrella of the Ministry of Energy, is the Mozambican partner organization co-executing the project. In the light of the foreseen feasibility studies, FUNAE hosted me during 2.5 months in order to analyse the problem and the different options available for water supply to the rural poor.

The Belgian Cooperation initial project proposal opted to invest € 500 000 in wind water pumping (Belgian Technical Cooperation, 2009), but without having all the arguments in favour of such choice. The analysis made in this thesis was realized on request of the BTC project in order to enable strategic decisions. Was the initial option to invest in wind water pumping the most optimal, taking into account the environment of poverty, no electricity supply, and the economic aspects of durability and maintenance requirements?

The first chapter starts with a literature review to gain a basic knowledge on Mozambique as a country, with its geographical and climatological context and its specific rural conditions. Further on, the theory about pumping technology and renewable energy is elaborated, and lastly the problems surrounding maintenance of installations is analysed.

Chapter 2 covers the methodology used in the study. Absence of reliable and systematically collected data obliged the study to make use of mathematical modelling and argued fixed values for several parameters.

Chapter 3 combines the obtained results, the data analysis and the discussion. Estimates of effectiveness and costing allow comparing the different types of installations under study: PV, wind turbine, windmill, diesel pumping and hand pump systems.

Chapter 4 and 5 deal with respectively the conclusions and the further research needs. The conclusions in this work can only be local. As every country in the world, Mozambique has particular environmental and economic conditions that shape the analysis of the several technical options available. Other conditions might alter the conclusions. The methodology followed though, is applicable to many situations.

1. LITERATURE

1.1. Introduction

In 1990, 76% of the world population had access to safe drinking water. In 2010 it had increased to 89% (United Nations, 2012). This means that the Millennium Development Goal, which states that by 2015 the proportion of the population without sustainable and safe drinking water access must be halved, has already been reached. However, this statement is disputed (Roox, 2013) as the terms “sustainable”, “safe” and “access” are not clearly defined (Claesen, 2012). Moreover, quality, quantity and access are only indirectly assessed (Claesen, 2012). At least 783 million people do not have a reliable water source (United Nations, 2012), including in Mozambique, a developing country that is still struggling with decent and enough water supply for the whole area.

Mozambique is a country in South-eastern Africa with Maputo as the capital city and bordered by the Indian Ocean to the east as shown in Figure 1. The neighbouring countries are South Africa and Swaziland to the south, Tanzania and Malawi to the north and Zimbabwe and Zambia to the west. The country is divided into ten provinces which are further subdivided into districts.

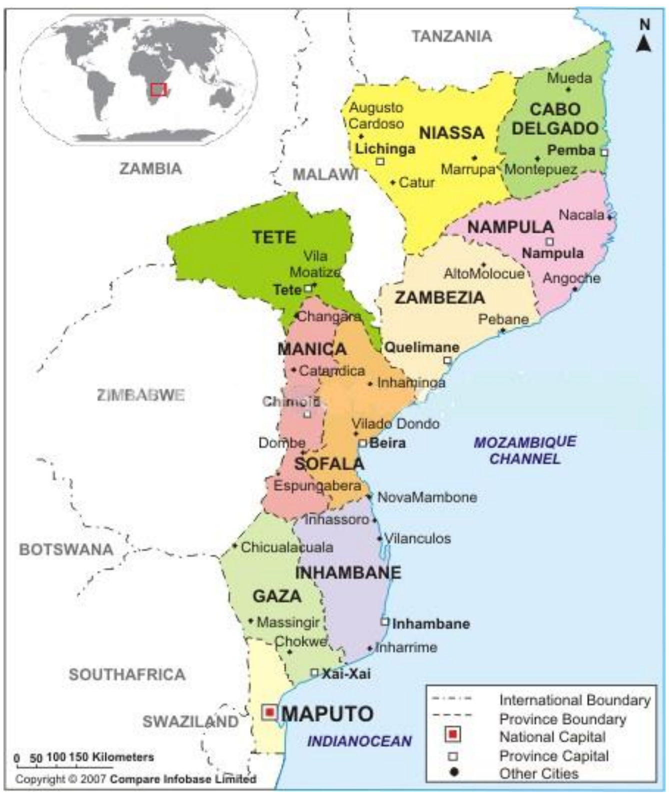


Figure 1: Map of Mozambique (Maps of World, 2012)

In 2008, 60% of the population of Mozambique was living on less than US$ 1 per person per day (WHO, 2011). This is an indication of extreme poverty which is generally more accentuated in rural than in urban areas. The financial resources of rural populations are limited, including for water pumping technology and other basic needs. The choice of what kind of pumping system is the best fit for the Mozambican rural circumstances is therefore not purely technical. Three major components can be recognized when dealing with the problem, but each of them can be further subdivided in a multitude of interacting factors: the socio-cultural aspects, the economic aspects, and finally the technical aspects.

1.2. The water sector

1.2.1. Water demand and supply

Water supply installations can serve different purposes. The highest quality is demanded for drinking water, but water is also needed for general domestic needs (washing, cooking, cleaning etc.), for irrigation and livestock drinking water. Combinations are of course possible. The minimum water needed for human consumption is about 7.5 L $person^{-1}$ d^{-1} but a higher quantity of 20 L $person^{-1}$ d^{-1} is needed for basic personal and food hygiene (Howard & Bartram, 2003). When laundry and bathing must be assured too, an average amount of 50 L $person^{-1}$ d^{-1} is needed (Howard & Bartram, 2003). In a case study in the Upper East Region in Ghana, an estimated average use of 35 L $person^{-1}$ d^{-1} has been reported for 125 to 300 users for one hand pump (Drouin, 2005).

As the available quantity of water increases, the level of health concern decreases (Howard & Bartram, 2003). Table 1 shows general estimated human water needs. A daily consumption of 30L per person is reported for the life circumstances of Africa. Amounts used for irrigation for different crop types are listed in Table 2. This asks for relatively high supplies without too much worry on quality whereas for drinking water it is of the highest importance. Water for livestock is another possible application; these amounts are listed in Table 3. The most suitable water supply installation depends therefore also on its objectives.

Table 1: Human water consumption (Royer, et al., 1998)

Humans	Water consumption (L d^{-1})
Survival	5
Minimum eligible	10
Normal life conditions in Africa	30

Table 2: Estimated daily water requirement for irrigation of various crop types (Argaw, et al., 2003)

Crops	Water demand (m^3 ha^{-1} d^{-1})
Rural village farms	60
Rice	100
Cereals	45
Cotton	55
Sugar cane	65

Table 3: Typical daily water requirement for farm animals (Argaw, et al., 2003)

Animals	Water consumption (L animal^{-1} d^{-1})
Dairy cows	80
Beef brood cows	50
Horses	50
Calves	30
Donkeys	20
Pigs	20
Sheep and goats	10
Chickens	0.1

Currently, rural provision of water in Mozambique is mainly done by hand pumps, as there are no waterworks in local villages. Hand pumps will be discussed later on.

The water obtained from the borehole should be more than the daily demand when using a renewable energy power source as the output depends on the weather. There is possibly shortage when the weather is unsatisfying, during maintenance or when the system is broken. Therefore, a storage tank must be installed to provide enough water to overcome this period. The size of the storage tank should be for 2 to 5 days of demand (Practical Action, 2010) which depends on climate and the pattern of water usage (Buschermohle & Burns, n.d.). When the tank is sized too small, a shortage in bad weather periods can occur and if it is sized too large, the water is not refreshed often enough (SARWP, 2009). Therefore, a good balance between the two is needed. However, when another water source is available, like a river, lake or rainwater collection, the tank can be sized smaller. It is important to notice that an oversized tank is less expensive than an oversized PV or wind system (Argaw, et al., 2003). However, usually the available water is all consumed by the rural population and the need for storage is minimal (Hansen, 2012). Therefore, installing several storage tanks is unnecessary (Hansen, 2012).

Storage tanks can be open or closed. Open tanks have the disadvantage that evaporation losses can be considerable and dirt can enter the tank easily, while closed tanks are more expensive (Buschermohle & Burns, n.d.).

Storage is different for drinking (or domestic) water, livestock water and water for irrigation (Argaw, et al., 2003). Water tanks for livestock are usually low, open, circular and have a large area so that the animals can drink directly from the tank and no additional tap is needed. This is shown on the left picture in Figure 2. Water for drinking and domestic use must be kept in a closed tank to prevent contamination. These tanks are usually also circular but have a smaller base area as shown in the right picture of Figure 2.

Figure 2: Storage tank for (left) livestock drinking water and (right) human drinking water

For irrigation a storage tank is not required and water can be pumped directly to the field, which is the cheapest option. However, this type of irrigation is harder to manage for the farmers and is therefore not the best option (Argaw, et al., 2003). The most commonly used methods are using channel, drip, flood, sprinkler or hose and basin irrigation (Argaw, et al., 2003). When all the purposes mentioned above (drinking, domestic, livestock and irrigation) are used the safest type of storage, that for human drinking water, must be applied and livestock must be supplied by a connection (which can be material or man-kind) from the tap to a drinking barrel.

The most commonly used materials for storage tanks are steel, PVC (Polyvinyl chloride), fiberglass, concrete or masonry, where the first three are most used for PV or wind systems as these are cheaper (Argaw, et al., 2003). These, however, have some disadvantages too: steel tanks need an antirust treatment which must not affect the quality of the water. In addition the water can become hot during the day which accelerates evaporation and increases the risk of waterborne diseases.

The height of the storage tank must be so to provide enough pressure at the tap (using gravity), except for livestock use only. However, the pressure must be balanced: if it is too high, there is unfortunate water spillage, when it is too low, there can be shortage. The distance of the tank to the borehole must be as small as possible to reduce pressure losses (Ratterman, et al., 2007). Therefore, storage tanks can be installed on the ground or above. Sometimes it is buried in the soil to keep the water cool and so reduce evaporation (Argaw, et al., 2003).

1.2.2. Geographical and climatic conditions of Mozambique

The choice of the most appropriate water supply strategy depends on the groundwater-level. This in turn depends on the climatic conditions, geomorphology and geology (Bonsor & MacDonald, 2011). The area of Mozambique is about 800 000 km². The climate differs a little in the north and the south as it is an outstretched country and can be subscribed as tropical in the north and subtropical in the south (McSweeney, et al., 2010). The wet season from October to April is hot and rainy, and the dry season between June and September is cooler (World Weather and Climate Information, 2010).

The geography of Mozambique can be subdivided in four categories approximately from east to west (Cuamba, et al., n.d.):

- the coast area: these are plains of altitudes from zero to about 200 m;
- the lower plateau with altitudes from 200 to 500 m;

– the middle plateau with altitudes from 500 to 1000 m;
– mountains with elevations above 1000 m.

The temperature and other climatic factors are shown in Figure 3 for Maputo. The temperature is lowest in winter, between June and October, which corresponds to the dry season. The average is approximately 20°C in winter and 25°C in summer. The average wind speed is also given, three Beaufort, which is between 3.4 and 5.4 m s^{-1}. These data need to be used with caution as they are only valid for the capital city Maputo.

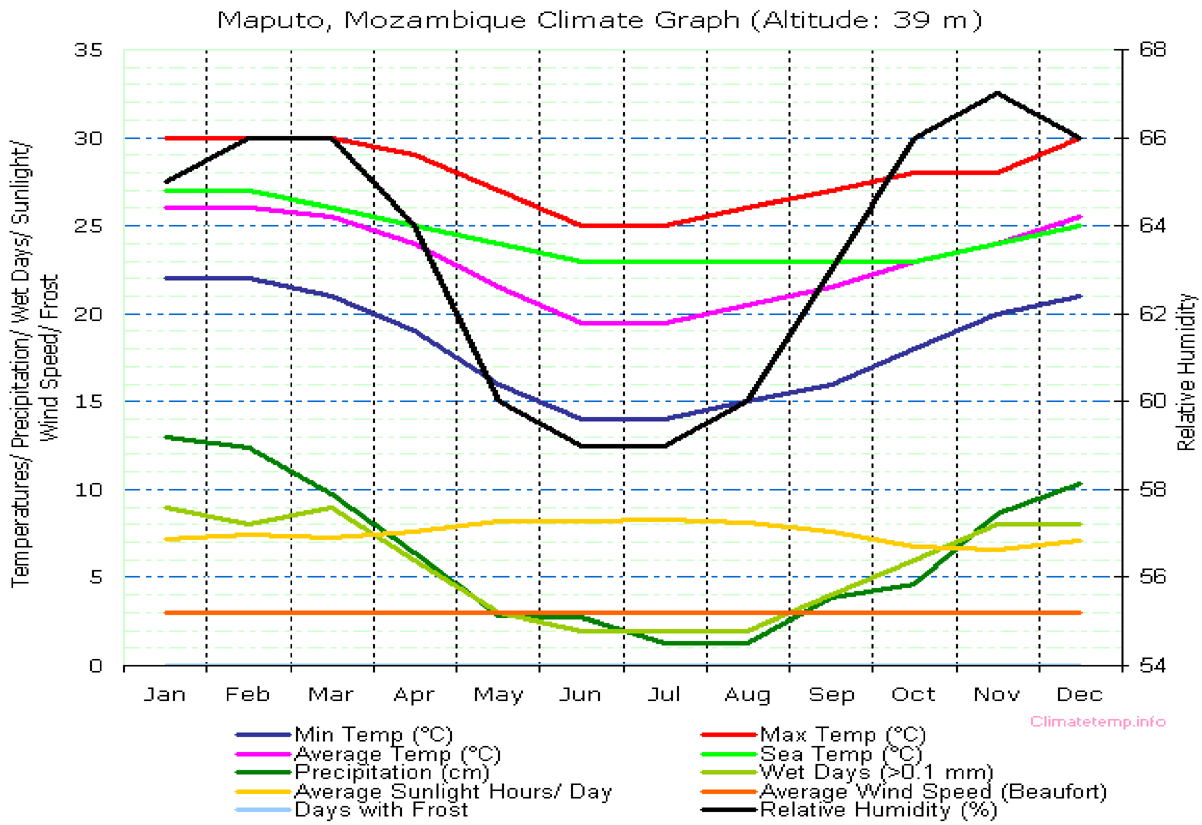


Figure 3: Graph of the climate of Mozambique (Climatemps, 2008)

The yearly precipitation is an important factor because it determines partly the depth where water can be searched for (Bonsor & MacDonald, 2011). Mozambique has a high variation of precipitation on its territory: from 800 to 1000 mm in coastal areas, around 1200 mm in the central region and between 1000 and 2000 mm in the north (FAO, 2007). The average is about 970 mm with variations from 300 mm to 2600 mm (WaterAid, 2002). Generally, the groundwater table is less deep in wet areas than in areas of lower average annual rainfall (Bonsor & MacDonald, 2011). Depths of the water table vary strongly in such a big area like Mozambique. When it is deeper, more power is needed to pump the water and the less likely simple manpower (and thus hand pumps) suffices for pumping the needed water.

The geology of Mozambique is of interest because this determines partly water availability (Bonsor & MacDonald, 2011). In the north, mainly ancient crystalline rocks are found, whereas in the south Tertiary and Quaternary sediments as well as volcanic rocks are present (WaterAid, 2002). In southern Mozambique, aquifers are more productive with water table depths of about 50 m. However, in the north where crystalline rocks are found, lower yields are obtained, not more than 2 L s^{-1}, and the boreholes are deeper (WaterAid, 2002). However, specific borehole data give more information about local water depths than geological formations.

Data about groundwater-level in Mozambique, or generally in Africa, are scarce (Bonsor & MacDonald, 2011). Therefore, other approaches are needed to obtain realistic data about the depth of the water table in Mozambique.

Estimated depths of water levels in boreholes were gathered by interviews with the local population, not by measurement (Rhebergen, 2012) and are given in Figure 4. One can see that the deepest boreholes are found in the west of the province Gaza where the groundwater is found at more than 75 m down. This is also the case in the east of the province Niassa. The coastal area knows a lot of variation. Shallow groundwater is found as well as very deep water. Normally groundwater is not that deep in coastal areas, but the water can be saline. To find fresh water, one has to dig deeper. Therefore, some data can be for saline water and others can be for fresh water (Rhebergen, 2012).

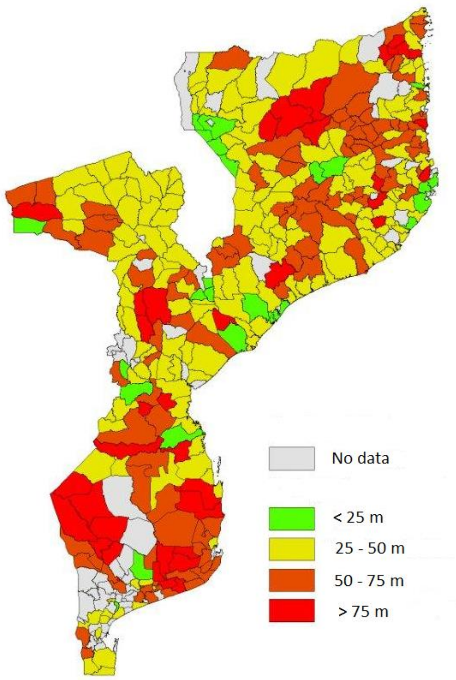


Figure 4: Estimated depths of water levels in boreholes (Ministério das Obras Públicas e Habitação - Direcção Nacional de Águas, 2012)

In a groundwater science program of the British Geological Survey, an estimated depth to groundwater map for Africa was developed by using an empirical rule based approach. Three sets of rules were used based on:

- average annual rainfall
- basement rocks
- distance to perennial rivers.

The final map for southern Africa is shown in Figure 5. The groundwater-level in Mozambique varies from 0 to 100 m according to this map. In the north and middle part of the country shallow depths are estimated, from 0 to 25 m. In the south, average depths of 25 to 50 m are predicted. There is a small part in the province of Gaza in the southwest of Mozambique where deeper groundwater levels are estimated, between 50 to 100 m. It should be mentioned that directly observed data are needed to confirm these assumptions and model (Bonsor & MacDonald, 2011).

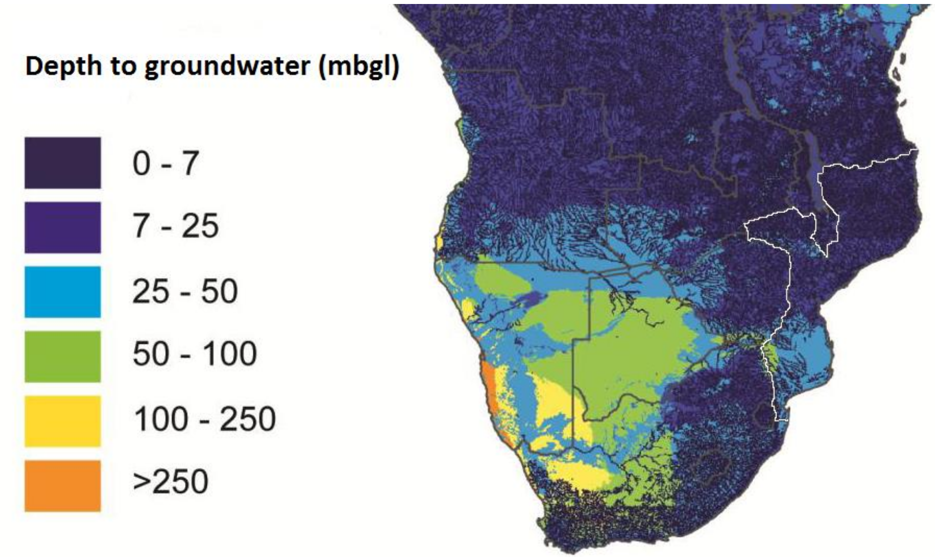


Figure 5: Initial estimate of depth to groundwater in meters below ground level (mbgl) in Southern Africa with Mozambique highlighted by a white country borderline (Bonsor & MacDonald, 2011)

1.3. Pumping technology

1.3.1. Characteristic curves

The characteristic pump head capacity curve (or pump curve) expresses the amount of energy that a pump transfers to the liquid as a function of the flow rate Q. The higher the flow, the lower the energy transfer per mass unit, so the pump curve will be descending with increasing flow (Ronsse, 2011-2012).

The system curve gives the system height of the piping (energy head) as a function of the flow rate (Cengel, et al., 2008). At zero flow the height is the geometrical head; when the flow is non-zero this is increased by the energy losses in the piping (Ronsse, 2011-2012). The intersection between the system and pump curve is the operating point. The energy head produced by the pump at this point is equal to the head requirements of the system at that particular flow rate. Thus the pump installed in this piping system will operate at this point (Cengel, et al., 2008).

The efficiency of a pump is highest for a certain head – flow rate combination, where it shows a maximum in the h – Q plot (Ronsse, 2011-2012). This is the best efficiency point (BEP). One should choose a pump whose characteristic pump head capacity curve intersects the system curve at the desired flow rate, nearby the best efficiency point (BEP) (Ronsse, 2011-2012).

The system, pump and efficiency curve are shown in a theoretical graph in Figure 6. These curves are determined experimentally by the pump manufacturer.

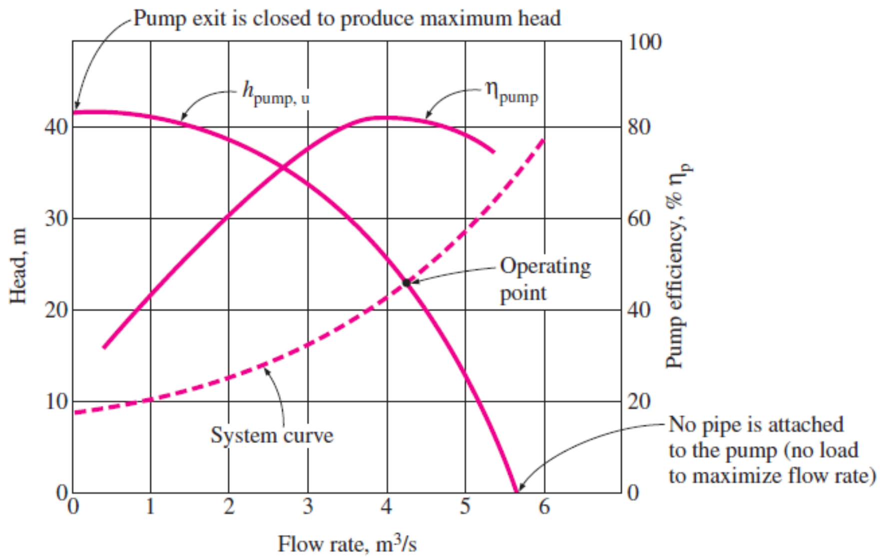


Figure 6: Characteristic pump curve and system curve for a piping system (Cengel, et al., 2008)

A practical example is shown in Figure 7 where the pumping curve of a particular type of Wilo pump (Wilo-Sub TWI 4-...-QC-B) is presented. This type of pump is further classified in subtypes, based on the nominal volume flow ($m^3\ h^{-1}$), which have their own range in the h – Q plot. Depending on the head and the flow one can choose the appropriate pump, e.g. pump 02 for a head of 80 m and a needed flow of 1 $m^3\ h^{-1}$, or pump 03 for a head of 60 m and a flow of 5 $m^3\ h^{-1}$.

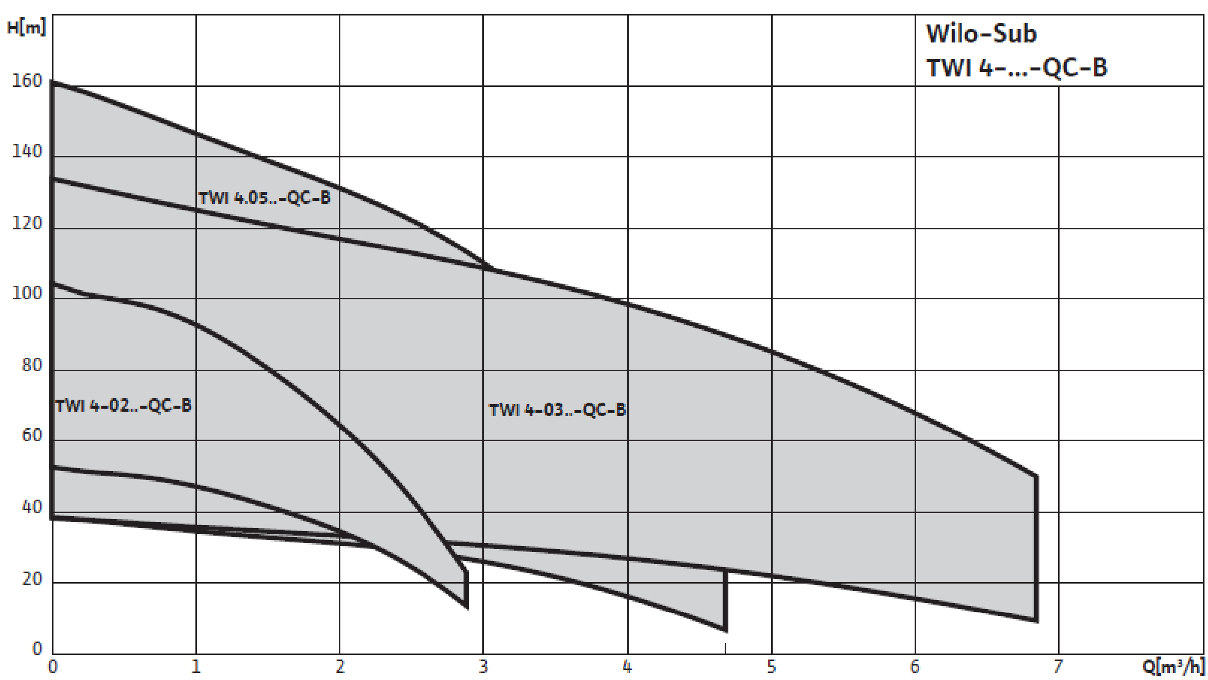


Figure 7: Pumping curve of Wilo-Sub TWI 4-...-QC-B (WILO SE, 2013)

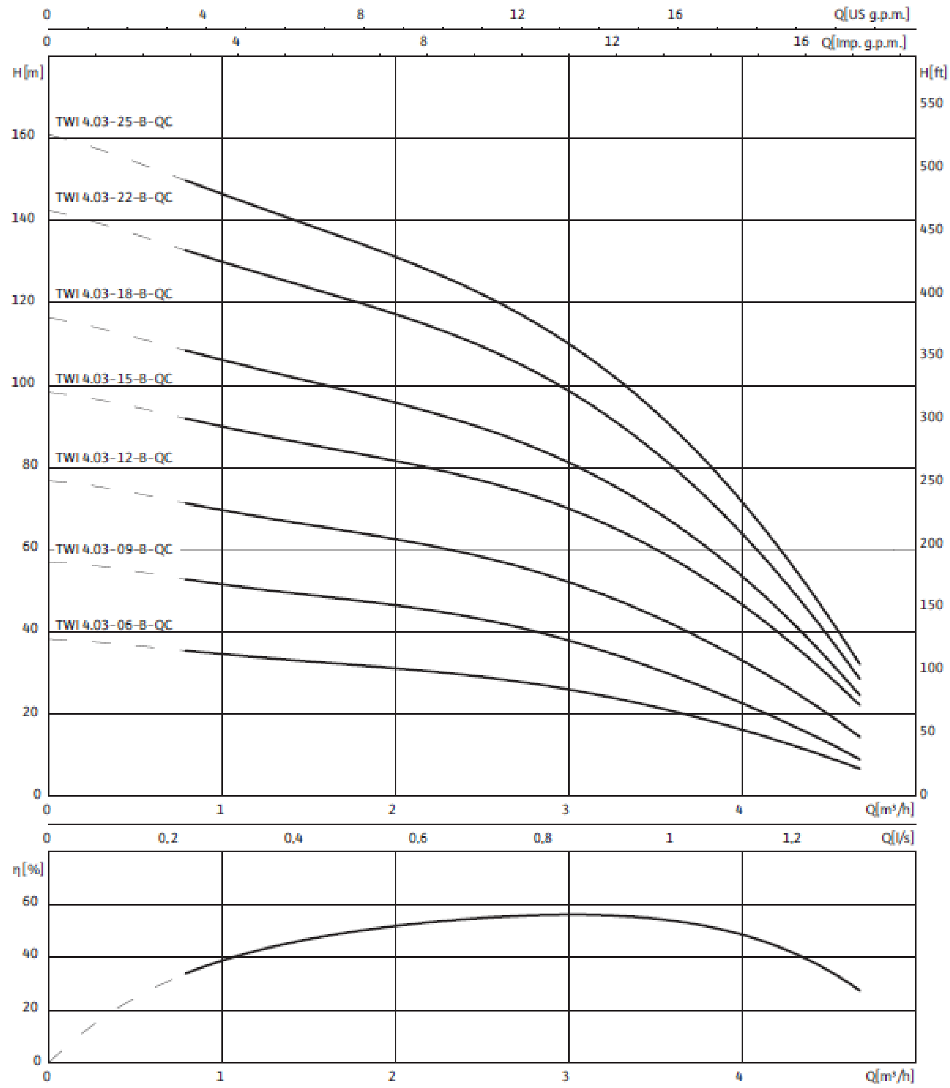


Figure 8: Pump performance curves for the Wilo-Sub TWI 4.03-…-B-QC types (WILO SE, 2013)

The pumps (e.g. TWI 4.03-…-B-QC) are further classified based on the number of hydraulic stages. The separate pump curves are given in Figure 8. In the bottom graph the efficiency is plotted against the flow rate, where η_{max} is approximately 0.55, corresponding to a flow rate of 3 m^3 h^{-1} which is the nominal flow rate.

1.3.2. Types of pumps

1.3.2.1. Hand pumps

The most commonly used pumps in Mozambique are hand pumps, and more specifically the rope pump and the Afridev (Africa Development) pump.

A rope pump and its principle are shown in Figure 9. Pistons with equal diameter as the inner tube of the casing are attached between two knots in the rope. The rope passes through the water, traps it in the casing between the pistons and lifts it. When the rope reaches the upper part of the pump where the casing diameter is larger, the water is discharged. The rope and pistons go further over a pulley wheel and the cycle restarts. The pulley is provided with a handle which must be turned by human power to pump the water. The pump and well can be covered or not, depending on the application and the available budget (Erpf, 2005).

The most important advantages of the rope pump are the simple technique and adaptation, as well as the manufacture which can be done locally with simple materials. This also simplifies the maintenance. However, this type of pump is difficult to use when the head is high because the turning of the pulley wheel becomes more difficult. The maximal head for a rope pump is 40 m; however it operates optimally up to 20 m because water from deeper boreholes becomes more difficult to extract (Group URD, 2009). The yield depends on the depth of the borehole (RWSN, 2012):

- 10 m head: 1.4 $m^3 h^{-1}$
- 15 m head: 1.1 $m^3 h^{-1}$
- 20 m head: 0.7 $m^3 h^{-1}$.

Another disadvantage is the rotation of the rope which can be a source of contamination from above ground to the well and vice versa. A casing around the pulley wheel can be a first improvement. The number of people that can be served with one pump is approximately 70 (RWSN, 2012), which is relatively low.

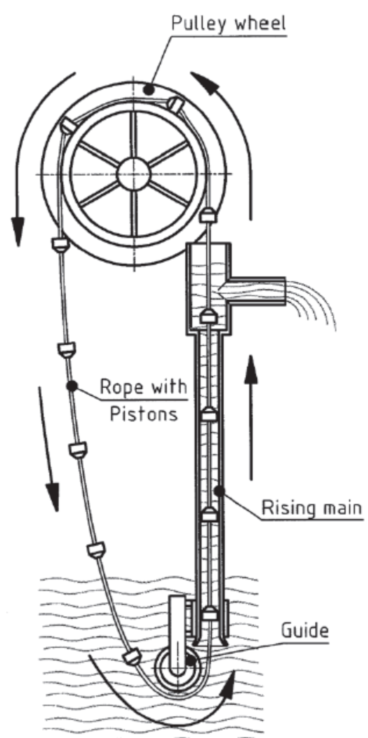


Figure 9: Scheme of a rope pump (Baumann, et al., 2010)

The Afridev pump, presented in Figure 10, is well known and frequently used in rural areas. The working principle is that of a reciprocating hand pump, which includes suction pumps, direct action pumps and lever action pumps (Baumann, et al., 2010). The Afridev pump is one of the latter type.

Reciprocating hand pumps use the principle that water flows from a high to a low pressure area (Baumann, et al., 2010). Such a low pressure area is created above the water body so that the water moves upwards. The cycle is shown in Figure 11. A rod, directly connected to the handle, moves a plunger inside a cylinder up and down when manipulating the handle. The raising and lowering movements of the piston cause the water to rise.

In the first step in Figure 11, the rod is pulled up by moving the handle down. By doing so, a lower pressure area is created in the cylinder which causes the water to flow into the cylinder, passing the first foot valve (non-return valve). This allows the water to flow into the cylinder but not back into the well. In the second step the rod is pushed downwards by moving the handle back (upwards). The pressure in the area between the piston and the first foot valve (which is closed now) rises whereby the water flows through the second foot valve (attached to the piston) to the lower pressure area in the upper part of the cylinder. When there is enough water in the upper part, the pressure on the second foot valve causes this one to close. The water moves upwards until it flows out through the spout. The piston goes up because the pressure due to the water body falls, the pressure in the lower part of the cylinder drops and the first foot valve opens so that water from the well flows again into the cylinder. By repeating this cycle, water is collected at the surface.

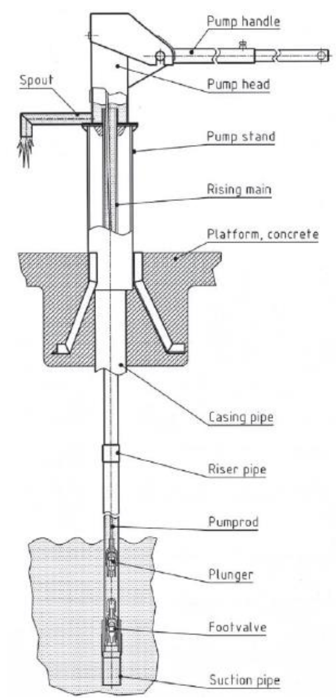


Figure 10: Afridev hand pump (Baumann, et al., 2010)

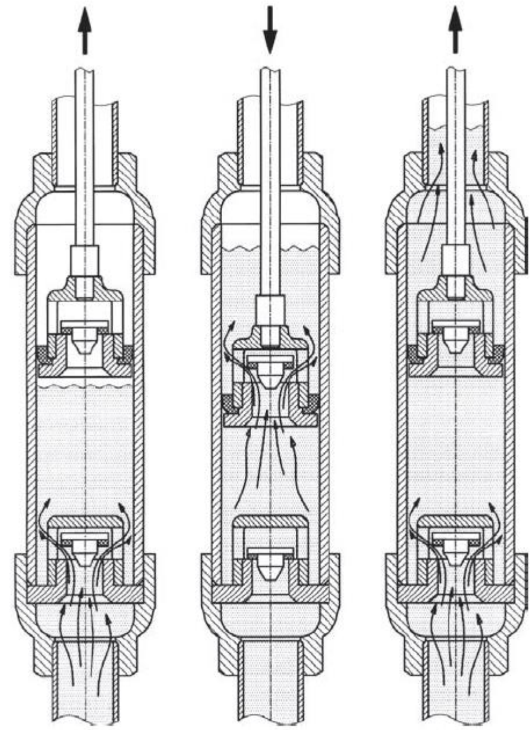


Figure 11: Principle of a reciprocating hand pump (Baumann, et al., 2010)

As the rope pump, the Afridev pump can be manufactured locally and up to 300 persons can be served by one pump (RWSN, 2012). The head can vary from 10 to 45 m (Nampusuor & Mathisen, 2000). The discharge (75 watt input) depends again on the depth (RWSN, 2012):

- 10 m head: 1.4 $m^3\ h^{-1}$
- 15 m head: 1.1 $m^3\ h^{-1}$
- 20 m head: 0.9 $m^3\ h^{-1}$
- 30 m head: 0.7 $m^3\ h^{-1}$.

The water consumption can be 15 to 20 L per capita and community-based maintenance is possible as the pump is easy to repair by a local caretaker (Baumann, et al., 2010).

1.3.2.2. Electrical pumps

Electrical pumps are driven by a motor device. There are two basic types of electrical pumps: the positive displacement and the centrifugal pump. The positive displacement pump converts the energy of the motor mostly into potential energy (high pressure, low velocity), and the centrifugal pump converts it into kinetic energy (Ronsse, 2011-2012).

Positive displacement pumps

Positive displacement pumps use direct lift, suction or displacement to move the water to the surface as shown in Figure 12. A volume of water, which varies with the frequency of the pumping cycle, is first trapped and then displaced. This is called the displacement rate. The displacement rate is lowered to the actual flow rate because of internal leakage (leakage flow) (Ronsse, 2011-2012).

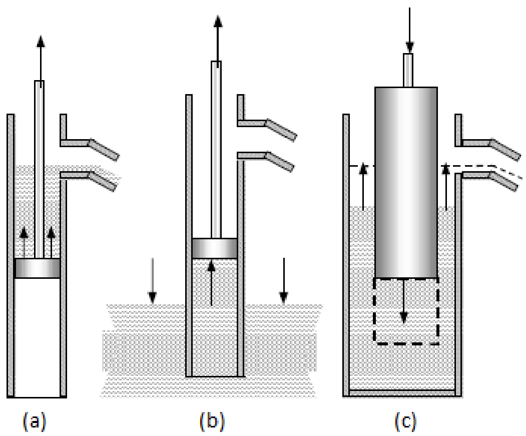


Figure 12: Basic operating principles of positive displacement pumps: (a) direct lift (b) suction (c) displacement (Argaw, et al., 2003)

Generally, positive displacement pumps are better for low flows, less than 15 $m^3\ d^{-1}$, and high heads, from 30 to 150 m (Argaw, et al., 2003). The flow rate remains almost constant with increasing head, but drops rapidly to zero when a limit value is reached (Ronsse, 2011-2012). The water output is therefore almost independent of head but depends on the frequency. The efficiency increases with the head for a particular pump diameter.

Positive displacement pumps can be subcategorized in two types: submersible pumps, which include the diaphragm pump amongst others, and non-submersible pumps, which include the jack pump, piston pump and rotary vane pump (Argaw, et al., 2003).

Centrifugal pumps

In centrifugal pumps a spinning impeller is used to exert a centrifugal force on the water as presented in Figure 13. It consists of two parts: the pump casing and the impeller, which consists of several vanes. These pumps work at high velocity and are connected to a motor directly (Ronsse, 2011-2012). The flow rate in the impeller is directly proportional to the speed of the impeller, and the latter is proportional to the power transferred by the engine (Argaw, et al., 2003). A multistage centrifugal pump has several impellers in series in the same casing which enhances the pressure and thus the achievable head.

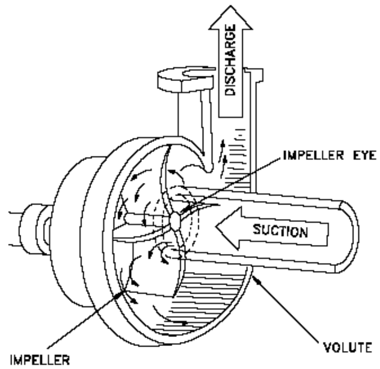


Figure 13: Schematic drawing of a centrifugal pump (Engineers Edge, 2000)

Centrifugal pumps are used for large volumes at low to medium heads although the head that can be overcome depends on the diameter of the impeller. The most important advantages are the low maintenance and the tolerance for dirty water (Argaw, et al., 2003).

1.3.3. Choice of the pump

The choice of the pump depends on different parameters. The robustness and the cost effectiveness are important, especially in rural areas where replacement is not obvious. Good choices should therefore be made from the start. Important technical factors to take into account when choosing a water pump are:

- the depth of the water table
- the needed output in $m^3\ d^{-1}$
- the ease of maintenance.

Based on the depth of the water table, one can use the left scheme in Figure 14 to determine the pump placement and subsequently the pump type. When groundwater is used, the choice is reduced to jack pumps or submersible pumps depending whether the depth is more or less than 75 m respectively.

Based on the demand, one can use the right decision tree in Figure 14 to determine the pumping mechanism that should be used. The limit flow rate is 19 L min^{-1} (27 $m^3\ d^{-1}$).

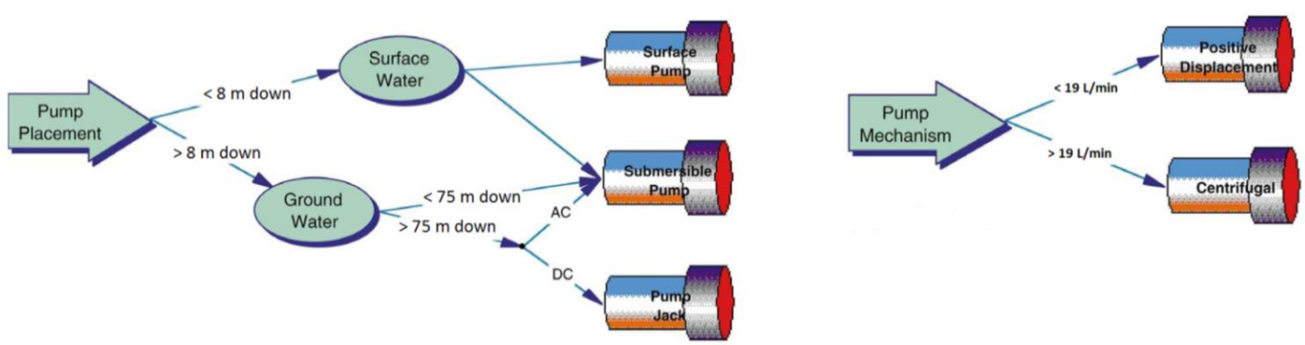


Figure 14: Decision tree for pump type based on (left) placement and (right) demand (Dankoff, 1995)

1.3.4. Sizing of the water pumping system

The sizing of any pumping system starts with the water requirement Q (also known as flow rate or pumping capacity) which is expressed in litres per hour (L h^{-1}) or in cubic meters per hour ($m^3\ h^{-1}$). Daily amounts are also commonly used. The required flow rate should correspond with the demand during the period of maximal need, called the critical period (usually on a monthly basis), so no shortage is experienced at any time of the year. The monthly demand must therefore be known and the highest value must be used to size the system.

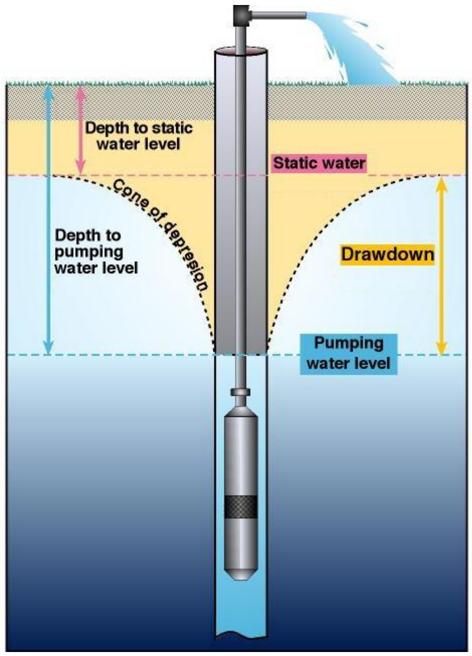


Figure 15: Water pumping diagram showing the static water level, the pumping water level and the drawdown (Ohio Department of Natural Resources, 2011)

In Figure 15 a borehole scheme is presented. The static water level is the depth of the water table in the zone where the water pump has no influence. A borehole causes the water table to incline (cone of depression) to a level called the drawdown. When the pump is running, the water level decreases further in the borehole which is an additional drawdown. This is shown in Figure 16.

The total vertical lift is the vertical height from the drawdown level to the inlet of the storage tank. The total dynamic head (h_{TD}), expressed in meters, must be calculated as the total vertical lift adjusted upwards by frictional losses due to piping and pressure (Ratterman, et al., 2007). This value is obtained by a borehole test or can be calculated with the Moody diagram.

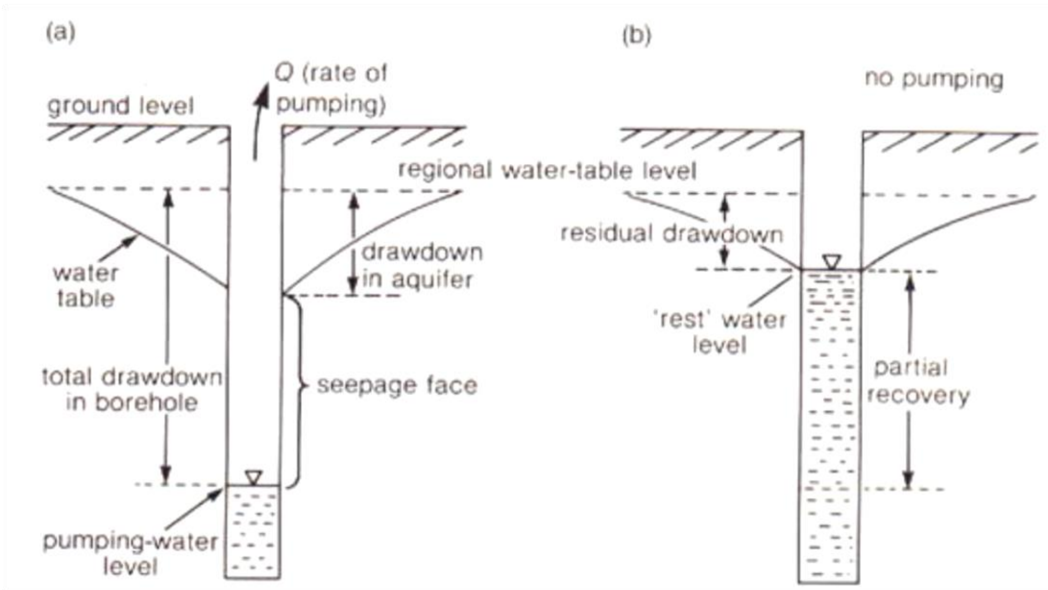


Figure 16: Water pumping diagram when (a) the pump is running and (b) the pump is not running (Purdue University, 2010)

With these data, the required electric energy expressed in J d^{-1} (which can be converted to the more common unit kWh d^{-1}) for the pump can be calculated by Equation (1) (Royer, et al., 1998):

$$E_{elec} = \frac{\rho\ g\ Q\ \ h_{TD}}{\eta_{pm}} \tag{1}$$

where ρ is the density of water, g is the gravitational acceleration, Q is the needed flow rate (m^3 d^{-1}), h_{TD} is the total dynamic head (m) and η_{pm} is the efficiency of the pump-motor subsystem.

1.4. Renewable energy for water pumping application

Poor rural communities often have no easy access to energy sources. As a power grid is usually not present, only off-grid systems are discussed. In Figure 17, the power grid of Mozambique is shown. Only the distribution lines (blue) provide electricity to the towns. A buffer zone of 10 km indicates where expansion of the grid is possible in the near future. Standalone systems must be installed outside this boundary.

The project aim is to use renewable energy. Although micro-hydro potential exists in Mozambique, this is very local and is not considered for a groundwater pumping application here. About 83% of the energy consumed in Mozambique is generated with biomass (Cuamba, et al., n.d.), used for heating and cooking. Solar and wind powered systems are the two main options for a water pumping application.

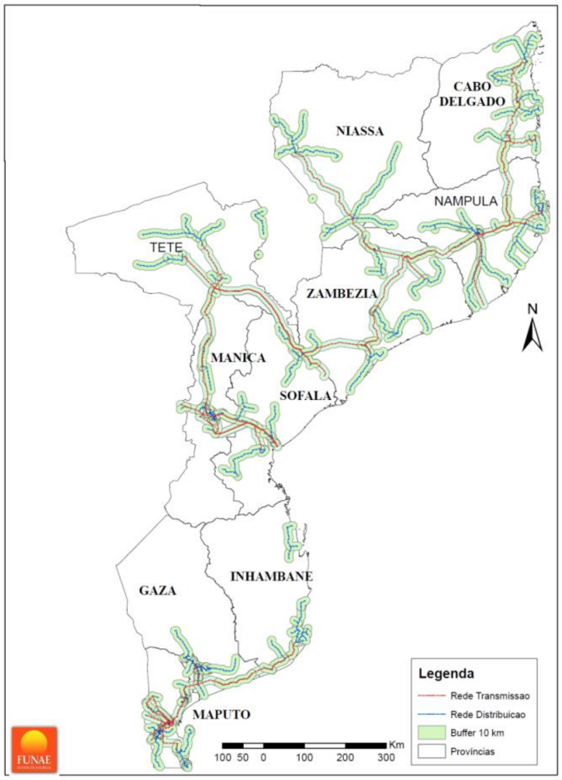


Figure 17: Power grid of Mozambique (FUNAE, 2012)

1.4.1. PV water pumping system

1.4.1.1. PV energy theory

In photovoltaic systems the solar array provides electricity needed for the pump to generate hydraulic power. A solar cell, the main component of a solar array, is made of semiconductor material, usually silicon. The efficiency of the panel depends on the material and the structure (amorphous, mono- or polycrystalline).

The use of these systems depends on the incident sunlight (time and flux) which is dependent of the latitude. The solar irradiation (in W m^{-2}) can be divided into direct and indirect (or diffuse). The total incoming radiation (global radiation) is the sum of both. The optimal inclination of solar panels for maximal energy capture is obtained by a compromise between the two irradiation types.

For Maputo, Beira and Pemba, three coastal cities, the global daily radiation on a horizontal surface is given per month in Figure 18. The same is given in Figure 19 for three inland cities, namely Maniquenique, Chimoio and Lichinga. There is an important decline in solar radiation between May and August, which is not surprising as this is the winter period with the lowest elevation above the horizon. June is the sizing month for all cities, as then the radiation is lowest.

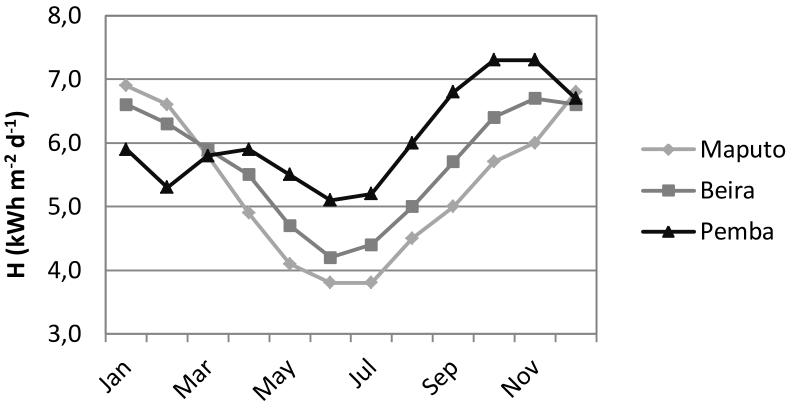


Figure 18: Average daily global solar irradiation on a horizontal surface per month for stations in coastal cities in Mozambique (Cuamba, et al., 2006)

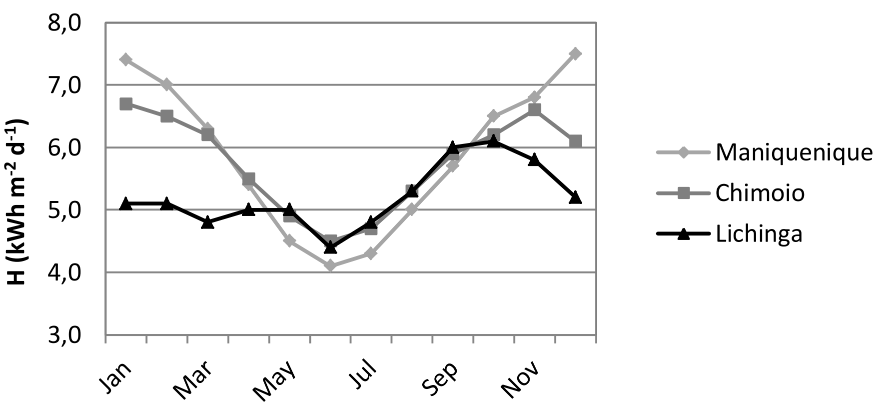


Figure 19: Average daily global solar irradiation on a horizontal surface per month for stations in inland cities in Mozambique (Cuamba, et al., 2006)

1.4.1.2. Working principle

A scheme of a PV pumping system is shown in Figure 20. The system consists of several basic parts:

- PV modules
- controller and/or inverter
- pump-motor device
- storage tank
- wiring and piping.

Batteries can be used to store the excess of energy, but they are not indispensable. They increase the investment as well as the maintenance costs (Enciso & Mecke, n.d.) and are an extra source of possible breakdowns. Water storage, instead of power storage, is a cheaper and easier option.

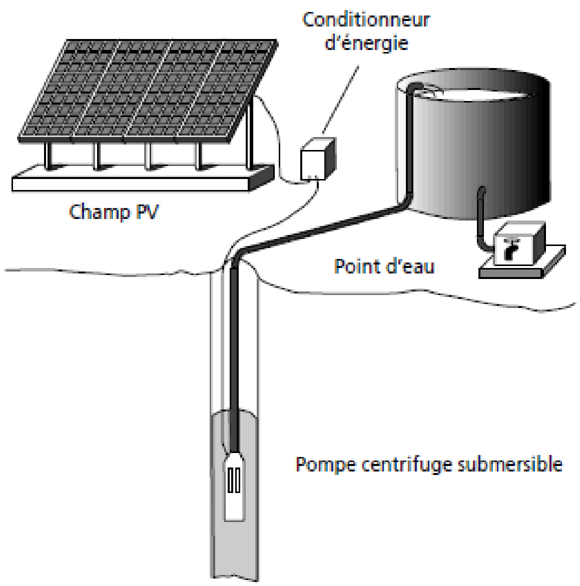


Figure 20: PV water pumping system (Royer, et al., 1998)

A controller, often in combination with an inverter, is used to protect the pump from overcapacity: it isolates the PV panels from the motor-pump device and provides the optimal power for the pump (Meah, et al., 2006). It also has other functions like protecting the pump from running dry and turning the system off when the storage tank is full (Meah, et al., 2006). The electrical output of a solar array is DC (direct current). Depending on the pump requirements, a DC/DC or a DC/AC inverter must be installed. When converting to AC (alternating current), the loss of energy is higher than controlling the power with a DC/DC inverter. This extra cost due to the energy loss from DC/AC conversion must be balanced with the choice of a DC pump with a DC/DC conversion.

In most of the water supply installations using solar energy, water tanks store the water and gravity supplies the necessary pressure at the tap level. This has been discussed earlier.

The initial cost of the solar array is high, but the low maintenance requirement is an important advantage. On the other hand, when repair is needed, it often requires skilled technicians. Therefore, there cannot be a PV water pumping program without a decent maintenance program. Theft of the PV panels has been mentioned as a major constraint (Practical Action, 2010). Therefore, a fence can be installed but this is not a warranty for security.

1.4.1.3. Sizing of the PV system

When sizing a solar system, one must size for the period (usually monthly basis) with the lowest irradiation so enough energy is provided all year long. The power required from the solar array can be calculated with Equation (2) (Royer, et al., 1998):

$$P_{solar} = \frac{E_{elec}}{H_h \, \eta_{PV}} \quad \textbf{(2)}$$

Here, H_h is the solar irradiation expressed in hours, E_{elec} is the energy required for the pump-motor system (Wh) and η_{PV} is the efficiency of the panel.

Nomographs can also be used (Thomas, 1996) but this method is less accurate.

In Figure 21, the performance curve of a Grundfos SQFlex water pump driven by a solar array of varying size is given. When the demand (in $m^3 d^{-1}$) is known, as well as the total head (in m), the appropriate size of the solar array can be determined.

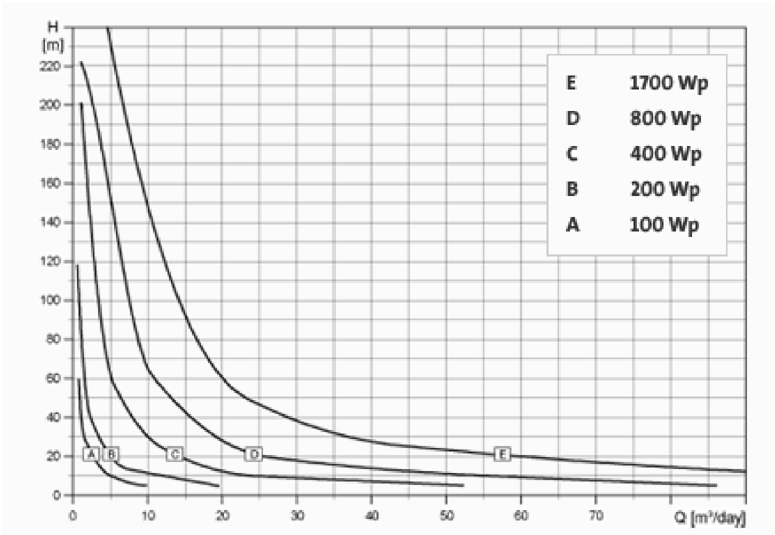


Figure 21: SQFlex solar performance curve (Grundfos, 2012)

In Figure 22, the water delivery from a 6 SQF-2 Grundfos pump powered by a 640 W photovoltaic array is shown (Clark & Vick, 2008). The pumping starts at approximately 100 W m^{-2} for the three heads. The maximum delivery is reached at 800 W m^{-2}.

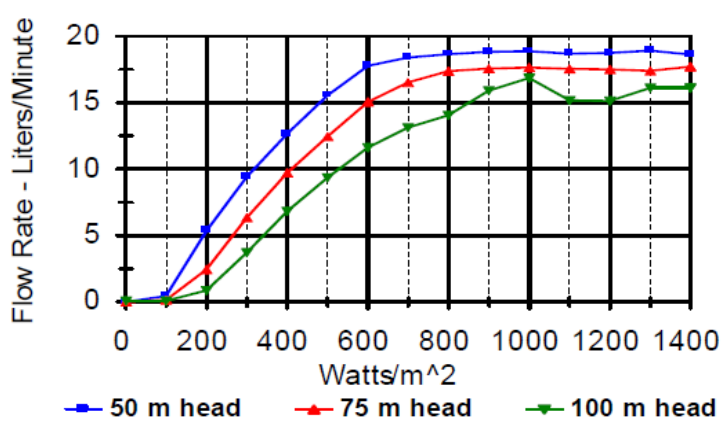


Figure 22: Measured flow rate from a 6 SQF-2 Grundfos pump powered by a 640 W photovoltaic array (Clark & Vick, 2008)

Using Table 4, one can assess whether a PV water pumping system is a correct technical solution or not, depending on the required yield (L d^{-1}) and the head (m).

Table 4: Chart for decision making for use of solar pumping system (Ratterman, et al., 2007)

	Head (m)	1	2	5	10	20	30	50	60	75	100	200	500
# of families	Demand (L d^{-1})												
10	2000		Hand Pump Range										
20	4000												
50	10000												
80	15000												
110	20000												
130	25000												
160	30000												
180	35000					Solar Pumping Range							
210	40000												
240	45000												
260	50000										Diesel Generator Range		
290	55000												
320	60000												
340	65000												
370	70000												
400	75000												
420	80000												
450	85000												
480	90000												
500	95000												
530	100000												

1.4.2. Wind water pumping system

1.4.2.1. Wind energy theory

As wind speeds (v) are not constant, they are represented by a wind speed distribution curve projecting the chance a wind speed occurs against its frequency value. The Weibull and Rayleigh probability distribution functions are mostly used. The Weibull distribution contains three parameters: the shape parameter k, the scale parameter a and the location parameter γ. The location parameter is often set as zero, which gives a simplified Weibull distribution with two parameters. The Rayleigh distribution is a special case of the Weibull distribution, where the shape parameter k is equal to 2. The simplified Weibull distribution and the Rayleigh distribution are given in Equations (3) and (4) respectively.

$$p_{Weibull}(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} exp\left[-\left(\frac{v}{a}\right)^{k}\right] \quad \textbf{(3)}$$

with $\bar{v} = a\left(0{,}568 + \frac{0{,}434}{k}\right)^{1/k}$

where k is the shape parameter and a is the scale parameter which are site-specific.

$$p_{Rayleigh}(v) = \frac{2}{a^2} v \; exp\left[-\frac{v^2}{a^2}\right] \quad \textbf{(4)}$$

with $\bar{v} = \frac{\sqrt{\pi}}{2} a$

The wind speed increases with height as shown in Equation (5) (Monteith & Unsworth, 1990). Therefore, the best investment in wind energy is to increase the height of the pillar and the height at which a wind speed measurement is done must always be indicated.

$$v(z_2) = v(z_1)\ \frac{ln\left(\frac{z_2 - d}{z_0}\right)}{ln\left(\frac{z_1 - d}{z_0}\right)} \tag{5}$$

In Equation (5) z is the height, z_0 is the roughness length which is the height for which the wind speed is zero and d is a parameter that takes into account the displacement of the boundary layer from the ground due to the height of surface elements (Cuamba, et al., n.d.) (Monteith & Unsworth, 1990). A higher roughness length means a higher increase in wind speed versus height (Vervaeren, 2013). The roughness length and roughness classes are used to characterize the landscape to evaluate the wind conditions at a specific site (Ragheb, 2012). In Table 5 different roughness classes and associated roughness lengths are given (Cuamba, et al., n.d.).

Table 5: Roughness length and description of the landscape (Cuamba, et al., n.d.)

Roughness length (z_0)	Landscape
0.0002	water surface, open sea
0.005	mud flats
0.03	open flat terrain, pasture
0.1	agricultural land with low population density
0.25	agricultural land with high population density
0.5	park landscape with bushes and trees
1	regular obstacles (woods, village, suburb)
2	city centres with low and high buildings

When evaluating the roughness of the site, it is important to know the prevailing wind direction which is shown in a wind rose, as presented in Figure 23. Obstacles behind the windmill or turbine when turned to this wind direction are less important than objects on the path of the wind towards it.

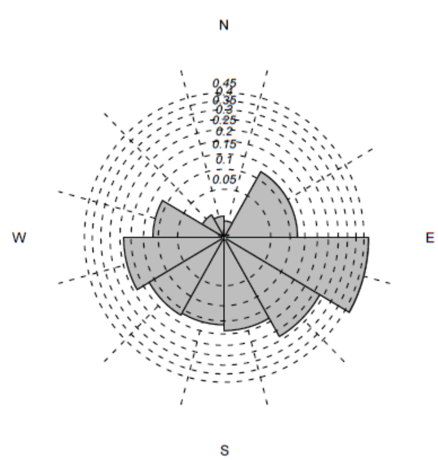


Figure 23: Wind rose of wind station Chibuto (Maure, 2011)

The kinetic energy content W of the wind passing perpendicularly through a vertical m² is given in Equation (6) (De Vos, 2012), where μ is the density of air (1.23 kg m^{-3}) and v is the wind speed. It can be considered as the available energy of the wind.

$$W = \frac{1}{2}\,\mu\, v^3 \qquad \textbf{(6)}$$

$$U = \frac{1}{2}\,\eta_r \mu\, A_r v^3 \qquad \textbf{(7)}$$

Equation (7) gives the mechanical power of the rotor with an area A_r and an efficiency η_r. This equation can also be seen as the part of the kinetic energy of the wind that is available by slowing down the wind (Lancashire, et al., 1987). The power is directly proportional to the cube of the wind speed. This is therefore a very important factor: when the wind speed doubles, the power increases by a factor eight. On the other hand, when one does not make a good estimation of the wind speed, the consequences for the power are very important. Therefore, good data must be available to correctly size the wind system. The power is also proportional to the air density, but at a lesser extent than the wind speed. The air density itself depends on several factors: the altitude, the temperature and the atmospheric pressure where altitude is the most important one (Lancashire, et al., 1987).

When average wind speeds are used, Equation (8) for the power from the wind turbine is valid when considering a Rayleigh distribution, where $\bar{v}$ is the mean wind speed:

$$U = \frac{1}{2}\,\eta_r \mu\, A_r\, \frac{6}{\pi}(\bar{v})^3 \qquad \textbf{(8)}$$

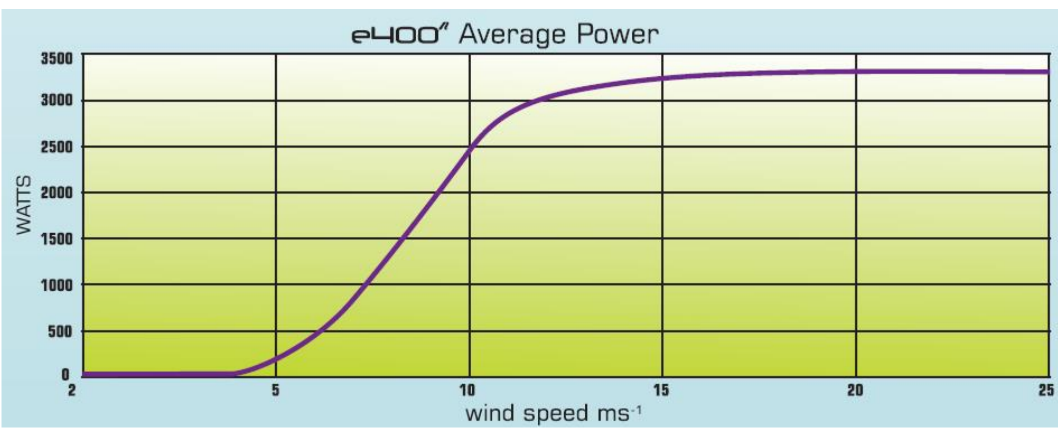


Figure 24: Wind power curve of the e400" Kestrel turbine (Kestrel Renewable Energy, 2012)

In Figure 24 a typical wind power curve is shown for a e400" Kestrel turbine with a 4 m rotor diameter. The cut-in wind speed, which is the speed needed to start the turbine, is 4 m s^{-1} (Kestrel Renewable Energy, 2012). The rated wind speed, defined as the wind speed needed to achieve the nominal power, is 12 m s^{-1} (Kestrel Renewable Energy, 2012).

1.4.2.2. Working principle

There are two possible configurations for a wind pump: the direct wind pump (windmill) and the electrical wind pump (wind turbine).

Only horizontal axis upwind configurations are discussed as these are the most common, also for the water pumping application.

Direct wind pump

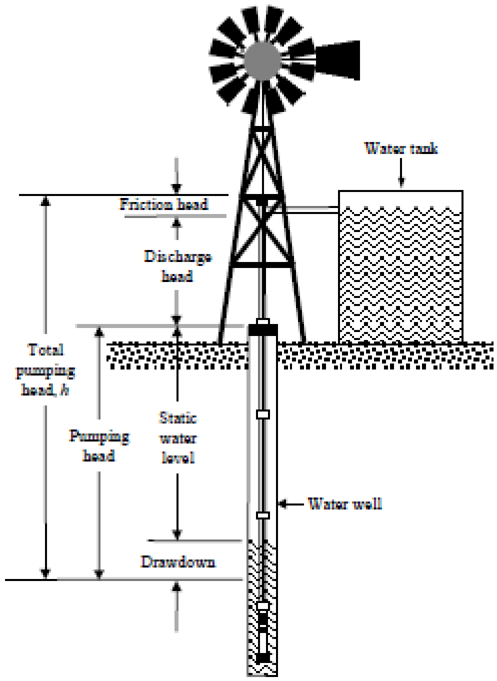


Figure 25: Windmill pumping system (Argaw, et al., 2003)

The direct wind pump, shown in Figure 25, also known as the American farm windmill (Gipe, 2004), transfers mechanical energy from the rotor to the pump. No electricity is involved, the rotating motion is converted by gear transmission or directly to a vertical pumping motion. Typical windmills are horizontal-axis and multi-bladed. They are designed for low start-up wind speeds and slow-speed operation (Moore, 2008). Other designs have not led to the same performance (Lancashire, et al., 1987).

The working principle can be described as follows with Figure 26 (Ironman Windmill, 1970 - 2013): in the hub centre, the wind wheel is attached to the main shaft of the gearbox. When the wind blows, the wheel rotates and the shaft turns. This generates a turning of the drive gear and subsequently of the driven gear. This turning is converted into an up- and down-motion of a pitman arm and subsequently a reciprocating motion of the guide wheel and guide wheel shaft. This causes the pump rod to move up and down as well, which is the pumping motion needed.

The pumps used in combination with windmills are piston or positive displacement pumps. The water delivery depends on the diameter of the pump and the wind speed, for a constant head (Argaw, et al., 2003). A pump with a larger diameter will deliver a higher amount of water but needs a higher starting torque (Argaw, et al., 2003).

The torque can be defined as the turning force produced by the rotor (Lancashire, et al., 1987). This means that a higher wind speed is needed to start the wind pumping system than is needed to operate it (Lancashire, et al., 1987). This principle is shown in Figure 27. Multi-bladed wind pumps produce more torque than wind turbine installations and a higher starting torque is usually needed (Lancashire, et al., 1987).

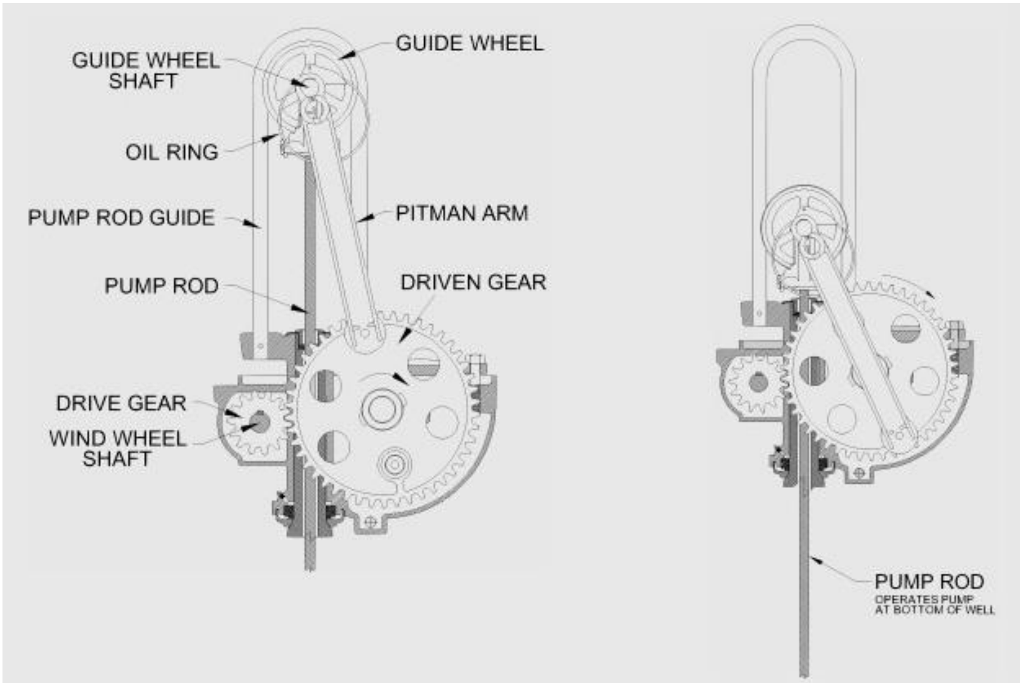


Figure 26: Working principle of a mechanical windmill (Ironman Windmill, 1970 - 2013)

Multi-bladed windmills operate efficiently at low wind speeds, approximately 2.5 m s^{-1} (Cuamba, et al., n.d.), in contrast to electrical wind pumping systems. But to start the system, the wind speed must be at least 5 m s^{-1}, which means that at lower wind speeds the rotor will not be able to start the pump. This is an important factor that needs to be taken into account when looking for good wind regimes and for sizing the system. However, the low operating wind speed is an advantage.

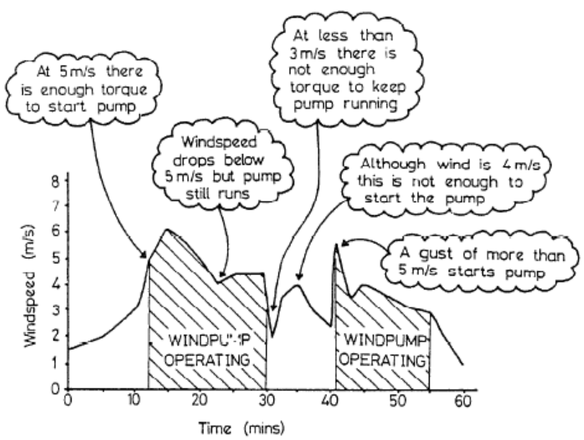


Figure 27: Illustration of the high wind speed (high starting torque) needed to start the pumping system (Lancashire, et al., 1987)

Other advantages of the direct wind water pumping system are the simple design and possibility of being manufactured locally (Badran, 2003). The long life expectancy, sometimes more than 20 years, the great reliability and the little maintenance are also important (Lancashire, et al., 1987). Theft is not a major problem as it is for photovoltaics (Lancashire, et al., 1987). The main disadvantage is the location: they have to be placed directly over the borehole because of the pump rod that connects the pump cylinder on one side (in the borehole) and the shaft and gears on the other side (rotor) (Moore, 2008).

This is not always convenient because of practical problems, but also because of better wind regimes (e.g. fewer obstacles) further from the well.

The tail of the windmill has two functions (Lancashire, et al., 1987), it keeps the rotor facing the wind at low and medium wind speeds and it turns the rotor sideways (not facing the wind) at high wind speeds (10 – 12 m s^{-1}) to prevent damage.

Electrical wind pump

An electrical wind pump produces electrical current which is used by the motor-pump device, so the pump is driven indirectly by the power of the wind. Only small electrical wind turbines are considered for the application of water pumping. Figure 28 shows an electrical wind energy pumping system. There is no need for placing it above the borehole, so the optimum spot (although not too far from the well because of losses in transfer lines and the associated costs) can be selected.

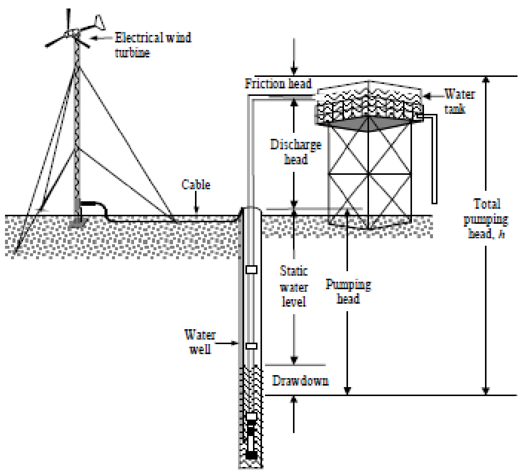


Figure 28: Electrical wind pumping system (Argaw, et al., 2003)

In Figure 29 a detailed drawing of an electric wind turbine is shown from which the working principle can be derived. The kinetic energy of the wind is converted to rotation of the rotors which drive the low-speed shaft. The gear box transfers the energy to a high speed shaft which is connected to a generator that converts the rotational energy into AC electricity (Vervaeren, 2013).

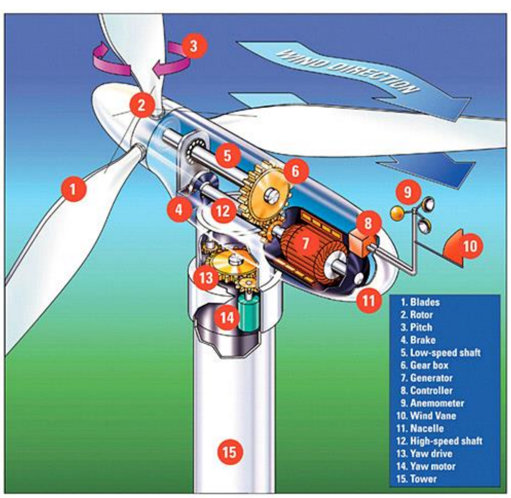


Figure 29: Elements of an electric wind turbine (Alternative Energy News, n.d.)

Electric wind turbines perform better at higher wind speeds and are twice as efficient as the mechanical wind pumps (Argaw, et al., 2003). Because of fewer moving parts, the maintenance costs are lower. The theoretical maximal efficiency is 59.3 % according to Betz. This, however, is never reached in practice, where the maximum is about 40 % (Argaw, et al., 2003).

Local manufacturing of some wind turbines is possible which could make it low-cost. The main disadvantage is the difficulty in installing and there is more maintenance needed than for a solar system because of the moving parts (Enciso & Mecke, n.d.). The higher required average wind speed, about 4.5 m s^{-1}, than for direct wind pumps, is another disadvantage (Cuamba, et al., n.d.).

1.4.2.3. Sizing of the wind system

Wind energy is less predictable than sun hours and not distributed evenly during the day. But wind energy can be available day and night. The daily variation of wind speed is higher than that of sun irradiation. Wind speeds below a certain level, 2.5 m s^{-1} (Cuamba, et al., n.d.), cannot provide enough power needed for pumping. Areas with likely good wind energy regimes should be identified before installation of a wind turbine (Cuamba, et al., n.d.). The long coastline of Mozambique, 2800 km, can result in a good wind regime. However, data must confirm this assumption.

For the sizing of the wind system, the same primary procedure about the water pumping system must be completed.

Direct wind system

After the calculation of the pumping capacity and the pumping head, one can use Table 6 to determine the required cylinder diameter with the appropriate blade diameter for a windmill. However, the wind speed corresponding to these data is not given, which makes its use unreliable.

Table 6: Pumping capacities for different cylinder diameters and blade diameters of the windmill (Enciso & Mecke, n.d.)

Cylinder diameter (cm)	Wheel diameter (m)		Blade diameter (m)					
	2	2.5 to 5	2	2.5	3	3.5	4	5
	Pumping capacity (m^3 h^{-1})		Pumping elevation (m)					
5	0.5	0.7	29	43	66	98	140	229
6.5	0.9	1.2	20	29	43	64	91	149
7.5	1.2	1.8	14	21	30	47	67	110
9	1.7	2.4	11	15	23	35	49	81
10	2.2	3.1	8	12	18	26	38	61
12	-	4.4	-	-	12	19	27	43
13	3.4	4.9	5	8	11	17	24	40
15	-	7.1	-	5	8	12	17	26
20	-	12.5	-	-	4	7	9	15

The calculation of the required rotor area (which can be converted to diameter) can be done by Equation (9) (Lancashire, et al., 1987),

$$A_r = \frac{1.14\ Q\ h_{TD}}{(\bar{v})^3} \tag{9}$$

where Q is the demand in m³ d^{-1}, h_{TD} is the total dynamic head expressed in m en $\bar{v}$ is the average wind speed of the critical month expressed in m s^{-1}. This empirical equation, calculated by the Overseas Development Administration Wind pump test programme in Kenya, uses a "typical" performance wind pump with "typical" efficiencies and a "typical" tropical wind regime. However, it should not be used when good local wind speed data are available or when the wind regime is highly variable (Lancashire, et al., 1987).

The use of nomograms is also possible (Argaw, et al., 2003), of which an example can be found in Appendix A for a rotor diameter of 2 m. The reading is first counter clockwise, beginning with the water demand and head to obtain the hydraulic power and then clockwise starting with the average wind speed, which will result in the power from the rotor. Lastly, the two powers can be combined to read the subsystem efficiency.

Electrical wind system

In Figure 30, the performance curve of a Grundfos SQFlex pump driven by a wind turbine (electrical) is given for different wind speeds. The higher the wind speed, the higher the performance curve. When the demand (in m³ d^{-1}) is known as well as the total head (in m), the minimal 'needed' wind speed can be determined.

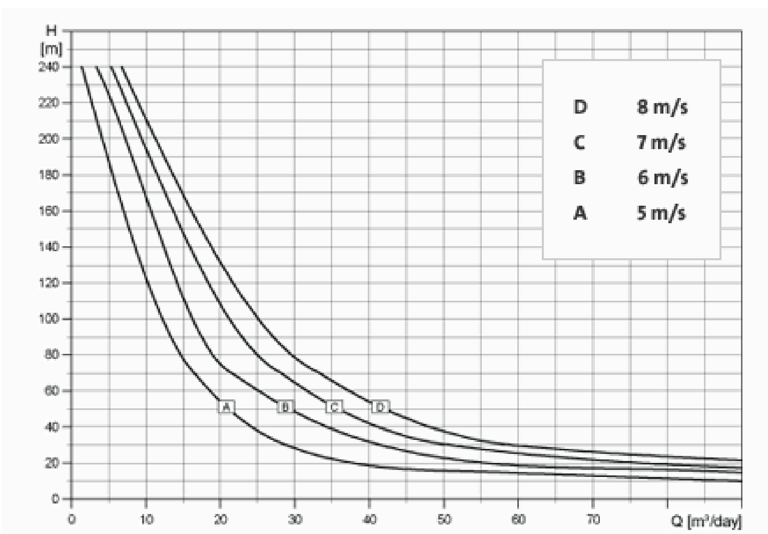


Figure 30: SQFlex wind performance curve (Grundfos, 2012)

The performance of a 6 SQF-2 grundfos pump has been tested when powered by a 1 kW wind turbine for different borehole depths (Clark & Vick, 2008). The result of this test is shown in Figure 31. The turbine manufactured by Grundfos, the Whisper 200, is also a 1 kW turbine. From Figure 32, one can see that water pumping starts at 4 m s^{-1} for the 50 m head and at approximately 5 m s^{-1} at higher depth.

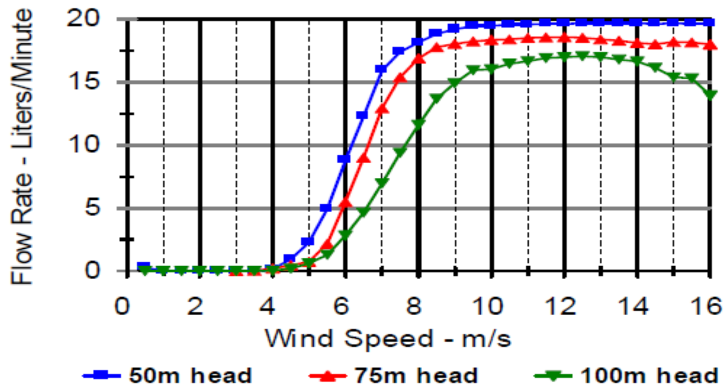


Figure 31: Measured flow rate from a 6 SQF-2 Grundfos pump powered by a 1 kW wind turbine (Clark & Vick, 2008)

1.4.3. Hybrid water pumping systems

A hybrid plant can be defined as a combination of two (or more) renewable power sources like wind and PV, or a mixture of renewable and conventional energy sources like fuel-generators or grid-connection. In Figure 32 a scheme of a hybrid PV/wind system for water pumping is given.

Combination with the grid is not usually done as grid-connection is often the cheapest and most reliable option, which would make addition of a renewable source less necessary in rural areas. Compensation for peak hour demand by a renewable source (large scale) in combination with the grid is used in developed countries (Argaw, et al., 2003). In rural areas in developing countries a grid network is usually not available as mentioned before, which increases the demand for another type of power source.

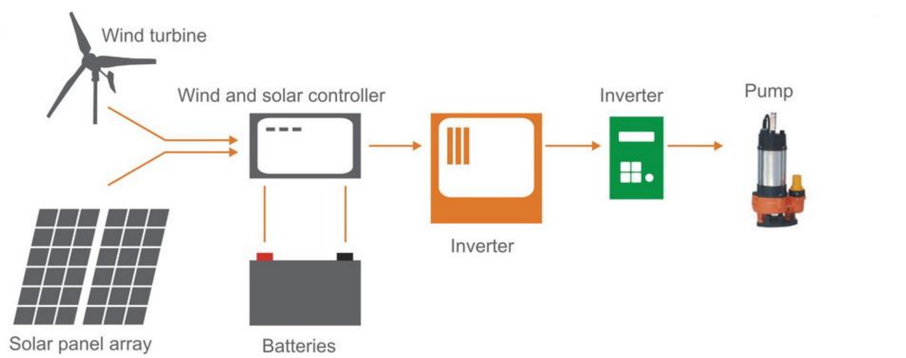


Figure 32: Hybrid water pumping system (Focus Technology Co., Ltd., 2012)

The combination of a solar and a wind system offers greater reliability. Hybrid systems of this kind do not have to be designed for the critical month because the power is not derived from a single source (Argaw, et al., 2003).

The different components can be sized smaller, which reduces the individual costs, but the investment cost is still high as two systems are implemented and a connection between the two is needed in a central control system.

The main drawbacks of hybrid systems are the complexity, which necessitates highly skilled personnel for maintenance and repair (Argaw, et al., 2003), and the high investment cost.

1.4.4. Choice of the energy resource

In Figure 33 the pumping cost is given as a function of the flow rate – head product for different energy systems. The volume – head product is a measure for the hydraulic energy needed (Lancashire, et al., 1987) and is defined as the product of the daily demand volume (Q) and the total dynamic head (h_{TD}) which leads to the unit m^4 d^{-1}. The pumping costs are highest for diesel and grid-connected (2 km extension) pumps. Two grid-connected pumps are considered: the ones that were directly connected to the grid, and the ones that needed an extension of the grid to the pumping site at a cost of US$ 15 000 per km. Solar-pumping devices are more cost-effective than diesel for a yield up to 1000 m^4 d^{-1} (Araya, 2010). The cost of a wind pump is a little higher than for the hand pump, grid connection (no extension) and solar pump (non AC). The range of use of the systems is also different and needs to be considered as well: a hand pump is suitable for a low flow – head range, whereas a diesel pump can be used at higher values as shown in Figure 33.

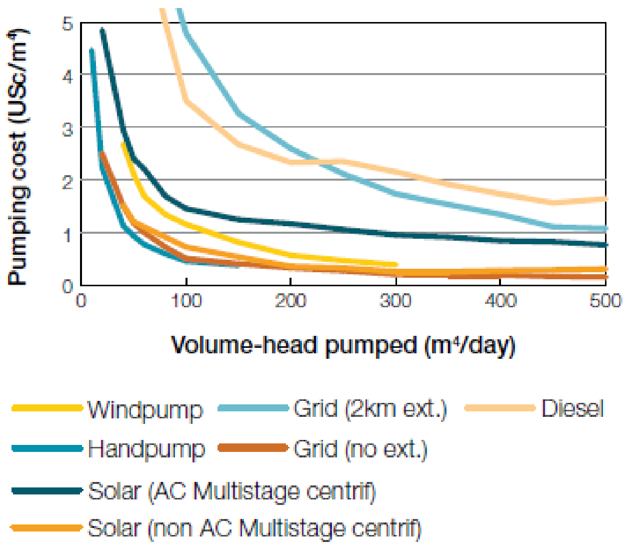


Figure 33: Life-cycle costs of water supply (Araya, 2010)

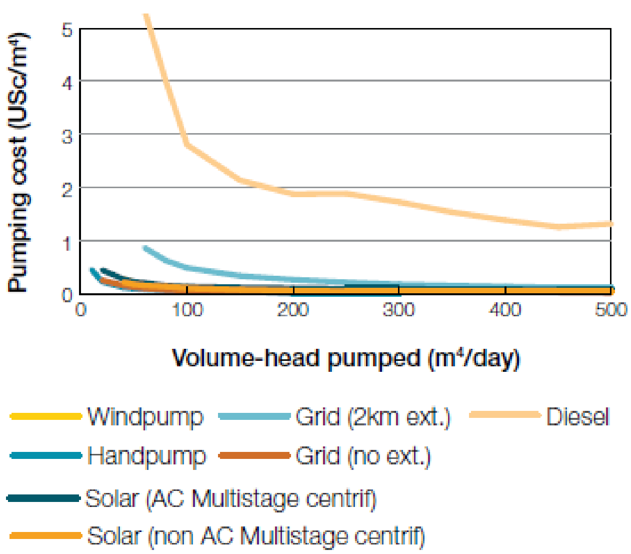


Figure 34: Operating costs of water supply (Araya, 2010)

Generally, operating costs are more important for the community since the investment is usually provided by the government services or a donor. In Figure 34 the operating costs of water supply are given for different energy systems. One can notice that PV, wind and hand pumps have lower operating costs than diesel pumps, but grid-connected pumps (without extension) are competitive.

1.5. Maintenance

1.5.1. Lifetime of the installation

The lifetime of water supply installations depends on the quality and type of installation and on maintenance performance. Both factors interact, some installations demand more maintenance than others, some installations have a shorter lifespan than others, even under optimal maintenance conditions. The higher the lifespan of an installation, the higher the investment costs may be allowed without decrease in cost-effectiveness. Photovoltaic panels are known to have a lifespan of 20 years or more, however this can be considerably shorter depending on the circumstances. Wind turbines, because of higher maintenance requirements, last usually shorter than that.

1.5.2. Investment and maintenance costs

Clearly, the water pumping installations that can be proposed to the communities have to take into account their cost. Although pumping installations are often offered for free through a donor, the investment cost remains important. With the limited resources in mind, it makes a difference when expensive or cheap installations are provided, because the cheaper, the more people can be served. Cheap often goes together with less quality though and hence the investment cost has to be weighed against the longevity of the installations and the needed performance. Maintenance costs are more difficult to assure (high operational cost to disburse small amounts of money on irregular intervals, scattered over a huge territory) by central governments or development agencies and therefore they often remain the responsibility of the local community (Nampusuor & Mathisen, 2000). The Village Level Operation and Maintenance (VLOM) system is often used, also called 'Community Management', approaches that aim to involve the communities (especially the responsible committee) as much as possible in the management for the water supply and the maintenance of the system with the aim to create responsibility and a sense of ownership (Drouin, 2005). The training can be subdivided in two categories for different persons: a training of area mechanics and a training of community pump caretakers (Nampusuor & Mathisen, 2000). Low maintenance costs and access to spare parts are major concerns when dealing with the question which installations are the best suited for a given community. Locally manufactured installations have the advantage that spare parts are usually available in the area. This must be weighed against possible shortfalls in quality and performance.

Maintenance is undertaken to increase the longevity of installations, or to increase its useful life. But maintenance by itself evidently includes costs. The effectiveness of the maintenance system in place influences its cost. But maintenance costs are also depending on the life of installations. The older any technical installation, the higher the probability of breakdowns, hence the higher annual maintenance costs become. When maintenance costs become more important than what can be gained by a longer useful life of the installation, maintenance should make place for replacement of the equipment (Riha, et al., 1998).

The saving per year due to maintenance can be expressed through Equation 10 (Riha, et al., 1998), in which SA is the saving per year, D_0 is the annual replacement cost without maintenance, D_m is the annual replacement cost with maintenance and X is the improvement factor of life expectancy of the installation due to maintenance.

$$SA = D_O - D_m = D_O - \frac{D_m}{X} = D_O \left(1 - \frac{1}{X}\right) \tag{10}$$

As the annual maintenance cost should not exceed the achievable saving on replacement cost per year due to maintenance, the annual maintenance cost ceiling should not exceed SA (M_{max} = SA) (Riha, et al., 1998).

A "relative maximum annual maintenance cost" is also proposed in which the maximum allowed maintenance cost is expressed as a percentage of the investment cost (Riha, et al., 1998). This is estimated as particularly useful for planning, for decisions on replacement of equipment and for monitoring maintenance system's performance.

1.5.3. Maintenance skills

Maintenance requires technical skills, and if maintenance is a local responsibility, it is the local community that should develop these skills. Tools for maintenance are most of the time not locally available either. Therefore, most water supply projects foresee the training of local volunteers (caretakers) that after a minimal training can take responsibility for basic preventive maintenance and for small (uncomplicated) repairs. For more complex repairs (often also more rare events) the local community can ask support from a more skilled person responsible for a bigger region and several installations (pyramidal organization). Although these problems can be anticipated and are often addressed in an integrated global package of water supply strategies, the solutions are not without difficulties.

Caretakers do not always remain motivated, are not always available at the moment they are needed, the money to buy spare parts is not always timely available either and lastly, preventive maintenance seems difficult to apprehend. Preventive maintenance like lubricating moving parts to anticipate breakdowns are often neglected because people want to save scarce resources for other (more urgent) things and have the tendency to postpone investments that have no obvious direct (observable) impact on their living conditions. The notion of prevention in general seems very little developed in rural Africa.

1.6. Renewable energy potential

The possibility of using a renewable energy system, in this case for a water pumping application, depends on several factors (National Renewable Energy Laboratory (NREL), 2012). These are shown in Figure 35. The resource must be sufficiently available to make its use viable. Secondly, there are some technical constraints that must be considered, e.g. the efficiency of the system (the resource cannot be used for the full 100 %). Thirdly, the costs must be acceptable, for the donor as well as for the community and lastly the market and policy makers should support initiatives for the use of such renewable energy systems. All these factors must be considered before implementing a renewable energy system. In this master thesis, the focus will be on the first three, namely the resources, the technical part and the economical part.

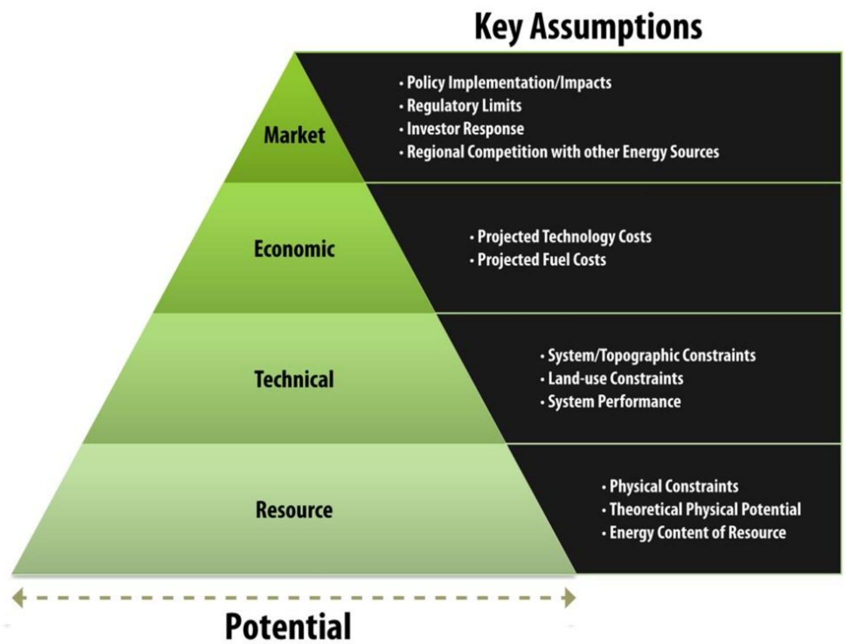


Figure 35: Renewable energy potential (National Renewable Energy Laboratory (NREL), 2012)

1.7. Objective of the study - The research question

The BTC development project on renewable energy for drinking water supply in Mozambique asked the question which type of installation would be the most appropriate to supply drinking water for the rural Mozambican population. In more technical-economic terms, the question can be put as: “Which type of water pumping system has the highest cost-effectiveness, taking into account the conditions of rural Mozambique?”

A cost-effectiveness analysis can be defined as a tool that aims to provide information about the relative efficiency of alternative solutions that serve the same goal (Polinder, et al., 2011). The research question contains a technical aspect, the effectiveness of different types of water pumping systems, but also an economical aspect, examined through a life cycle cost analysis for every system. This implies two study designs. The combination of the results of both studies should answer the question which investment is the most advantageous.

2. METHODOLOGY

2.1. Conception (setup) of the study

2.1.1. The technical study

The global research question can only be answered by the combination of the results of two studies. The effectiveness of different types of water pumping is the most important and voluminous part.

The effectiveness of a water pumping installation at first glance is a purely technical issue. When looking deeper into the matter though, environmental, economic and cultural factors complicate things. Indeed effectiveness of an installation under field conditions also depends on the quality of the installation, the regularity and quality of the maintenance, the promptitude of repairs, the risk of misuse or theft, etc.

The most reliable approach to measure effectiveness would be a prospective or retrospective study of installations in the field. This was the initial intention, but soon after arrival in Mozambique, it was clear that the necessary conditions for such studies were not present. For a prospective study, as the installations have an estimated lifetime between 10 and 20 years, the time frame is long, too long surely for the situation of a development project that hardly started and that would like to get answers as soon as possible for their strategic decisions. For a retrospective study, many data of good quality should be available for an important number of installations of each type, and this in comparable circumstances. Clearly such data were not available either, despite the presence of a Ministry of Energy and despite the fact that the research question is straightforward and already pertinent for tens of years.

In absence of such solutions, the only alternative was to use and combine national and international databases and recognized norms. These data were used in mathematical models and formulas. The big advantage of this approach is the short time investment and the low cost of such a setup. The main drawback is the fact that 'the field conditions' can only be indirectly estimated, conditions that could alter solutions or recommendations significantly. For example, the factor 'theft of solar panels' is difficult to integrate in lifetime estimations of solar installations but have potentially a huge impact on the overall performance of such installations under field conditions. Maintenance (or absence of it), which is known to be an important problem in rural areas in developing countries, is another example. Two simplifications were therefore incorporated in the mathematical study. First, the field conditions are different for every location, even on a village scale. This complexity is difficult to include in the mathematical models, also because a clear overview must always be preserved. Hence, some of these field conditions are assumed constant for all installations, e.g. the water demand. Other factors, like the borehole depth, are divided into a minimal number of categories to partly take into account different field situations. As a second simplification, some variables are excluded from the analysis, as these are far too specific, e.g. the borehole capacity. This must be determined for every borehole drilled and on this basis appropriate pumping systems (which do not run the borehole dry) can be installed. In this study, the capacity is assumed to be high enough to deliver the constant demand set at 40 $m^3\ d^{-1}$. The variation of the quality of a borehole is considered independent of the type of pumping system that would be installed. This factor would therefore be neutral to effectiveness when different pumping installation systems are compared. When the water supply must be higher than the foreseen constant demand factor, for instance in a bigger village, a second borehole is proposed.

During the stay in Mozambique, a field trip was conducted to PV and direct wind water pumping systems installed by FUNAE. The three locations visited were Mubalo (Homoine) and Chitondo in Inhambane province and Chicualacuala in Gaza province. At the first site a direct wind system was installed, at the latter two there were PV water pumping systems. The only instrumentation available was a GPS and a tape measure. Data were collected from the different sites, by measurement, but mostly by interviews with the local caretakers. These visits do not provide systematically collected (reliable) data one would like for a study. But it did provide some important field impressions on the circumstances in which installations are put up and have to be maintained. It was also the occasion to observe the virtual absence of a systematic monitoring system that, as mentioned earlier, prevented to conduct a retrospective study.

This study assumes that the quality of the installations is correct. Under developing country conditions this is not assured though as can be deduced from several observations. For example, during the field visits it was observed that at a gas station near Chicualacuala, some of the solar panels were actually in the shadow in the middle of the day (approximately 1 pm) as shown in Figure 36. When looking for flow capacity data on the actual boreholes in Mozambique, the data of DNA were very incomplete. In practice this might mean that ineffective boreholes are used and that pumps run dry. The optimal inclination of the panels is yet another factor that is not guaranteed in practice because of lack of rigorous controls by installation. These realities might negatively affect the effectiveness of the installation but are not included in the study as a variable factor.

Figure 36: Gas station with shadowed solar panels

2.1.2. The economic study

In the economic study, the three renewable energy water pumping systems, namely PV, wind turbine and direct wind, are compared to a diesel water pumping system and a hand pumping system. First, the different costs were estimated per system to compare the costs for the three borehole classes and secondly per borehole category to be able to compare the different powering systems.

Four types of expenses were considered: investment, maintenance, operating and borehole costs. The investment costs for the different components of the installation were estimated through a local and sub-regional market study and/or prices obtained from websites of international firms. Where applicable and possible, average prices per system type were calculated. Installation costs like salaries for workmen and transportation of the systems to the site are not considered and assumed constant for the different systems. Some of the installations require multiplying the number of boreholes because it is technically impossible to reach the needed capacity through only one borehole installation. In such case, only the additional need for boreholes is brought in as an extra cost. They will be illustrated in the graphs separately from the investment cost of the installation for the reader to see the relative importance of this factor in the overall cost. Different borehole categories (or classes) were considered in the technical but also in the costing analysis, as costs rise according to depth.

Also for the maintenance costs, FUNAE did not dispose of detailed field data. The field visits to the installation sites and informal interviews gave some valuable impressions on the field reality concerning the organization of the maintenance of water pumping installations. The differences between theory and practice can be said to be important. Relatively high maintenance cost estimates were used in the mathematical models to include a safety margin. Operating costs were only considered for the diesel water pumping system, and data for fuel cost were gathered during the field trip to have an idea of the fuel price in rural areas, transport of fuel having an important impact on the pricing. Clearly, the maintenance cost theories expanded upon in Chapter 1 (Riha, et al., 1998) could not be applied in practice due to lack of specific reliable data.

In the costing study, two indicators were calculated and compared. First, in the lifecycle cost analysis, total costs decomposed for total investment, maintenance, operating and additional borehole costs for each type of water pumping installation are compared. This parameter was also calculated per depth class of the boreholes. Besides simply comparing total costs between different systems, it allows estimating the relative contribution of each type of cost to the total cost for an installation with a given capacity. This breakdown is necessary to have a closer look into the robustness of the figures.

A second parameter that was calculated is the unit water cost which is the cost of one m^3 of water pumped, based on the total costs. This indicator is important to estimate how realistic cost-recovery through financial community participation would be. People are asked to pay small amounts for the water they use in order to cover at least partially maintenance and replacement costs. At the same time, this should not cause an important barrier for the use of the water either.

2.1.3. The social study

A social study was not included in this analysis. This requires data from lots of communities, country-wide, and the number of interviewees must be large. The system preference of the local population as well as the participation through a fee-paying system for the water use could be examined. This might be an important aspect of viability because independent (from official authorities) local financial resources can prove very useful for effective early routine maintenance. It has potentially also implications for long-term viability of the system. However, the cost-effectiveness is least affected by this research area. Therefore, this study focusses on the technical and economic part, and considers the social study parameters as constant field conditions, irrespective of the type of installation.

2.2. Technical analysis

2.2.1. Population and borehole data

Population data for every province were provided by FUNAE (Fundo Nacional De Energia, 2012). The classification is as follows: the province is divided in districts, which in turn consist of administrative posts. These contain localities and lastly every locality has a few villages. Data of these villages are available for the year 2011. In the dataset, population numbers of 10 000 and more are not considered as rural villages and are removed from the dataset. This is also done for a lower limit value of 10 persons.

The governmental organization Direcção Nacional de Águas (DNA) has provided the water level data from boreholes they have drilled in localities in Mozambique (Direcçao Nacional de Aguas, n.d.). These data are categorized by province and then further to the level of localities and data for every province are available. Outliers were removed from the dataset with threshold values of 5 m as lower limit and 200 m as upper limit. Lower and higher depths are considered unlikely.

2.2.2. PV water pumping system

2.2.2.1. Solar resources in Mozambique

Solar data were gathered from the database PV GIS, where information on the optimal inclination angle and the solar irradiation can be found.

Mozambique is an elongated country and therefore the optimal angle for a solar panel varies significantly from north to south which is shown in Figure 37. The lowest latitude is 10° in the point upper north, the largest latitude, in the south, is 26° and the optimal inclination angle varies from 14° to 31° from north to south.

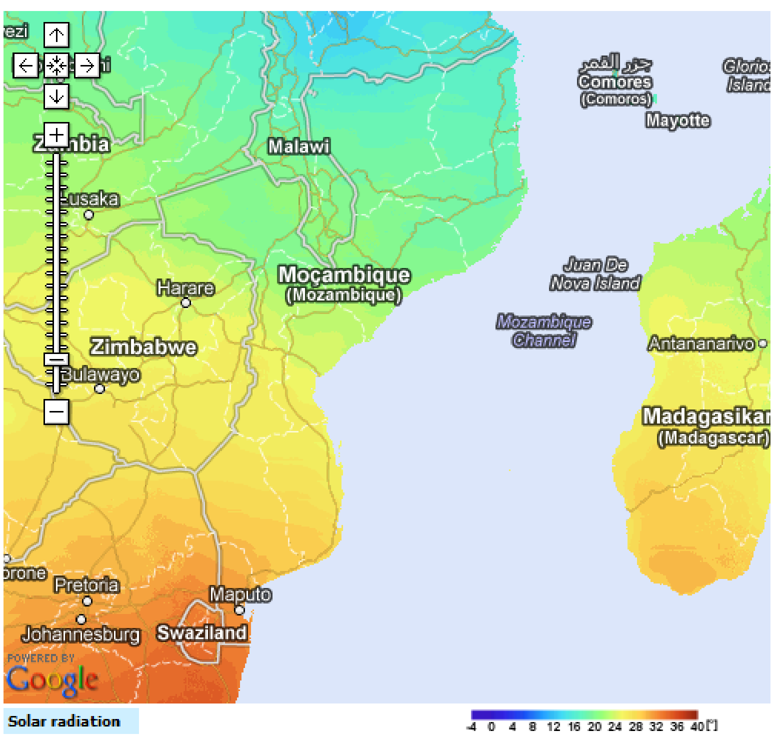


Figure 37: Optimal inclination angle of PV panels for Mozambique (PVGIS European Communities, 2001 - 2007)

The solar irradiation on a plane with an optimal inclination for Mozambique is shown in Figure 38. This varies from approximately 1900 to 2400 kWh m^{-2}. A few locations per latitude were selected, shown in Figure 2 in Appendix B, and averaged to obtain one mean solar irradiation value per latitude for the same optimal angle. The data that were used for further calculations are shown in Figure 39 which gives the solar irradiation H expressed in kWh m^{-2} d^{-1} on an optimal angle given between brackets.

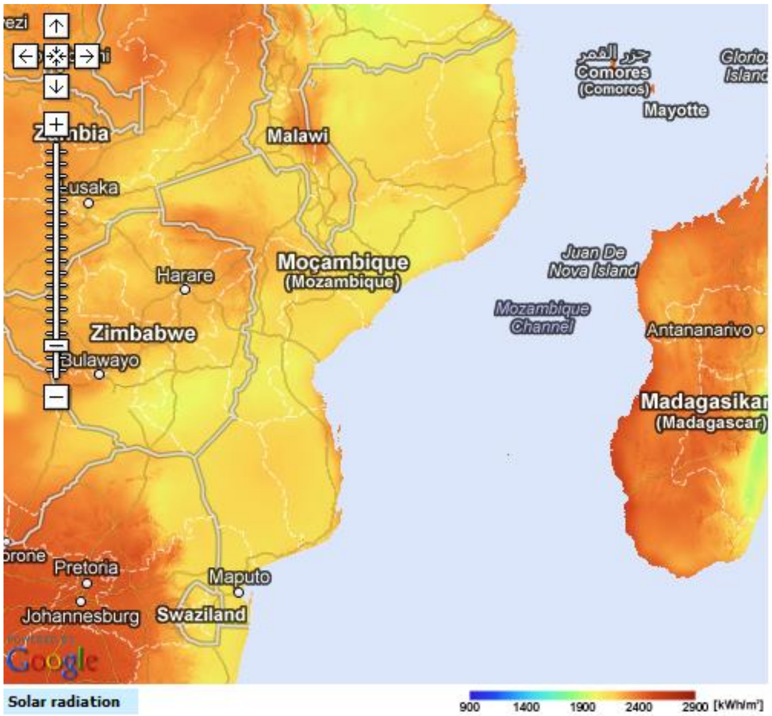


Figure 38: Solar irradiation on a plane with an optimal inclination angle for Mozambique in kWh m^{-2} (PVGIS European Communities, 2001 - 2007)

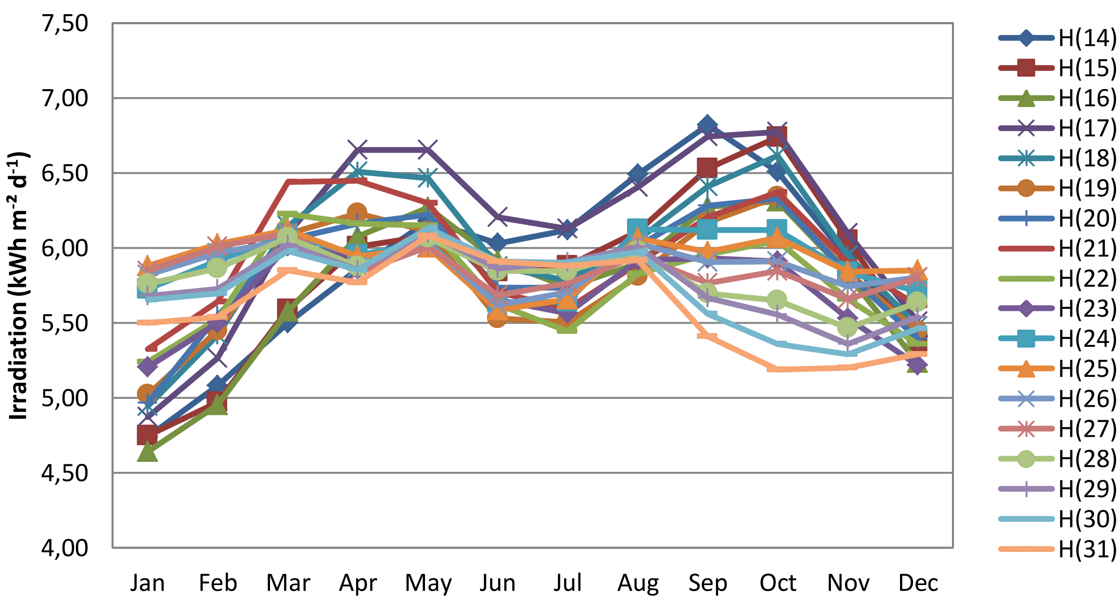


Figure 39: PV GIS data of solar irradiation H (kWh m^{-2} d^{-1}) on a plane with an optimal inclination angle (given between brackets) in Mozambique (PVGIS European Communities, 2001 - 2007)

2.2.2.2. Energy calculation and data processing

Three methods were used to evaluate the solar resource potential in Mozambique.

In the first method, the solar energy (kWh d^{-1}) that can be collected from an installation of a certain peak power (P_p) is calculated by using Equation 11 (De Vos, 2012), where H is the incoming radiation in kWh m^{-2} d^{-1}. The correction factor η_L is a loss factor used to take into account the loss due to temperature, dust deposition, the system wiring, inverter losses etc. PV GIS uses a default value of 14 % for estimation of grid-connected solar systems, but the assumption has been made that in rural circumstances the losses are greater and grid-connection can be considered as the ideal application. Therefore, 20 % loss is assumed for the water pumping system. From this equation, one can determine how many W_p must be installed to achieve the needed electricity output for the pumping system.

In the second method, the solar energy (kWh d^{-1}) that can be collected from n solar panels is calculated by using Equation 12, with A the area and η_{PV} the efficiency of a photovoltaic panel which were taken as 1 m² and 13 % respectively.

$$E_{solar} = P_p \frac{H}{1000 \frac{W}{m^2}} \eta_L \tag{11}$$

$$E_{solar} = H\, A\, \eta_{PV}\, \eta_L\, n \tag{12}$$

Lastly, in the third method, the software of PV GIS is used to estimate how much electricity in kWh d^{-1} can be generated with the peak power calculated in Equation 11. The system in the software is considered grid connected to simulate the connection to the motor of the pump. Standalone systems in this software use batteries, but this simulation of the pumping system is less accurate than a grid-connected simulation. The azimuth orientation is taken as 180° (facing north) and the same locations as considered previously (Appendix B) are used and averaged per optimal inclination angle.

A Grundfos sizing of the solar water pumping system with the WinCAPS tool (version 2012.01 DVD) was done for the three borehole categories. There are four sizing locations possible in Mozambique: Beira, Lumbo, Maputo and Umbeluzi. The pumping system was sized for each location and averaged. The water volume is set at 40 m³ d^{-1} and a non-tracking solar system was assumed.

2.2.3. Wind water pumping system

2.2.3.1. Wind resources in Mozambique

Wind speed data were gathered from the Canadian database RETScreen which provides meteorological data from NASA and groundstations, 22 in total for Mozambique, at 10 m height. The locations are shown on the map in Figure 3 in Appendix B. The wind availability is presented in two ways: in the first one, average daily wind speeds per month are shown for every station (Figure 40) and per province (Figure 41). Secondly, daily wind speed data from 01/01/2002 to 31/12/2012 were taken from the NASA database in RETScreen to analyse the overall pattern.

The average wind speed over all locations in Mozambique is 3.86 m s^{-1}.

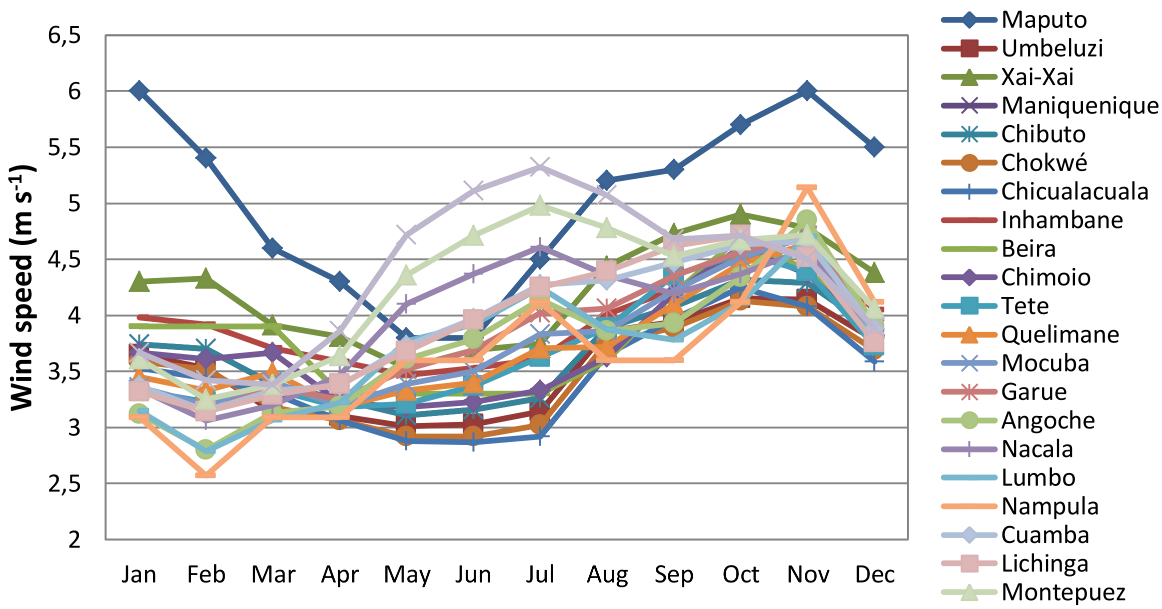


Figure 40: RETScreen wind speed data (m s^{-1}) for all stations in Mozambique (Minister of Natural Resources Canada, 1997 - 2012)

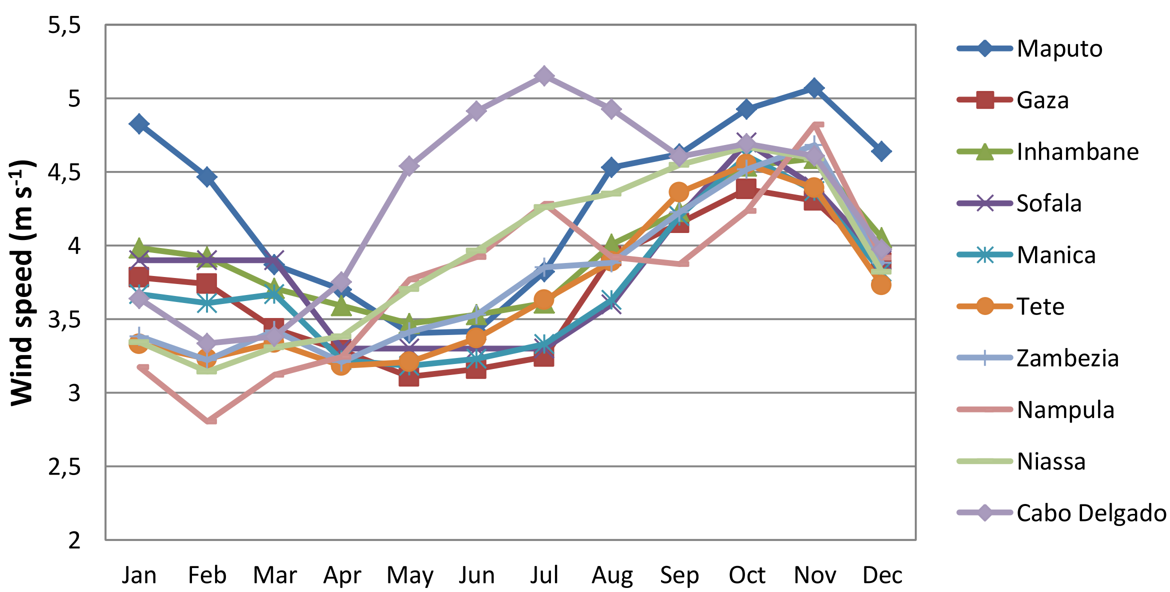


Figure 41: RETScreen wind speed data (m s^{-1}) per province in Mozambique (Minister of Natural Resources Canada, 1997 - 2012)

2.2.3.2. Energy calculation and data processing

Electrical wind system

The daily energy that can be provided by a wind turbine expressed in kWh d^{-1} is given by Equation (13).

$$E_{wind} = \frac{1}{2} \rho \, v^3 \, \eta_{Betz} \, \eta_t \, A \frac{24}{1000} \qquad \textbf{(13)}$$

where ρ is the density of air, v is the wind speed and η_{Betz} is the theoretical maximal efficiency that can be provided by the wind which is 59.3 %. η_t is the efficiency of the turbine taken as 30 % (Ramos & Ramos, 2008) and A is the rotor area, which is $\frac{1}{4}\pi D^2$ with D the diameter. The factor $\frac{24}{1000}$ is a unit converter factor.

However, when using average wind speeds, Equation (14) should be used (De Vos, 2012) when working with the Rayleigh distribution:

$$E_{wind} = \frac{3}{\pi} \rho \, (\overline{v})^3 \, \eta_{Betz} \, \eta_t \, A \frac{24}{1000} \tag{14}$$

with $\overline{(v^3)} = \frac{6}{\pi} (\overline{v})^3$.

The height of the pole and the rotor area can be varied to achieve a higher power. However, here they are chosen as a constant value according to the values found on the Mozambican market. The height is taken as 10 m and the rotor area is considered 2 m.

A Grundfos sizing of the electrical wind water pumping system with WinCAPS (version 2012.01 DVD) is done for the three borehole categories. Again, the four possible locations from Grundfos are used and the water volume is set at 40 m^3 d^{-1}.

Direct wind system

To calculate the power provided by a mechanical windmill, the same Equation as (14) can be used. However, efficiencies of such windmills are little known. Therefore, power charts from suppliers are more practical and will be used in the analysis.

A tool on the website of Ironman windmills is also used to estimate the capacity of direct wind water pumping systems.

2.2.4. Pump and head

The daily electrical energy consumed by the motor of the pump (J d^{-1}) is given by Equation (15). This is the minimal energy that the system should produce, taking into account all the losses in the system.

$$E_{elec,motor} = \frac{\rho \, Q \, g \, h_{TD}}{\eta_p \, \eta_m} \tag{15}$$

The factors ρ and g are the density of water (1000 kg m^{-3}) and the gravitational constant (9.81 m s^{-2}). Q is the daily water demand expressed in m^3 d^{-1} and h_{TD} is the total dynamic head (m). The two factors in the denominator are the efficiencies of the pump and the motor respectively whereby the product is the motor-pump efficiency η_{pm}. This combined efficiency is assumed to be 0.55, according to the WILO TWI 4.03-B-QC pump (Figure 8). When multiplying this equation by the factor $(3.6 \cdot 10^{-6})^{-1}$, the unit is converted to kWh d^{-1} (instead of J d^{-1}).

The total dynamic head is the elevation head corrected upwards for friction (h_f) and minor losses (h_m), pressure difference and velocity differences as shown in Equation (16) (Ronsse, 2011-2012).

$$h_{TD} = \Delta z + \frac{\Delta p}{g \, \rho} + \frac{(\Delta v)^2}{2 \, g \, \alpha} + h_f + h_m \tag{16}$$

The factors on the right hand side in this equation are (from left to right) the elevation head, the pressure head, the velocity head, the friction head and lastly the minor losses head. The factor α is a coefficient that depends on the flow regime and is equal to 0.5 for laminar flow and 1 for turbulent flow (Ronsse, 2011-2012).

The elevation head is the geometric head plus the drawdown due to pumping. The geometric head was calculated as the height from the storage tank, taken as 2 m above ground level, to the water surface in the well. The drawdown was calculated by Equation (17) (Verhoest, 2011):

$$S_W = \frac{Q}{2\,\pi\,T}\,\ln\frac{R}{r_w} \tag{17}$$

where Q is the pumping rate (40 $m^3\ d^{-1}$), T is the transmissivity ($m^2\ d^{-1}$), R is the radius of influence and r_w is the well radius. The transmissivity in Mozambique is estimated to be between 5 and 10 $m^2\ d^{-1}$ (Bonsor & MacDonald, 2011), whereas the average value of 7.5 $m^2\ d^{-1}$ was used. The radius of the well is taken as 0.5 m. When varying the radius of influence from 30 to 100 m, the drawdown varied between 3.5 and 4.5 m. The latter value was taken for further calculations to include a safety margin.

The pressure head is the loss due to pressure difference but this term was considered zero as there is atmospheric pressure at both the surface of the borehole and of the water tank.

The velocity at the surface of the water tank is assumed to be zero due to the large surface area, so only the velocity in de borehole at the pump is used. The friction losses h_f are calculated by using the Moody chart as shown in the procedure below. First the velocity is calculated using Equation (18) where D is the inner diameter of the piping system and Q is the flow rate which is 40 $m^3\ d^{-1}$. However this is converted to 0.0014 $m^3\ s^{-1}$ by only considering 8 pumping hours a day. The velocity should not exceed 1.5 $m\ s^{-1}$ (Washington State University, 2013), therefore the minimum inner diameter of the duct is 34 mm. The pipe chosen here is DN50 (SDR 13.6), which has an inner diameter of 42.4 mm (Waters & Farr, 2005) and the same is taken for every borehole category. Then the Reynolds number is calculated with Equation (19). If Re is higher than 10 000, the flow is fully turbulent (Cengel, et al., 2008).

$$v = \frac{Q}{\pi\,\frac{D^2}{4}} \tag{18}$$

$$Re = \frac{\rho\,v\,D}{\mu} \tag{19}$$

Next, the relative roughness ε/D is calculated, with ε the roughness of the material of the piping system, polyethylene in this case, which is 1.5 10^{-6} m (American Water Works Association, 2006) and D the diameter of the tube. The value of ε/D is thus equal for every borehole category and is 3.5 10^{-8}. This is used with the calculated Reynolds number to determine the Darcy friction factor f in the Moody chart.

The pressure loss is calculated with Equation (20), where L is the length of the piping which is the elevation head (geometric head + drawdown).

$$\Delta P = f\,\frac{L}{D}\,\frac{\rho\,v^2}{2} \tag{20}$$

Lastly the head loss due to friction is determined using Equation (21).

$$h_f = \frac{\Delta P}{\rho\,g} \tag{21}$$

Minor losses are caused by components that interrupt the smooth flow of the fluid. These components can be bends, elbows, inlets, exits, enlargements and many others. In Equation (22) the minor loss due to these components is given:

$$h_m = K_L \frac{v^2}{2\,g} \tag{22}$$

with K_L the loss coefficient which is different for every component. The minor losses components that will be considered in this piping system and the corresponding K_L values are listed in Table 7. At the water tank the pipe inlet is considered re-entrant. The piping diameter is assumed constant over most of the length of the piping, some small expansions and contractions are considered to obtain a more realistic system, as well as some elbows as the piping will probably not be perfectly straight. Lastly, some smooth 90° bends in the piping are incorporated. The number of minor losses is considered to be proportional to the length of the piping. Therefore, the number of components is lowest for the 40 m and highest for the 100 m category. These are also given in Table 7.

To take into account the head loss because of the filter, one meter is added to the head of each system.

Table 7: Minor losses considered for every borehole category with corresponding K_L value (Cengel, et al., 2008)

Component	K_L	40 m	70 m	100 m
Pipe inlet in water tank, reentrant	0.80	1	1	1
Gradual expansion with angle = 20°	0.30	2	3	4
Gradual contraction with angle = 30°	0.02	2	3	4
Elbow, 45° and threated	0.4	3	4	5
Bends, 90° and smooth	0.3	4	4	4

2.3. Economic analysis

As the cost-effectiveness is to be determined, a life-cycle cost analysis was carried out for every system. The costs are subdivided into the initial investment costs (including the water storage tank), the maintenance, operating and additional borehole costs.

To estimate the investment cost, the prices from different companies who provide water pumping systems are used. The companies considered representative of the market of Mozambique are listed in Table 8 and described below. They were contacted by the Belgian company RA Collectoren to provide offers for the three borehole classes.

Grundfos is a Danish international company with its headquarters in Denmark. The Grundfos Group is represented worldwide in more than 55 countries. Mozambique is one of them, where Blue Zone Ltd is a distributor, located in Maputo. Grundfos products include waste water pumps, industrial pumps, water supply pumps but also distribution and treatment systems, and many more. The renewable energy water pumping system is an all in one package (not only a pump). There are two systems available using the same SQFlex pump: a PV water pumping system and a wind turbine water pumping system. They also provide diesel generators which can be used for a water pumping system. Hand pumps, like the Afripump, are also available at Blue Zone.

Stewarts&Lloyds, located in South Africa, sells windmills of the brand Climax. There are several distributors per province in South Africa and they export products to other southern African countries. They also provide Grundfos pumps and the SQFlex renewables (PV and wind turbine).

Lorentz solar pumps can be provided by the South African company KG Electric, which is located in Johannesburg. Several types of pumps and solar panels are available according to the system.

Kijito Windpower is a Kenyan company that sells windmills for water pumping applications. They export their products, which makes it a relevant player on the Mozambican market.

Kestrel Renewable Energy is part of the Eveready Group, which is based in Port Elizabeth in South Africa. They offer grid connected, off-grid, telecommunication and water pumping systems with wind turbines. There are some distributors in South Africa and Swaziland from where import to Mozambique is easy.

Agro Alfa S.A. is a metal industry company located in Maputo. It is a distributor of Climax windmills which are imported from South Africa and they manufacture Afridev pumps. They also provide diesel generators for water pumping.

Wilo is a German manufacturer of pumps, active worldwide. They are present in South Africa and serve other southern African countries, but they only provide pumps, not the whole renewable energy package, and are therefore not considered here.

Table 8: Representative companies of the Mozambican market for water pumping systems

Solar PV	Windmill	Wind turbine	Diesel	Hand
Blue Zone	Stewarts&Lloyds	Blue Zone	Blue Zone	Blue Zone
KG Electric	Kijito	Kestrel	Agro Alfa	Agro Alfa
Stewarts&Lloyds	Agro Alfa			

In Table 9 the assumptions used for the economic analysis are listed. The lifespan of the solar system is said to be five to ten years in rural areas (Hansen, 2012) which is considerably shorter than the generally accepted lifespan of 20 to 30 years in West European conditions. KG Electric reports a lifespan of 15 years, in case of proper care. An average lifespan for the PV system of 10 years was assumed for this study. The lifespan of the other systems was also assumed to be 10 years, as specific data were not available.

The yearly maintenance cost was considered proportional to the number of moving parts and calculated as a percentage of the investment cost. For PV installations, literature proposes 2 % for the yearly maintenance cost (Al-Smairan, 2012). Taking into account the higher number of moving parts in the wind systems, 3 and 4 % estimates are used for the wind turbine and windmill system respectively. Diesel systems also need regular maintenance, e.g. oil replacement, which was taken into account by a 5 % yearly maintenance cost based on literature (Al-Smairan, 2012). The hand pump was considered to have a very low yearly maintenance cost of 0.5 %.

After five years, an overhaul, again proportional to the investment cost, was considered and the yearly small maintenance was included in this cost. The proportionality was set at 25, 15 and 10 % for the PV, wind turbine and windmill system respectively. This assumption is based on the replacement cost of several parts. A new PV panel for example will be more expensive than a major part of the other two systems and therefore the PV system will have a higher overhaul cost. The maintenance cost of the pump was assumed to be the same for the three borehole categories. The overhaul of diesel and hand pumping systems were taken as 10 and 2 % respectively. Abstract was made for transport costs related to installation and maintenance. They are highly variable depending on the location but considered constant on average for all types of installations.

Operating costs are only considered for the diesel water pumping system by means of the fuel price. The fuel price is likely to rise in the future, which will increase the operational cost but as a simplification, this is considered constant through the life span of the system in this economic study.

The cost of a 10 m³ storage tank without the support structure, estimated at € 804 (Ferragens Maputo, 2012), was included in the investment costs of all systems, except for the diesel and hand pump.

Table 9: Assumptions for the economic analysis

	Lifespan (years)	Yearly maintenance cost (%)	Overhaul cost (%)	Operating cost
PV	10	2	25	N/A
Wind turbine	10	3	15	N/A
Windmill	10	4	10	N/A
Diesel	10	5	10	Fuel cost
Hand	10	0.5	2	N/A

As a first method, the present value of costs (PVC) was calculated with Equation (23) (Al-Smairan, 2012):

$$PVC = I + \sum_{t=1}^{N} \frac{C(t)}{(1+r)^t} \tag{23}$$

in which I is the sum of the investment and additional borehole cost, C(t) is the sum of the maintenance and operating cost in year t and r is the discount rate which is taken as 10%. Borehole costs are indifferent for the type of pumping installation and were initially not included in the costing exercise. But technical limits of pumps in particular application settings make that in order to maintain the same pumping capacity, the installation has to be duplicated, including the number of boreholes. In this case, the additional borehole is an additional cost that must be taken into account, when compared with an installation based on one single borehole. The cost of a borehole in Mozambique is reported to be approximately € 7 000 (Gesti Canuto, 2011), which will be considered separately from the investment cost.

In the second method, the unit water cost was calculated by using Equation (24). C_T is the total cost, t is the lifespan of the system (years) and Q is the flowrate expressed in $m^3\ d^{-1}$. The availability (a in Equation (24)) is the number of days that the system can be used per year, so when no maintenance is done and no failure is occurring. This value is taken as 90 % of the time which is 328.5 days per year.

$$P = \frac{C_T}{a\ t\ Q} \tag{24}$$

3. RESULTS AND DISCUSSION

3.1. Population

The median population number per village for every province has been calculated and is shown in Figure 42. The choice to not use the average is to minimise the influence of outliers. To obtain a value for the whole country, the average of these median populations was calculated and resulted in 1030 ± 80. The population number that will be used to size the water pumping system is 1000 persons in order to provide every median village in Mozambique by one system.

The water demand was based on the use of 30 L $person^{-1}$ d^{-1} and an extra safety volume of 10 m³ was incorporated in case of bad weather conditions or during maintenance, which resulted in a total amount of 40 m³ d^{-1}. The local population was interviewed during the field visit to gather data about the water usage but they found it difficult to estimate. The demand also depends on other possible water sources like a river, lake or rainwater collection. Here, it is assumed the water is not used for livestock or irrigation, only the human demand is considered. The reliability of the borehole and the pumping system is therefore of utmost importance.

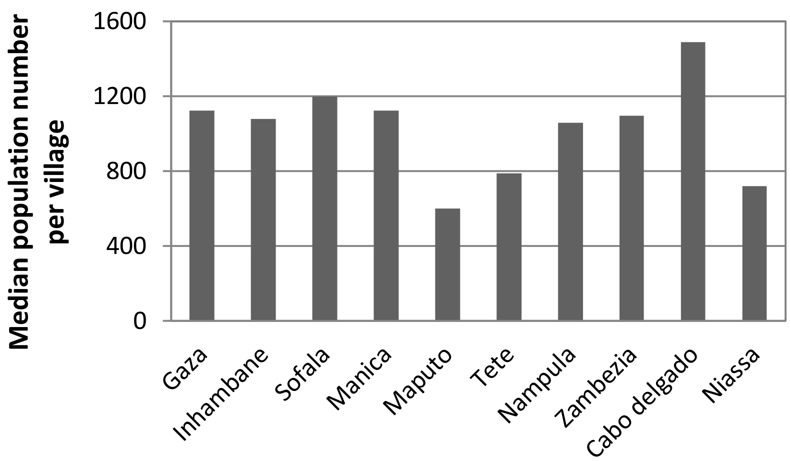


Figure 42: Median population per village for every province in Mozambique (Fundo Nacional De Energia, 2012)

For all further calculations and data analysis, the population and the water consumption needs are kept constant at respectively 1000 and 40 m³ d^{-1} and boreholes are assumed to be reliable for such flow.

3.2. Water boreholes

3.2.1. Borehole depths and flow rates

The average depths for every province are shown in Figure 43 and the mean depth for the whole country is (40.6 ± 0.5) m. It should be noticed that these are not total dynamic heads, but geometric heads from ground level to the surface of the water in the borehole.

Table 10: Minimum and maximum depths of drilled boreholes per province in Mozambique (Direcçao Nacional de Aguas, n.d.)

Province	Min depth (m)	Max depth (m)
Niassa	11.0	70.0
Nampula	5.0	57.0
Cabo Delgado	19.0	49.0
Tete	5.0	111.5
Maputo	5.0	197.0
Inhambane	9.1	180.0
Gaza	5.0	200.0
Manica	5.0	158.0
Zambezia	10.0	101.0
Sofala	9.0	163.5

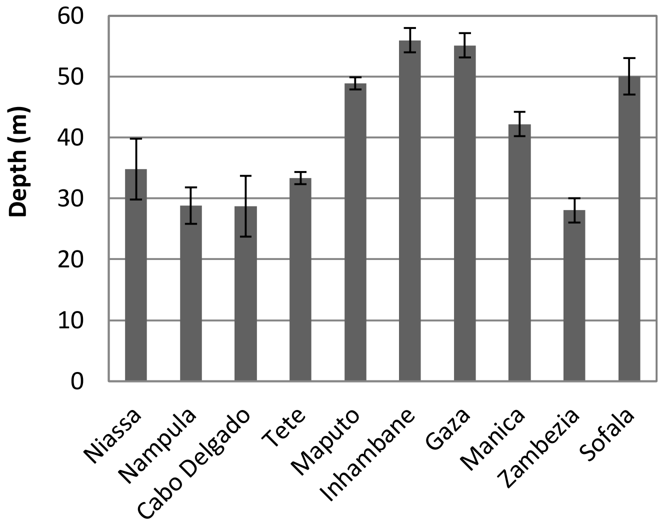


Figure 43: Average borehole depths per province for Mozambique (Direcçao Nacional de Aguas, n.d.)

From these data, three borehole depths were selected to standardise the sizing of the water pumping systems in further calculations, namely 40, 70 and 100 m. These are referred to as the borehole categories or classes. The need for a renewable energy power source for water pumping is more important at higher depth, where hand pumping is more difficult. In all the provinces, except Niassa, Nampula and Cabo Delgado, boreholes deeper than 100 m are found as shown in Table 10. This makes the need of deeper borehole categories clear.

As stated before, the demand is considered constant at 40 m³ d^{-1} and the borehole is assumed to be able to deliver this amount. In the same dataset provided by DNA, the maximum and recommended hourly flow rates are given. These were averaged and are presented in Table 11. From these data, the daily flow rates were calculated based on 8 and on 24 h pumping. In four provinces, the recommended flow rate is lower than the demand when considering 8 h of pumping. A borehole test should therefore always be conducted before installing a system with a certain capacity. The recommended flow rate when considering 24 h of pumping is in all cases higher than 40 m³, as are the averages for the whole country. From this information, the assumption that the demand of 40 m³ d^{-1} can be met by the borehole is considered realistic.

One storage tank of 10 m³ in incorporated in every renewable energy system as this is considered as a buffer water supply which can be used during maintenance, failure or poor climatic conditions. The buffer capacity was not sized larger as it is expected that the water pumped is almost all used directly. Even if the needs for drinking are fulfilled, the additional water pumped will probably be used for other needs instead of the water of another source. In Chicualacuala the two water tanks of 10 m³ each were never used as buffers. The water was always taken directly as many people had to be served.

Table 11: Average recommended flow rate for every province in Mozambique (Direcçao Nacional de Aguas, n.d.)

Province	recommended flow rate ($m^3\ h^{-1}$)	recommended flow rate ($m^3\ 8h^{-1}$)	recommended flow rate ($m^3\ d^{-1}$)
Niassa	4.0	31.9	95.7
Nampula	4.8	38.5	115.5
Cabo Delgado	2.0	16.1	48.3
Tete	10.2	81.4	244.3
Maputo	9.8	78.6	235.7
Inhambane	5.3	42.1	126.2
Gaza	7.5	60.0	180.1
Manica	3.7	29.9	89.8
Zambezia	5.5	43.7	131.0
Sofala	5.7	45.9	137.6
Average Mozambique	**5.9**	**46.8**	**140.4**

3.2.2. Head losses

The losses considered were the velocity head, the friction head and the minor head as shown in Equation (16). The results of the calculations are summarized in Table 12.

To obtain the friction losses, the velocity was calculated using Equation (18). The flow rate was taken as 40 $m^3\ d^{-1}$, but this is considered to be pumped in 8 hours, not 24, which gives a velocity of 0.98 $m\ s^{-1}$. The corresponding Reynolds number is $37 \cdot 10^3$ according to Equation (19) and thus the flow is turbulent (Cengel, et al., 2008). The friction factor f was obtained from the Moody chart and was approximately 0.0225 (Cengel, et al., 2008). Lastly, the pressure drop and the friction loss were calculated with Equation (20) and (21) respectively.

The velocity head was calculated according to the third term on the right hand side of Equation (16). The velocity at the surface of the water tank was considered zero, so only the velocity at the pump was calculated with Equation (18). As mentioned before, the flow is fully turbulent and thus α is equal to one. As the velocity is the same for the three borehole categories, this loss is also constant and equal to 0.05 m.

The total dynamic head was obtained by adding the three losses computed above (velocity head, friction head and minor head) and the drawdown level (4.5 m) to the geometric head. The head loss data are summarised in Table 12 for every borehole category.

Table 12: Velocity head, friction head, minor head and total dynamic head calculated for the different borehole categories

Borehole class	Velocity head (m)	Friction head h_f (m)	Minor head h_m (m)	Total dynamic head h_{TD} (m)
40	0.05	1.2	1.20	49
70	0.05	2.0	1.24	80
100	0.05	2.8	1.27	111

3.3. Technical analysis

3.3.1. Pumping system

3.3.1.1. Pump energy requirement

The daily energy required by the pump-motor system was calculated by Equation (15) and shown in Table 13. The daily water demand Q was taken as 40 m³ d^{-1} but only 8 pumping hours were considered to calculate the power of the pump-motor system, which is also shown in Table 13.

Table 13: Pump-motor energy requirement for borehole categories

Borehole category (m)	E_{pm} (kWh d^{-1})	P_{pm} (kW)
40	9.70	1.21
70	15.81	1.98
100	21.92	2.74

This is the minimal energy that the renewable energy system must supply in order for the pump to deliver 40 m³ d^{-1}. This is constant for every type of pumping system under consideration and per head. They are considered the norm to estimate the renewable energy equipment requirements.

3.3.1.2. Types of pumps used

Centrifugal pumps are used for high flows and low heads. These can be used for the 40 m borehole category with a daily delivery of 40 m³. In the quotation of Stewarts&Lloyds (providing Grundfos systems), the SQF 5A-7 was proposed for this borehole, which is a centrifugal pump. However, at higher depth, the transition to a helical rotor pump is probably needed. These pumps have lower flow rates but can deliver from boreholes deeper than even 200 m. Division of the capacity over two pumps, to achieve the needed 40 m³ is likely. This was also the case in the Stewarts&Lloyds offer, where the SQF 2.5-2 was suggested for the two deepest borehole classes (giving a different daily flow).

For a direct wind pumping system, centrifugal pumps are not used as a vertical motion needs to be generated, suitable for positive displacement pumps.

Pump qualities can be a limiting factor in renewable energy pumping system applications. No suitable pumps are for instance available to deliver the total demand of 40 m³ d^{-1} from 100 m head. For the direct wind water pumping systems, a suitable pump for a given installation can be selected through tables that combine installation parameters (see further Table 17 and Table 18). In the economic analysis, the prices are based on real systems with realistic delivery capacities of the pumps. When more than one system was needed to deliver 40 m³ d^{-1}, whether this was due to limitations of the pump or to another factor, the number of installations was increased to obtain a sufficient water supply.

3.3.2. PV water pumping system

3.3.2.1. Solar data analysis

The solar resource availability seems high when looking at Figure 38 and the irradiation data from PV GIS in Figure 39 which lie between 4.5 and 7.0 kWh m^{-2} d^{-1}. There is more variation in northern locations within a year as these show values over the whole range. The irradiation is lowest in January and highest in April and September – October. In southern and middle locations the monthly irradiation is more constant and lies approximately between 5.0 and 6.5 kWh m^{-2} d^{-1}. From these data the required energy to meet the pump-motor demand was calculated by two methods: using the peak power installed and secondly using a number of panels with an efficiency of 13 % and an area of 1 m². In a third method, the system was simulated by a grid-connected PV system and lastly a Grundfos WinCAPS sizing was conducted.

3.3.2.2. Energy calculation

The first approach described in the methodology was to determine the peak power needed to produce enough energy to drive the pump-motor system by using Equation (11) and the solar irradiation data from Figure 39. This resulted in a need of 2.6 kW_p for the 40 m borehole class and the daily energy generated from this installation is presented Figure 44. At any moment and at all sites, the PV system produces more energy than the E_{pm} baseline of 9.70 kWh d^{-1}. This is the needed minimum capacity of the PV installation in order to meet the requirements of the pump. The figures for the other borehole categories (70 m and 100 m) are analogous and can be found in Appendix C, the data are also summarized in Table 14.

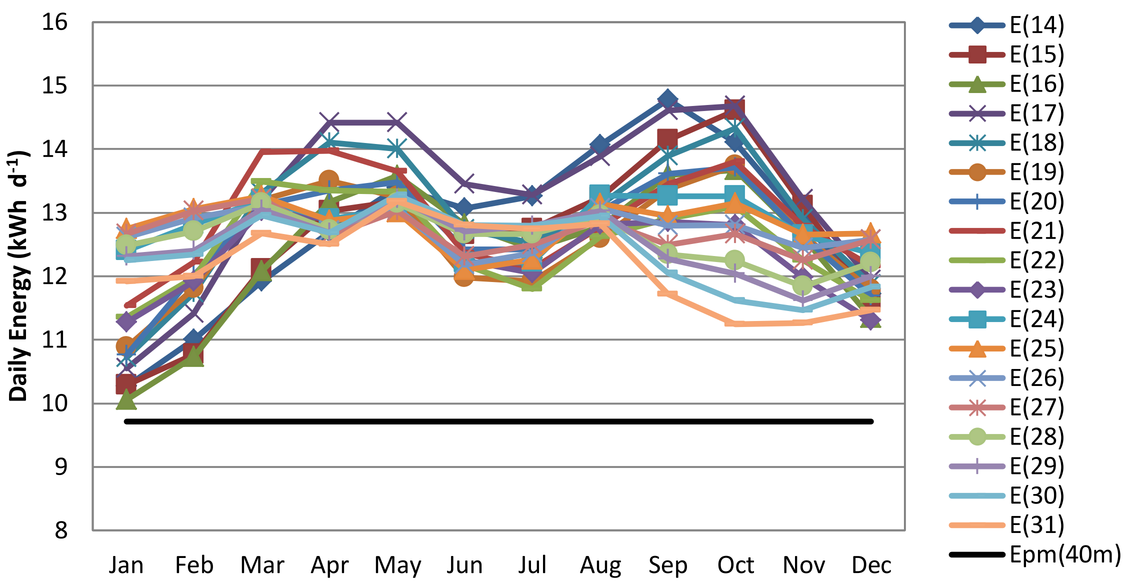


Figure 44: Energy from 2.6 kW_p (optimal inclination angle) and required pumping energy for 40 m borehole category in Mozambique

In the second method, the number of panels needed was calculated. The energy from one PV panel varies between 0.5 and 0.75 kWh d^{-1}. The results obtained were the same graph as shown in Figure 44 for the 40 m borehole category, as 20 panels with an efficiency of 13 % are needed to produce a value of 2.6 kW_p. Because of this analogy, the graphs for this method are not shown. The number of panels needed for the 70 and 100 m borehole categories are 34 and 48 respectively.

Table 14: PV sizing results for the 40, 70 and 100 m borehole categories

Borehole category	40 m	70 m	100 m
Peak power (kW_p)	2.6	4.4	6.4
# panels (A=1 m², η=13%)	20	34	48

It should be noticed that the number of panels in Table 14 is only valid for the properties of the panels assumed before. A different result would be obtained for other types of PV panels with for instance a different efficiency or surface area. This is for instance the case for the offer that was received from the South African company Stewarts&Lloyds: they sized a PV Grundfos water pumping system for the three borehole categories with 80 W_p solar panels with a surface area of 0.61 m². However the peak powers in the offer are analogous with the ones calculated and given in Table 14. But first it should be mentioned that only the 40 m borehole was sized for a supply of 40 m³ d^{-1} in the quotation. The other borehole categories could not deliver this amount: the maximum flows were 26 and 22 m³ d^{-1} for the 70 and 100 m borehole classes respectively. The peak power suggested for these systems must therefore be doubled to meet the required daily volume of 40 m³. This resulted in peak powers of 5.6 kW_p and 6.4 kW_p for the two deepest boreholes, which approximate the ones calculated in Table 14.

The results of the Grundfos WinCAPS sizing tool are shown in Table 15. The 70 and 100 m borehole categories could not be sized for the full daily flow of 40 m³: the maximum value is 13.4 and 13.0 m³ d^{-1} for the 70 and 100 m class respectively. This resulted in a lower peak power, but the system must be tripled to meet the requirement of 40 m³ d^{-1}. This gave a total power of 7.5 kW_p on average for the four locations for the 70 m head and approximately 8 kW_p for the deepest borehole. This is higher than the powers calculated earlier and also higher than the suggestion of Stewarts&Lloyds. This is probably because a different total dynamic head is used: the head loss due to the drawdown is not incorporated in the Stewarts&Lloyds quotation, but it was added in the Grundfos sizing tool. The piping diameter for the two deepest boreholes was also different: in the offer, a thinner pipe (DN32) is used because the flow rate is approximately half of the 40 m³ d^{-1} which is supplied by one system in the calculations. This gives a difference in friction head and therefore also in the total dynamic head.

Table 15: Grundfos WinCAPS solar water pumping sizing for the three borehole categories and four possible locations and the average case

	Beira	Lumbo	Maputo	Umbeluzi	Average
40 m borehole category					
Average daily water flow (m³ d^{-1})	43.4	42.5	43.1	43.0	43.0
Friction loss (m)	3.1	3.1	3.1	3.1	3.1
# GF 80 solar panels	48	42	48	60	49.5
Peak power (kW_p)	3.84	3.36	3.84	4.8	4.0
70 m borehole category					
Average daily water flow (m³ d^{-1})	13.0	13.2	13.6	13.9	13.4
Friction loss (m)	2.4	2.4	2.4	2.4	2.4
# GF 80 solar panels	24	24	32	45	31.3
Peak power (kW_p)	1.92	1.92	2.56	3.6	2.5
100 m borehole category					
Average daily water flow (m³ d^{-1})	12.7	13.4	13.7	12.3	13.0
Friction loss (m)	3.3	3.3	3.3	3.3	3.3
# GF 80 solar panels	25	32	40	28	31.3
Peak power (kW_p)	2.0	2.56	3.2	2.24	2.5

The delivery of a 6 SQF-2 Grundfos pump connected with a 640 W solar array was measured (Clark & Vick, 2008) and the result was shown in Figure 22. The flow rate is given in function of the wattage per m² for heads of 50, 75 and 100 m. To be able to compare this with the case of Mozambique, the daily radiation (W m^{-2}) in January for three locations, namely 17-2, 22-2 and 26-2 from Figure 2 in Appendix B, was calculated with PV GIS. The result is presented in Figure 45 from which can be seen that the minimal global radiation of 100 W m^{-2} is easily reached, already in the morning hours. The maximum values are approximately 1000 W m^{-2} for the three locations at clear sky and between 600 and 750 W m^{-2} for a real sky situation. In Figure 22, this resulted in deliveries between 10 and 20 L min^{-1} for the three heads.

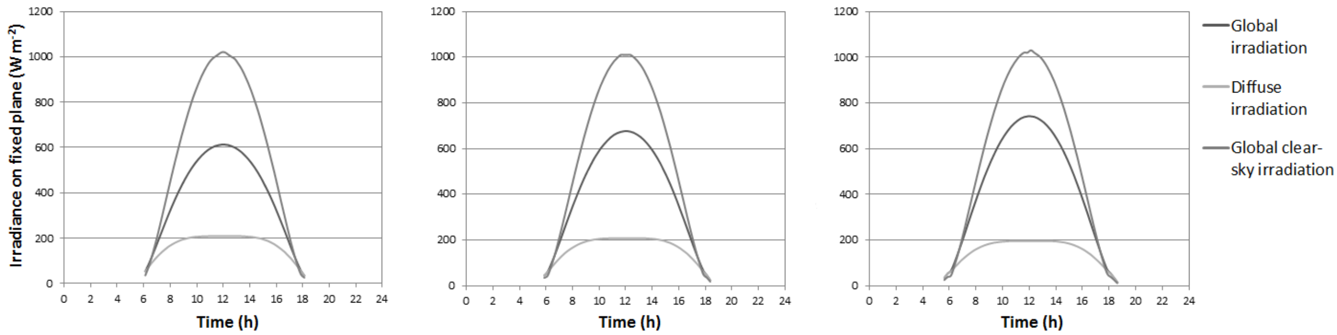


Figure 45: Daily radiation profile for three locations (17-2 left, 22-2 middle, 26-2 right from Appendix B) in Mozambique (PVGIS European Communities, 2001 - 2007)

In the last method, the electricity production (kWh d^{-1}) was calculated by PV GIS for a grid connected PV installation to simulate the water pumping system. This is shown in Figure 46 for the 40 m borehole category in combination with the required pumping energy. The figures for the other two classes (70 m and 100 m) can be found in Appendix C.

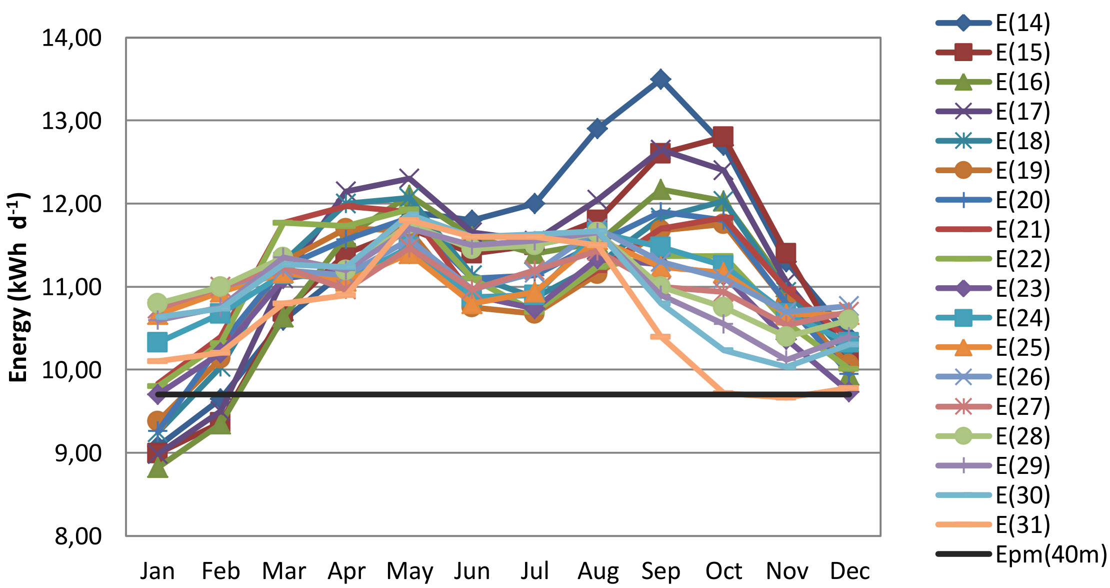


Figure 46: Electricity production (kWh d^{-1}) from 2.6 kW_p for a grid connected system (optimal inclination angle) and required pumping energy for 40 m borehole category in Mozambique (PVGIS European Communities, 2001 - 2007)

The simulation by PV GIS for a grid connected solar system gives slightly lower power outputs for all the borehole categories than the two earlier methods used. This is surprising as a grid connected system can be considered as the perfect pump connection. This outcome can be explained by the losses incorporated by PV GIS. These are assumed 14 % for cables, power inverters and dust for example, but are further enhanced by site specific losses, due to temperature and angular reflectance effects which raise the factor to approximately 27 % in Mozambique. This is higher than the safety factor of 20 % used in the calculations in the other two methods explaining their higher power output. The required pumping energy is not met in every month at every site when using the third method for the three borehole categories, with the biggest difference for the 40 m head and only one data point in the 100 m borehole (Appendix C). The PV system should therefore be sized a little bigger (higher peak power installed) to take into account these extra losses.

The PV installations delivering a flow rate of 40 m^3 d^{-1} are quite large (Table 14), but they are estimates maximising the effectiveness over the year. Individual installations can be downsized a bit at sites where yearly irradiation is higher or more evenly distributed.

In practice, the number of panels needed can be estimated for each site (specific irradiation to be expected), taking into account the local population size and the borehole capacity. In the field, the observed number of PV panels per system in rural areas in Mozambique was much less: in Chicualacuala and Chitondo 6 panels were used. However, in both cases the local population was not perfectly happy with the installations as they didn't provide enough water. Therefore, the village technician made a diesel-PV hybrid system in Chitondo and in Chicualacuala the solar panels were stolen and replaced by a diesel engine which in both cases was experienced as an improvement in spite of the fuel cost. This illustrates clearly that the basic water needs of the population should be met and that appropriate sizing is needed. In villages with less than 1000 inhabitants, the demand is probably lower and smaller systems can be used. For a higher population number, it can be more convenient to install two systems that combined deliver the volume needed.

For further comparison with other pumping systems, the standard sizes as represented in Table 14 will be maintained. The sized systems maximized the effectiveness as sufficient peak power was foreseen all year round at all sites and a safety production of extra daily 10 m^3 water was included.

3.3.2.3. Maintenance

The solar panels as such are said to be maintenance free (Hansen, 2012). However, a lot of sand and dust can deposit on them and washout by rain does not occur in the dry season. Cleaning the surface of the panels is therefore necessary but is not done in practice (Hansen, 2012). In Figure 47 the solar panels of the water pumping system in Chitondo are shown which were never cleaned, and there was no awareness of the consequences of the dirt (lower flow rate).

Figure 47: Dirty solar panels in Chitondo

Local caretakers should get aware of this consequence during their training and should probably be reminded during supervisory visits of higher instances. It should also be mentioned that for cleaning, water from another source than the borehole can be used (for instance a nearby river). The difference in quality is generally known by the rural population. However, this should always be stated when installing a new system.

Other regular maintenance, besides cleaning of the panels, mostly concerns the pumping system rather than the power system in case of a PV installation. This is a big advantage compared to other types of installations that should not be underestimated. When breakdown of one or more panels occurs, this is unlikely to be solved by the local technician and the panel(s) will probably be taken out of the system to continue pumping with a lower power.

Theft was mentioned as a major drawback of PV installations in rural Mozambique and elsewhere in Africa. This was also encountered during the field visit, namely in Chicualacuala. A fence was not installed as a first measure of prevention, unlike in Chitondo. This is however a little effort that can be crucial in some cases. This should therefore always be included when installing a PV water pumping system. A second method to prevent theft is welding of the bolts. This is already practiced in rural Niger for instance. The drawback of this prevention method is the difficulty in replacement of the panels.

A maintenance program for general control of the system, early repairs in case of breakdowns and replacements in case of theft is highly recommended. A contact system between the local caretaker, the local authorities, the donor and finally the company in charge of maintenance should be implemented. In practice this is not yet the case: in Chicualacuala the solar panels were stolen but this was not communicated to FUNAE and was only concluded on site during the field visit. The maintenance program must prevent ignorance of such problems at the donor level. A yearly check-up of the system as well as good communication in case of breakdown and theft are the key elements of a good maintenance program.

3.3.3. Wind system

3.3.3.1. Wind speed data analysis

Daily average wind speed data from 2002 to 2012 from the RETScreen database of two locations with the most extreme patterns, Xai-Xai and Mocuba, are presented in Figure 48 and Figure 49. Xai-Xai is located at the coast of southern Mozambique and Mocuba inland in the north. The wind regimes of other cities can be found in Appendix D. Two threshold values of 2.5 and 3 m s^{-1} are also drawn in the graphs as these should be reached every day in order to operate the water pumping system. The 2.5 value is based on the cut-in wind speed of a Kestrel 300i wind turbine, however 3 m s^{-1} is needed to deliver water. The Grundfos Whisper 200 has a cut-in speed of 3.1 m s^{-1} (Atlabara, n.d.) and Climax windmills are said to be viable when the average wind speed exceeds 3 m s^{-1} for 8 hours per day (Southern Cross Industries, 2013).

The average wind speed data of Xai-Xai are the highest of all in the dataset. All wind speeds exceeded the two threshold values on average every day of the year. From January to June, the average wind speed is about 4.5 m s^{-1} and this increases in the more windy months from July to October. The overall average wind speed is 4.8 m s^{-1} and the minimum and maximum values are 3.4 and 7.4 m s^{-1}. This can be a good wind regime for installation of a wind water pumping system. However, one has to take into account that these data are averages per day and will not hold that value for 24 hours. More variation on an hourly basis is expected which could mean a decrease in reliability of the water pumping system. Rated wind speeds of wind pumping installation are much higher. This signifies that at lower wind speeds, production will be much less and installations might not deliver the required water volumes. This will be further analysed in the next section.

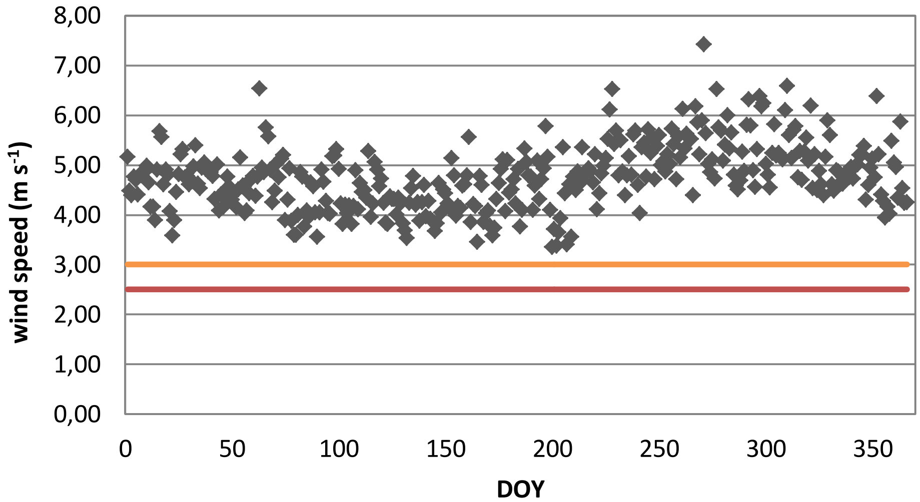


Figure 48: Daily wind speed data for Xai-Xai and threshold wind speed of 2.5 and 3 m s^{-1} (Minister of Natural Resources Canada, 1997 - 2012)

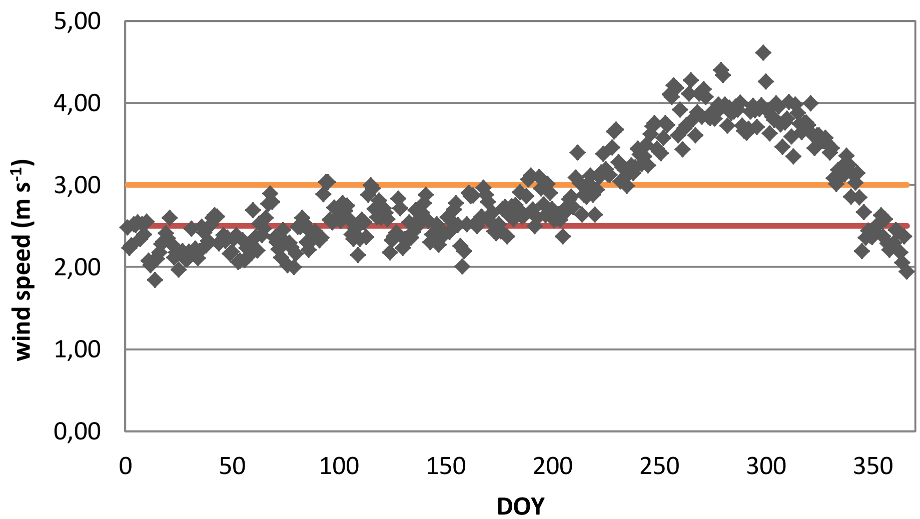


Figure 49: Daily wind speed data for Mocuba and threshold wind speed of 2.5 and 3 m s^{-1} (Minister of Natural Resources Canada, 1997 - 2012)

In Figure 49, the data from Mocuba are presented which show a less appropriate wind regime. 64 % of the data lie under the 3 m s^{-1} threshold and 33 % of the values lie under the 2.5 m s^{-1} line. This means that in 33 % of the time, 122 days per year, a wind water pumping system will probably not deliver enough water, if it does at all. Depending on the system used, the time range without water can be even higher. This can for instance be 234 days per year for the wind regime of Mocuba when considering no water delivery below an average wind speed of 3 m s^{-1}. Based on these threshold values, this is an example of a bad wind regime for installation of a wind water pumping system.

The data for other geographic sites in Mozambique can be found in Appendix D. They can be divided in different categories based on geographical position. This can be the north and south of Mozambique, or coastal and inland locations. It can be derived immediately that in most cases, wind speeds are relatively low for the required energy generation needed.

An ANOVA test in the statistical program R was used to determine if there was a statistical difference between the sites inland versus the coastal locations, and secondly between the south and north of the country. For this test, the monthly average values were used and Chimoio is considered as the last location in the south. If the p-value generated by this test is higher than 0.05, there is no statistical difference. The p-value obtained for the comparison between north and south was 0.7873 which indicates that there is no statistical difference in this dataset. For the coast – inland comparison, the p-value was 0.004674 which indicates there is a significant difference between coastal and inland locations regarding their mean monthly wind speed.

When considering a wind water pumping installation, the wind regime can be estimated based on the wind speeds of the closest site in Appendix D. Wind speed measurement at the particular site is however more accurate and should be conducted before installing a wind pumping system. This is however costly and time consuming.

3.3.3.2. Electrical wind system

Energy calculation and data processing

In Figure 50 the power delivered by a wind turbine with a rotor diameter of 2 m and 30 % efficiency is shown for the wind speeds given in Figure 41.

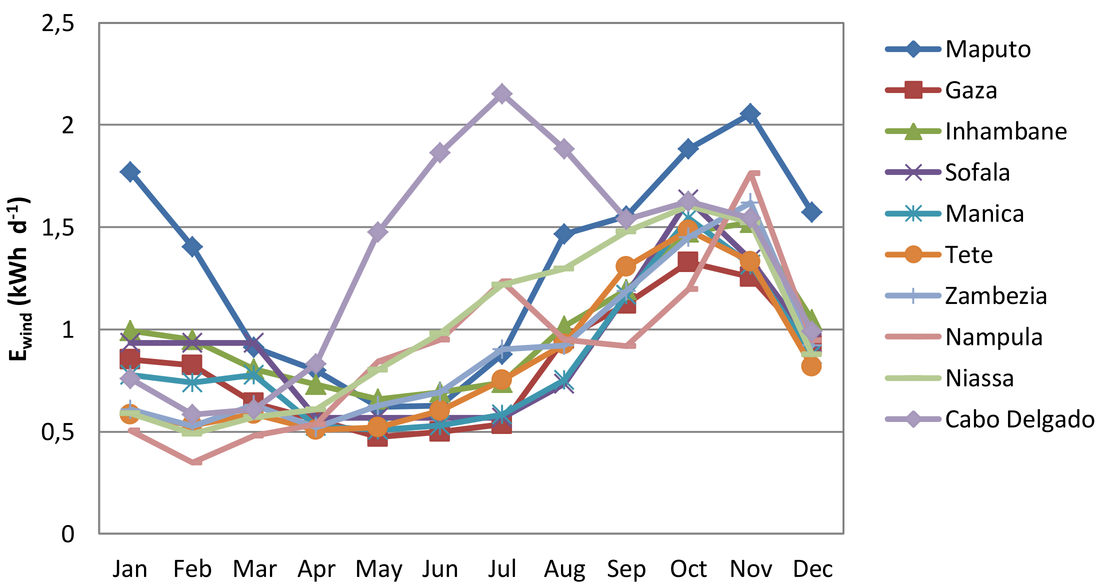


Figure 50: Daily energy delivered by a wind turbine with a rotor diameter of 2 m per province in Mozambique

The average is 1 kWh d^{-1} whereas the needed power for the pump is 9.70, 15.81 and 21.92 kWh d^{-1} for the different borehole categories (Table 13). The energy from solar panels is in the same order of magnitude: two solar panels (A=1 m² and η=13%) generate approximately the same power as one wind turbine (D=2 m and η=30%). However, this energy is much more constant in the case of PV panels. This entails that a higher energy excess is expected during the year when operating a wind turbine.

Figure 51 illustrates the number of turbines needed to achieve the required pumping energy. This is 28 for the 40 m borehole category, 46 turbines for the middle category and 65 for the 100 m head. For the two latter cases, the figures are shown in Appendix C.

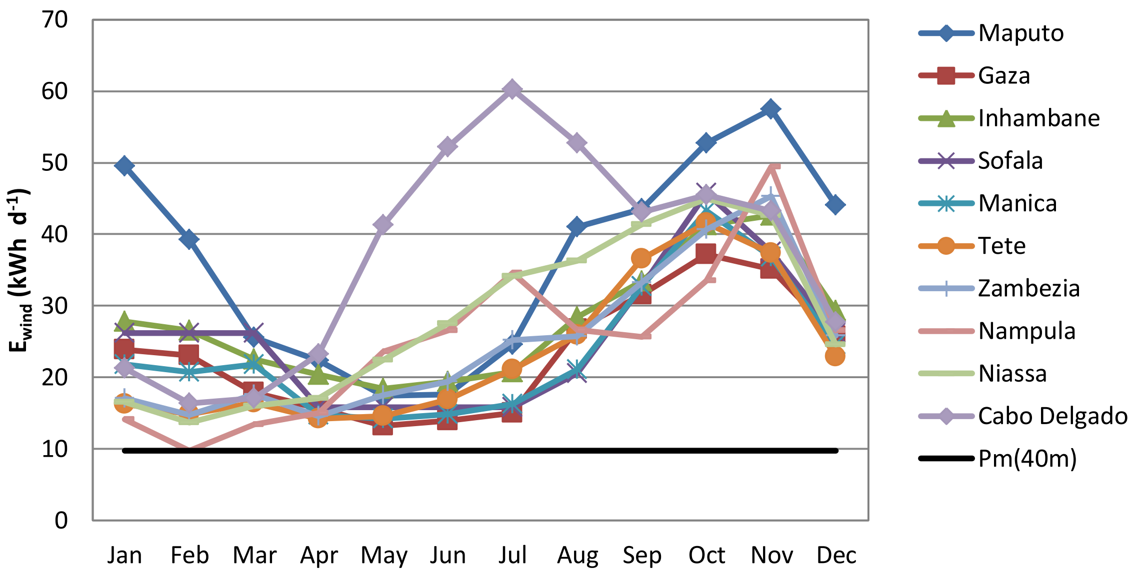


Figure 51: Energy (kWh d^{-1}) delivered by 28 wind turbines for the 40 m borehole category and the required pumping energy

These numbers of turbines needed per borehole are clearly too high to be reasonable. They are in the range of turbine farms, but are not thinkable for water supply from a single borehole. Moreover, this kind of installations would take a lot of area, far more than a solar system providing an equal amount of energy. This is due to a minimum distance needed between the turbines to prevent influencing the wind regime of another turbine. This distance should be at least 4 times the diameter of the rotor for units on the same row and the rows must be separated by 7 times the diameter (De Vos, 2012).

The water delivered by a 1 kW three-bladed Kestrel wind turbine is shown in Figure 52. The rotor has a diameter of 3 m, the cut-in wind speed is 2.5 m s^{-1} and the rated wind speed is 10.5 m s^{-1}. As the average wind speed in Mozambique is 3.86 m s^{-1}, the wind speed curve of 3.5 m s^{-1} in Figure 52 was used as a reference for further calculations. From this graph a delivery of 5 m³ d^{-1} can be expected for the 40 m borehole category with a total dynamic head of 49 m. For a head higher than 50 m a higher wind speed is needed to deliver water from the borehole. For the 70 m borehole (h_{TD}=80 m), the minimal wind speed needed is 4.5 m s^{-1}, which is clearly too high for the regimes in Mozambique. This is also true for the 100 m borehole category, where a minimal wind speed of 5 m s^{-1} is required. But even if this wind speed was reached, the delivery is low, about 6 m³ a day.

The Kestrel e400" wind turbine, from which the power curve was given in Figure 24, can also be used for water pumping applications. However, this turbine has a cut-in wind speed of 4 m s^{-1} which, in case of Mozambique, is rather a maximum wind speed than an average. This shows that installing bigger turbines is not a solution to supply more water as the cut-in wind speed increases as well and one might even end up with a lower delivery.

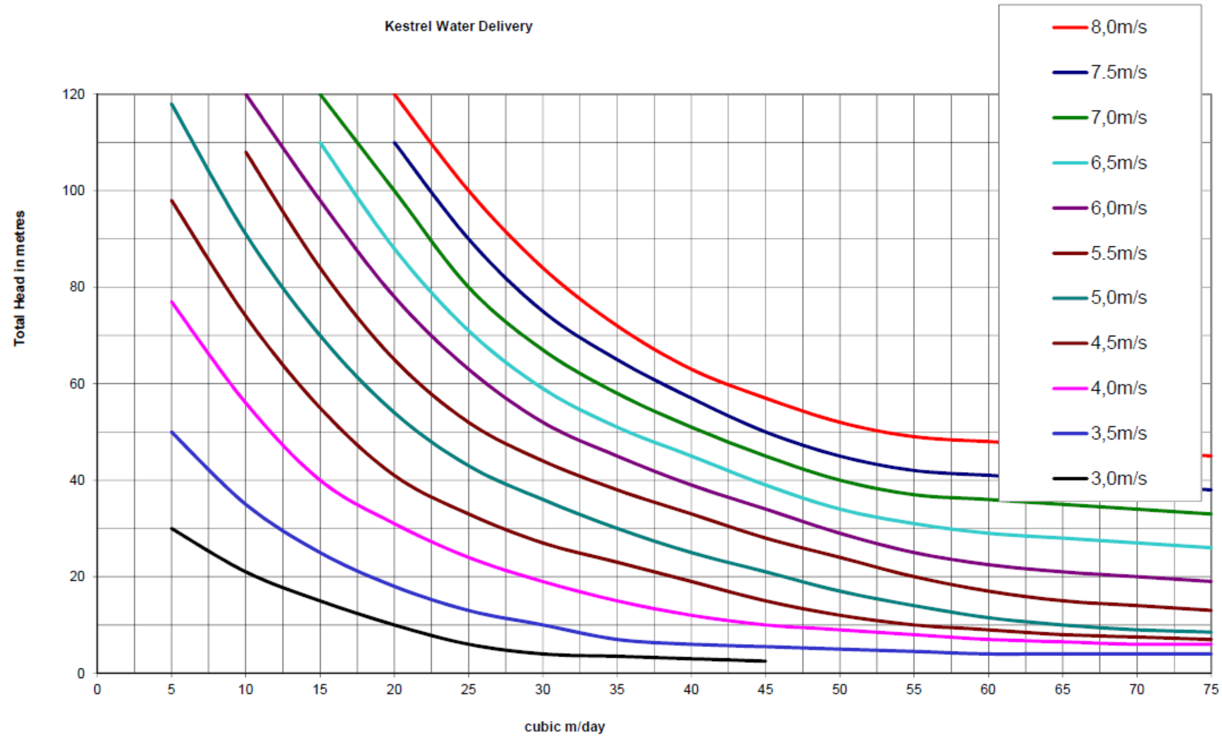


Figure 52: Water delivery (m³ d^{-1}) of e300i (1kW) Kestrel wind turbine for different wind speeds (Kestrel Renewable Energy, 2012)

The electric wind turbine used by Grundfos is the Whisper 200 with a rotor diameter of 2.7 m, a nominal power of 1 kW (at 11.6 m s^{-1}) and a cut-in wind speed of 3.1 m s^{-1}. The estimated maximum flow rates for the water pumping systems are given in Table 16. The water delivery is much less than the needed 40 m³ d^{-1}. Average flow rates of 3.75, 1.75 and 1.38 m³ d^{-1} were calculated for the 40 m, 70 m and 100 m borehole categories respectively, which is even less than a hand pump.

Table 16: Maximum flow rate for the Grundfos electrical water pumping system

Maximum flow rate (m³ d^{-1})	Beira	Lumbo	Maputo	Umbeluzi	Average
40 m borehole category	2.5	4.0	4.0	4.5	3.75
70 m borehole category	1.0	2.0	2.0	2.0	1.75
100 m borehole category	1.0	1.5	1.5	1.5	1.38

To meet the requirement of 40 m³ d^{-1}, one would need 11, 23 and 29 turbines of this type per pump for the three borehole classes respectively. These are lower numbers than calculated with the wind speed data from RETScreen in Figure 51, which was expected as different turbines are compared, but they are still too high to be practical as a water pumping solution.

When operating the 6 SQF-2 Grundfos helical pump with a 1 kW turbine, the water delivery only starts at a wind speed between 4 and 5 m s^{-1} (Clark & Vick, 2008) as can be seen in Figure 31. This is far too high for the wind speed regimes found in Mozambique, with an average wind speed of 3.85 m s^{-1}. This states that during the major part of the year, no water would be pumped. Secondly, the delivery is very low. For the 50 m head and a wind speed of 5 m s^{-1} during the whole day, 3.6 m³ water is pumped per day. When adopting this wind speed for 8 h per day, which is still not achievable in Mozambique, the delivery is 1.2 m³. This is even less than a hand pump, demonstrating that an electrical water pumping system will not meet the requirements in Mozambique.

Maintenance of electrical wind pumps

Lastly, the maintenance of the electric wind water pumping system should be considered. Hardly any of these systems are found in Mozambique, especially not in remote areas. Introducing a new system is a major constraint as local technicians are not familiar with it. This can be remedied by a training which is however less obvious compared to the use of PV panels which are far more present in rural areas (for pumping but also for electrification). A maintenance program is mandatory in this case, but even that will not ensure the proper working of the system.

On the basis of pure technical criteria, electric wind pumping systems can already be excluded as a realistic option for water supply in Mozambique.

3.3.3.3. Direct wind system

Water delivery from windmills

In Table 17 the technical data of the different Climax windmills are presented (Southern Cross Windmills, 2013). For a given head and flow, the required size of the mill and pump cylinder can be selected. The data are for a wind speed of 3.5 m s^{-1} during at least 8 h per day (Southern Cross Windmills, 2013). The depths in Table 17 are assumed to be geometric heads, although no specific information is given by Southern Cross Windmills. This assumption is based on the fact that such a table is a practical tool. Installers must have a simple relation between the physical depth of the borehole and the system to install. They are not concerned with calculating the friction losses caused by the system but encounter this in the (lower) measured delivery.

With this assumption, the potential systems for the 40, 70 and 100 m borehole category are highlighted in Table 17 in blue, from light to dark respectively.

From this table it is clear that small size wind turbines will not deliver enough water at the required head. In that case, several systems are needed to meet the demand. In the higher size ranges, with rotor diameters from 6 to 8 m, the water supply is higher and can be met by one windmill for the 40 m borehole category. On the other hand, starting torques are expected to be higher for these bigger windmills. For the deeper boreholes, approximately two systems are needed according to Table 17. This is much less than the number of electrical turbines calculated previously, which speaks in favour of the direct wind system. On the other hand, direct wind mill system cannot be combined in one borehole as for electric wind systems. Multiplying the system would mean multiplying the number of boreholes as well.

Table 17: Technical data sheet of Climax windmills (Southern Cross Windmills, 2013)

		Size pump cylinder (mm)								
Size mill (m)		**44**	**51**	**64**	**76**	**90**	**102**	**115**	**128**	**153**
2.5	Head (m)	41	34	24	17	13	10	9	7	5
	Flow (L d^{-1})	3980	5205	8140	11705	15930	20820	26345	32525	46845
3.0	Head (m)	70	60	43	32	25	20	16	13	9
	Flow (L d^{-1})	3885	5070	7930	11430	15545	20295	25700	31730	45685
3.7	Head (m)	96	80	58	43	33	26	21	17	12
	Flow (L d^{-1})	4205	5475	8570	12365	16820	21955	27800	34320	49410
4.3	Head (m)	140	110	81	66	52	37	33	27	19
	Flow (L d^{-1})	3590	4705	7365	10000	13615	20070	22500	27775	40000
6.3	Head (m)			125	98	76	61	47	38	27
	Flow (L d^{-1})			15000	21400	29100	38200	48200	59600	86000
7.5	Head (m)			162	130	107	85	67	55	38
	Flow (L d^{-1})			15000	18200	29500	38600	48600	60000	86000

In Table 18 the deliveries from Kijito windmills are given for the different rotor diameters possibilities. Three ranges of wind speeds are considered: 2-3 m s^{-1}, 3-4 m s^{-1} and 4-5 m s^{-1}. The wind regime of Mozambique is situated in the lower and middle range, between 2 and 4 m s^{-1}. The heads are, as discussed before, considered as geometric heads, as no specifications were given.

Table 18: Kijito windmill delivery for the different models (Kijito Windpower, 2013)

	Rotor diameter (m)														
	3.7			**4.9**			**6.1**			**7.4**			**7.9**		
Wind (m s^{-1})	**2 - 3**	**3 - 4**	**4 - 5**	**2 - 3**	**3 - 4**	**4 - 5**	**2 - 3**	**3 - 4**	**4 - 5**	**2 - 3**	**3 - 4**	**4 - 5**	**2 - 3**	**3 - 4**	**4 - 5**
Head (m)	**Delivery (m^3 d^{-1})**														
10	10	28	59	21	71	150	39	107	227	61	167	354	70	192	407
20	5	14	29	10	35	75	19	53	113	30	83	177	35	95	204
40		7	15	5	18	37	10	27	57	15	42	89	17	48	102
60		5	11	4	14	28	7	20	43	11	31	66	13	36	76
80		3	7	3	9	19	5	13	28	8	21	44	9	24	51
100		2	6		7	16	4	10	24	7	18	36	8	21	41
120			5		6	12	3	9	19	5	14	29	6	16	33
150			4		4	9		7	14	4	10	22	5	13	28

Ironman windmill developed a tool on its website that calculates the pumping capacity needed by a given head and proposes the windmill system accordingly. The results are presented in Table 19, Table 20 and Table 21, for the 40 m, 70 m and 100 m borehole category, respectively. In the tool, 'light winds' were defined as 3 to 4.5 m s^{-1}, which is already quite high when considering the wind regimes in

Mozambique (Appendix D). Therefore, only 8 h of pumping at this wind speed was considered as the tool gave a capacity per hour.

Table 19: Ironman windmill pumping capacity for light winds for the 40 m borehole category

Diameter rotor (m)	Diameter pump (mm)	Pumping capacity ($m^3\ d^{-1}$)
2.4	51	1.3
3.6	76	3.2
4.8	114	7.6
6.0	178	18.2

Table 20: Ironman windmill pumping capacity for light winds for the 70 m borehole category

Diameter rotor (m)	Diameter pump (mm)	Pumping capacity ($m^3\ d^{-1}$)
3.6	64	1.9
4.8	89	4.7
6.0	127	11.5

Table 21: Ironman windmill pumping capacity for light winds for the 100 m borehole category

Diameter rotor (m)	Diameter pump (mm)	Pumping capacity ($m^3\ d^{-1}$)
3.6	51	1.3
4.8	76	3.1
6.0	108	7.7

The flow rate one can expect from a windmill is highly dependent on the performance of the particular system. For instance, a 6.3 m rotor diameter windmill from Climax can deliver 15 m^3 per day water at a wind speed of 3.5 m s^{-1} and 125 m head (Table 17), while a 6.1 m rotor windmill from Kijito delivers only 9 $m^3\ d^{-1}$ for the same wind speed and a head of 120 m (Table 18). The pumping capacity of the Ironman windmill with a rotor and pump diameter of 6 m and 108 mm respectively, is 7.7 $m^3\ d^{-1}$ (Table 21). From this example and the other values in the corresponding tables, it seems that the Climax windmills perform better than the other two. However, one should be sceptical when analysing these data, as these are figures from the manufacturers themselves and the test circumstances and margins of errors of the measures are not given. For the Kijito windmills, the size of the pump cylinder is not given which makes comparison difficult.

The flow rates also decrease rapidly when lowering the size of the mill. Therefore, a bigger system is preferential as the delivery is higher and fewer systems are needed to meet the demand. On the other hand, these windmills have higher starting torques for which higher wind speeds are needed.

The last parameter that has to be taken into account is the appropriateness of the site. The windmill must be installed in an open area without major obstacles, especially in the prevailing wind direction. This was done properly at the pumping site of Mubalo, where the mill was installed next to the field for irrigation as shown in Figure 53.

Figure 53: Surrounding agricultural area at the windmill water pumping site of Mubalo

Maintenance of direct wind pumps

As the moving parts wear in these systems, lubrication is necessary. At the windmill water pumping site in Mubalo, shown in Figure 54, this maintenance was done on a regular basis. Other actions were not undertaken, like replacement of worn parts.

Figure 54: (left) Windmill water pumping system in Mubalo and (right) wearing of the moving parts

The regular maintenance needed is an important drawback for this type of systems. This kind of technology is less used than for instance PV panels, which makes the training of a local caretaker even more important. Again, a maintenance program is needed with a regular general check of the system and good communication in case of system failure.

3.4. Economic analysis

3.4.1. PV water pumping system

Stewarts&Lloyds (von Bargen, 2013) provided an offer for a Grundfos renewable energy solar water pumping system for the three borehole categories. For the 40 m class one pump can provide 40 m³ d^{-1}. For the other two depths, two systems (including an additional borehole) were needed to provide the needed capacity, as the outputs were 26 m³ d^{-1} for the 70 m category and 22 m³ d^{-1} for the 100 m category. Details about the quotation are given in Table 22.

Table 22: Offer details from Stewarts&Lloyds for a Grundfos PV water pumping system (von Bargen, 2013)

	40 m	70 m	100 m
Pump	SQF 5A – 7	SQF 2.5 – 2	SQF 2.5 – 2
Number of GF 80 PV panels	30	35	40
Total peak power (kW_p)	2.4	2.8	3.2
Friction loss (m)	3.0	8.1	10.0
Flow ($m^3\ h^{-1}$)	5.1	2.7	2.5

In Figure 55 the monthly and daily (January) water production for the 40 m borehole category is presented from the quotation of Stewarts&Lloyds.

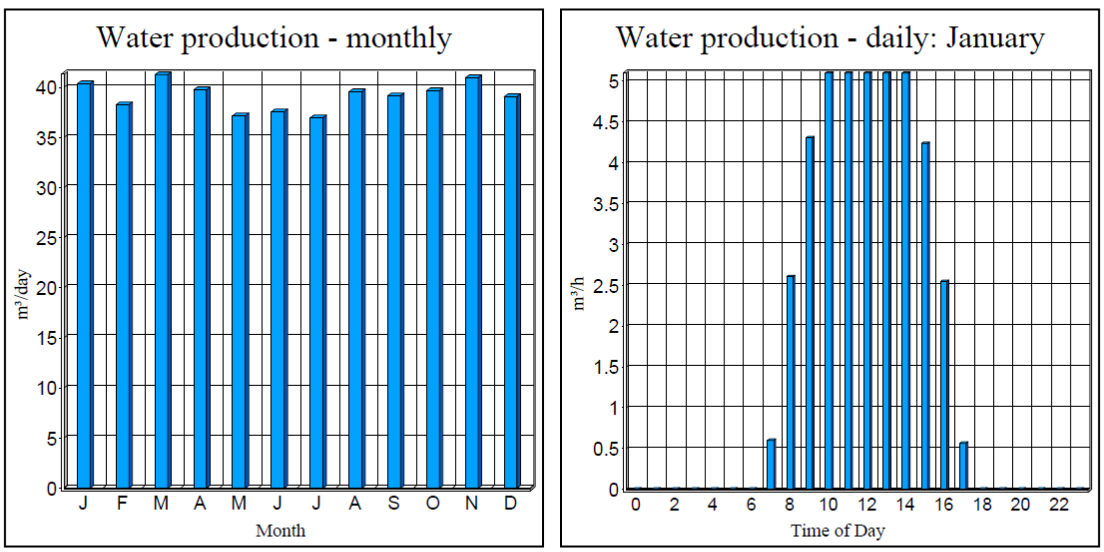


Figure 55: Monthly and daily water production for 40 m borehole category (von Bargen, 2013)

Pricelists from KG electric, who provides Lorentz PV water pumping systems, available on their website (KG Electric, n.d.), were used to size a second PV water pumping system. Two units are needed for the 100 m borehole category to meet the capacity of 40 m³ d^{-1}.

The prices of the two suppliers were averaged to obtain the reference investment cost for this study for the PV water pumping system and these are given in Table 23. An extra mean borehole drilling cost was included in the cost calculations due to the extra boreholes needed. The unit water costs are presented in Figure 56 for the three borehole categories.

Table 23: Costs of the PV water pumping systems

	40 m	70 m	100 m
Stewarts&Lloyds			
Number of systems	1	2	2
Investment cost (€)	10829	24637	26996
KG Electric			
Number of systems	1	1	2
Investment cost (€)	10193	14153	28211
Average extra borehole cost (€)	**0**	**3500**	**7000**
Average Investment cost (€)	**10511**	**19395**	**27603**

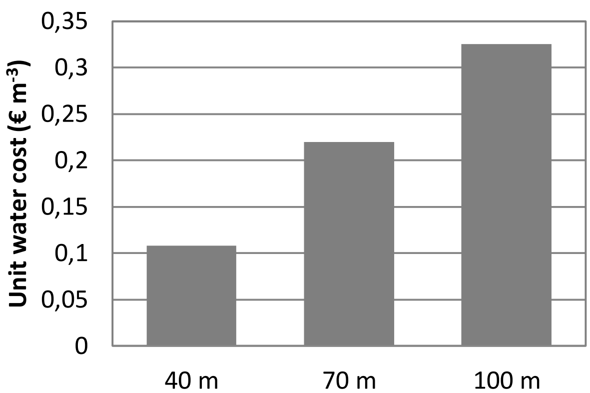


Figure 56: Unit water cost for the solar PV water pumping systems for the different borehole categories

3.4.2. Electric wind water pumping system

Kestrel has given an offer for an electric wind water pumping system with the e300i (1kW) wind turbine for € 7120. This includes the turbine and tower, a Grundfos SQFlex pump with controller and interphase box, support post, and lastly the cabling and attributes. Figure 52 was attached in the quotation from which the number of systems to meet the 40 m³ daily demand was determined. The wind speed of 3.5 m s^{-1} was used for the different borehole categories. This gives a water delivery of 5 m³ d^{-1} for the 40 m borehole category which implies the use of 8 systems to achieve the daily demand of 40 m³ d^{-1}. The other borehole classes are too deep for this pumping system for the average wind speed as can be derived from Figure 52.

The total investment cost for the 8 units is € 56 959 and the cost per m³ of water for the electric wind system is € 0.55. No extra borehole costs are added as it was assumed that the electricity from the turbines is collected to provide one pumping system.

3.4.3. Direct wind water pumping system

No offers were received for the direct wind systems but prices from Stewarts&Lloyds (Climax windmills) and Kijito were taken from their websites and averaged.

For the Climax windmills, the biggest one available with a rotor diameter of 4.3 m was taken for every borehole category. The cylinder sizes available are from 51 mm to 102 mm from which the flows can be derived in Table 17. The number of Climax windmills needed as well as the investment cost are given in Table 24.

The 7.9 m rotor diameter Kijito windmill from Table 18 is used for the three borehole categories. As the wind speed in Mozambique varies between 2 and 4 m s^{-1}, the average flow rate from Table 18 is taken to calculate the number of systems needed to meet the 40 m^3 daily demand.

Assembling a windmill water pumping system was not straightforward from the available pricelists with all the different parts. Therefore, two main costs per direct wind system were included: the windmill with tower price and the pump rod price (given per m so calculated for every depth). As this probably doesn't include all the necessary parts, the real investment cost is likely to be higher. For every additional system, an extra borehole is needed as well (unit price per borehole is estimated at € 7000). The results are summarised in Table 24 and the unit water costs for the direct wind water pumping system are shown in Figure 57.

Table 24: Technical and economic data for the direct wind water pumping systems

	40 m	70 m	100 m
Stewarts&Lloyds			
Cylinder size (mm)	90	64	51
Flow rate (m^3 d^{-1})	13.615	7.365	4.705
Number of systems	3	6	9
additional borehole cost (€)	14000	35000	56000
Investment cost (€)	18169	36977	56423
Kijito			
Average flow rate (m^3 d^{-1})	24.5	16.5	11
Number of systems	2	3	4
Additional borehole costs (€)	7000	14000	21000
Investment cost (€)	28254	43270	60064
Average Investment cost (€)	20762	36448	53343
Average additional borehole cost (€)	10500	24500	38500

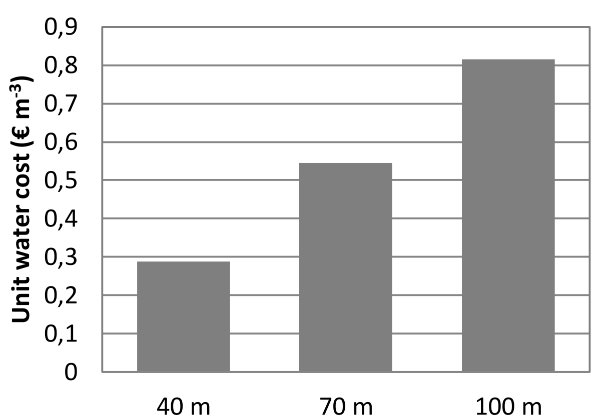


Figure 57: Unit water cost for the direct wind water pumping system for the different borehole classes

The unit water cost for the direct wind system is twice as high as that for the solar PV system for every borehole category. This is due to the high number of systems needed which increases the investment cost but also the additional borehole drilling cost.

3.4.4. Hand pump system

Different hand pumps are used for the different borehole categories. The Afridev pump can be used for the 40 m borehole category as the maximum head is 45 m. The price of a Afridev pump is said to be US$ 1500 by DNA (Grupo de Agua e Saneamento, 2011) and US$ 1300 by UNICEF (van der Velden, 2013). An average investment cost of US$ 1400, € 1092, was used in the economic analysis. The approximate flow rate is 12 L min^{-1} (Grupo de Agua e Saneamento, 2011), which means 7 units are needed for the demand of 40 m^3 d^{-1} when 8 pumping hours are considered. Also, 6 extra boreholes are needed with a unit cost of € 7000.

For the 70 m borehole category an extended version of the Afridev pump, the Afridev SB pump with a maximum head of 80 m (Grupo de Agua e Saneamento, 2011), can be used. The price is € 1560 per pump, and the approximate delivery is 10 L min^{-1} (Grupo de Agua e Saneamento, 2011). This implies that 9 pumps are needed as well as 8 extra boreholes.

Lastly, for the 100 m borehole category, the Afripump (not to be confused with the Afridev pump) is the best option as this pump provides 10 L min^{-1} for a maximum head of 100 m (Grupo de Agua e Saneamento, 2011). This depth is slightly lower than the total dynamic head of the corresponding borehole class, which is 111 m. However, for a hand pumping system no water tank is needed which lowers the total dynamic head by 2 m. Secondly, the friction losses will be smaller as the flow rate is only 4.8 m^3 d^{-1} instead of 40 used in the calculations. The total dynamic head will still be higher than 100 m but the use of an Afripump is however considered. When assuming this hand pump is a possibility for the 100 m borehole class, 9 units are needed to meet the demand.

The details are summarized in Table 25 and the unit water costs are presented in Figure 58. The cost of the water tank is excluded from the investment cost as this is not needed when using a hand pump.

Table 25: Technical and economic data for the hand pumping systems for the three borehole classes

	40 m	70 m	100 m
Pump type	Afridev	Afridev SB	Afripump
Flow rate (m^3 d^{-1})	5.8	4.8	4.8
Number of systems	7	9	9
Additional borehole cost (€)	42000	56000	56000
Average investment cost (€)	7 643	14 038	32 288

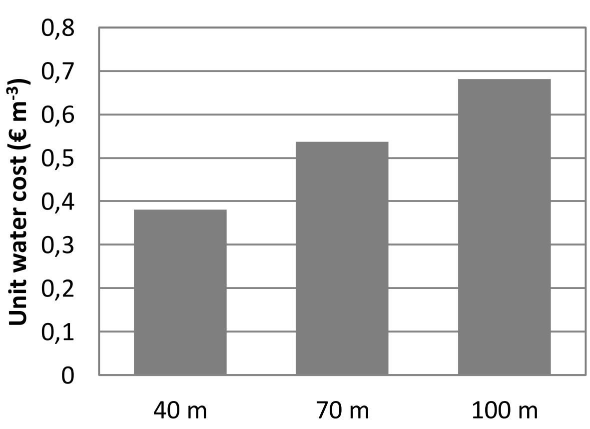


Figure 58: Unit water cost for the hand water pumping system for the different borehole categories

3.4.5. Diesel water pumping system

No offers were received for a diesel water pumping system. Therefore, prices had to be estimated based on several other sources. In a study where comparing diesel engines with PV arrays as applications for water pumping in Jordan, the cost of the diesel system was taken as € 3500 for delivering 45 m³ water per day (Al-Smairan, 2012). The cost of a diesel engine in Mozambique is approximately € 2560 (de Jongh, 2008), which can be combined with borehole pumps from which several brands and prices are available on the website of the South African company PumpsForAfrica. Lastly, on that same website, diesel driven pump sets are also available for heads up to 75 m and flows up to 20 $m^3 h^{-1}$ for the price of € 970. The use of a diesel engine and separate borehole pump is however more often used in rural areas. Based on these numbers, the investment cost of a diesel water pumping system is probably between € 1000 and € 3000. To include a safety margin, the latter value was taken for all the borehole classes.

Fuel costs were gathered during the field visit to obtain an estimate of the average price in rural areas which was used for estimations of the operational cost. In Chitondo where a diesel-PV hybrid water pumping system was visited, the fuel price was 1.02 € L^{-1}, whereas in Chicualacuala this was about 1.15 € L^{-1}. The diesel price per litre at a pumping station in Maçia was 0.96 €. This gives an average cost of (1.05 $\pm$ 0.06) € L^{-1}. Fuel consumption was estimated to be 25 L for a delivery of 40 $m^3 d^{-1}$ for the 40 m borehole category (Al-Smairan, 2012) and was increased by 5 L for the remaining classes.

The above information is summarised in Table 26 and the unit water costs are presented in Figure 59.

Table 26: Data summary of the diesel water pumping system for the different borehole categories

	40 m	70 m	100 m
Average investment cost (€)	3000	3000	3000
Average cost fuel (€ L^{-1})	1.05	1.05	1.05
Fuel consumption (L d^{-1})	25	30	35

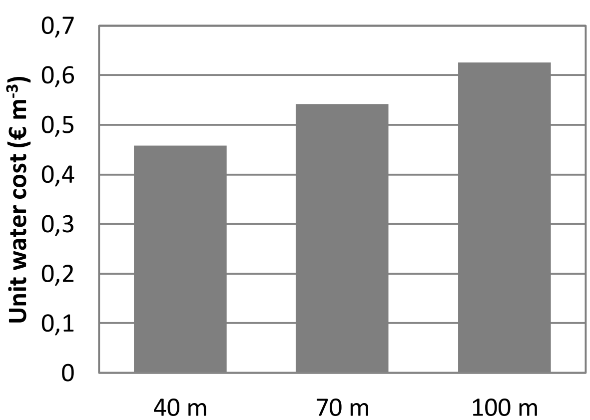


Figure 59: Unit water costs for the diesel water pumping system for the three borehole classes

These unit water costs are high but do not increase greatly with depth. This is because the only extra cost when increasing the depth is for fuel consumption. No extra boreholes are needed and the systems do not have to be multiplied to reach the 40 m³ daily demand. From these data, it is clear that diesel water pumping system become relatively more cost-effective with depth.

3.4.6. Comparative economic analysis per borehole category

To be able to compare the different power systems within a borehole class, the unit water cost and the life cycle cost for every system and per category are given below.

The cost of the electric wind water pumping is only included in the 40 m borehole category as water delivery was not feasible for the deeper boreholes at a wind speed of 3.5 m s^{-1} for a Kestrel e300i wind turbine, and therefore probably also for other electrical wind pumps at that wind speed.

From all the renewable energy systems, the solar PV is the most economic for the 40 m borehole category as can be seen in Figure 60. The investment cost as well as the unit water cost is much lower than for the two wind pumping methods. This is mainly due to the number of systems needed to meet the required output of 40 m^3 d^{-1}, which is one for the PV, 8 for the electric wind and 2 or 3 for the direct wind pumping system in the shallowest borehole class. The estimated maintenance cost has no influence on this ranking because the differences are too high. Even when maintenance costs for PV installations would be set at 10 instead of 2 %, the conclusions remain the same. The cost per m^3 water of the electric wind system was € 0.55, which is almost twice that of the direct wind system (0.29 € m^{-3}) and even five times higher than for the PV system (0.11 € m^{-3}). This pumping method is clearly the least economical. The hand pump has a surprisingly high unit water cost. From the right graph in Figure 60, one can see that this is due to the high additional borehole cost. The solar PV and the direct wind water pumping systems have higher investment costs but they do not need as much boreholes as they have a higher capacity. The diesel pumping system is the second most expensive of all for the 40 m depth. The investment cost was the lowest, but this was more than compensated by the operational cost. Between 87 and 90 % of the total cost is related to fuel consumption which is carried by the local population. In addition, this is expected to be even higher, as the diesel price was considered constant over the life span of 10 years, but it is likely to rise.

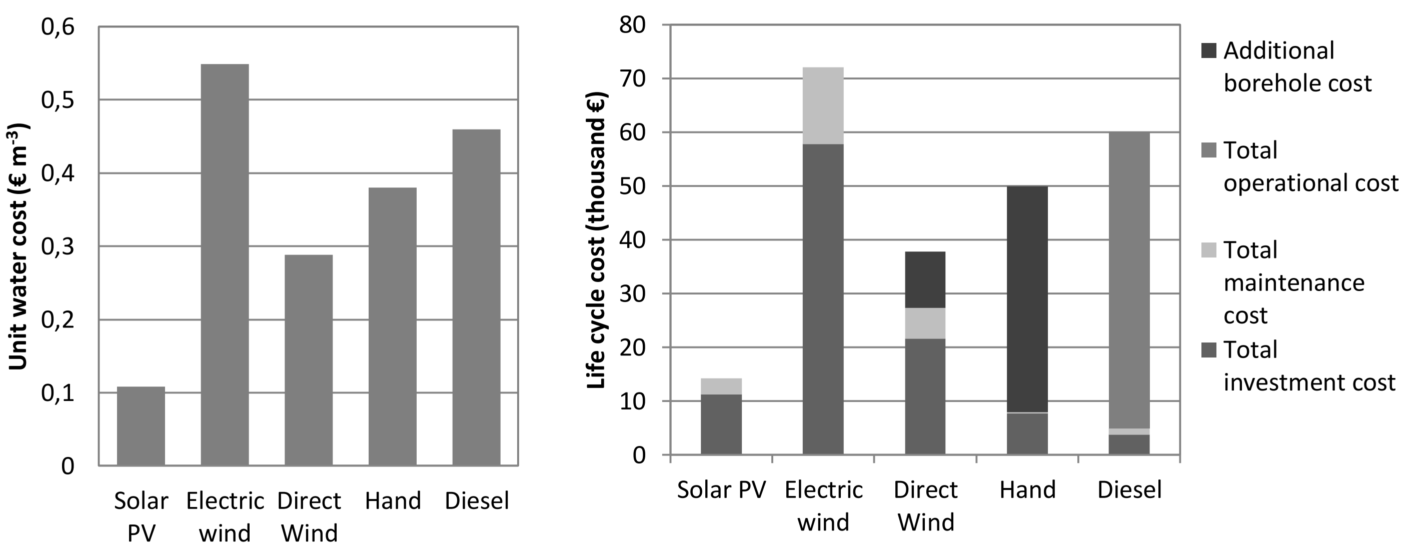


Figure 60: Unit water cost and life cycle cost of the different systems for the 40 m borehole class

From Figure 61 where the unit water and life cycle costs for the 70 m borehole category are given, the solar PV system is again the most economical because of the moderate investment cost and the low maintenance and additional borehole costs. The three other systems have a similar unit water and life cycle cost, but the distribution is different. The direct wind water pumping system has a high investment cost because of their low water delivery capacity. Between 3 and 6 windmills are needed which also implies a high additional borehole cost. The hand pump has a low investment and maintenance cost, but the high number of systems needed (9), resulted in eight additional boreholes which greatly increase the cost. The only difference of the diesel system with the one of the shallower borehole is the higher operational cost due to the increase in fuel consumption with increasing depth.

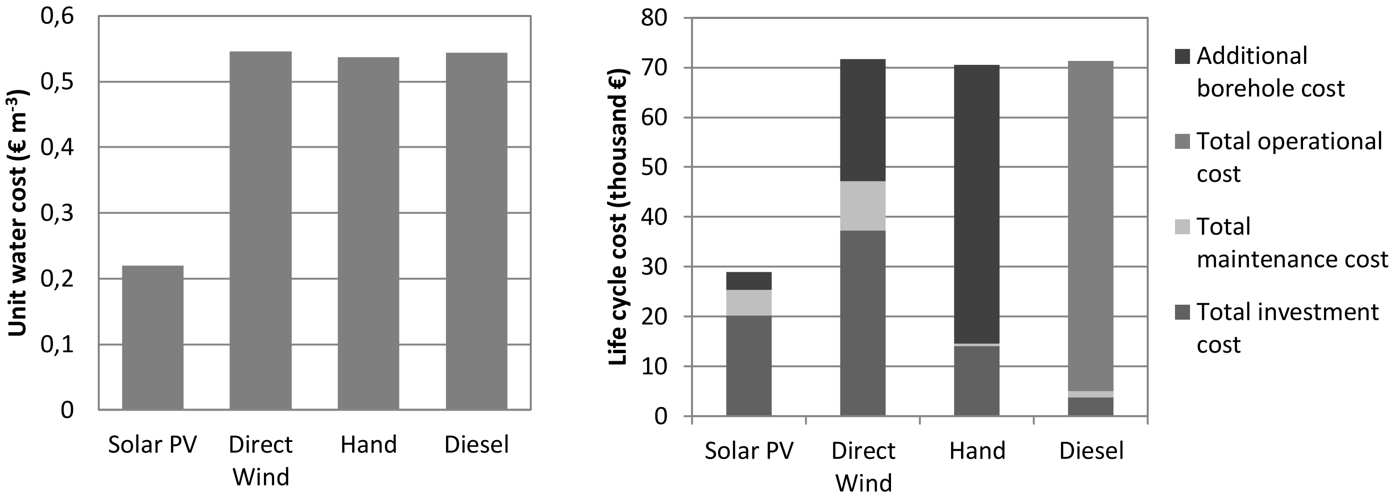


Figure 61: Unit water cost and life cycle cost of the different systems for the 70 m borehole class

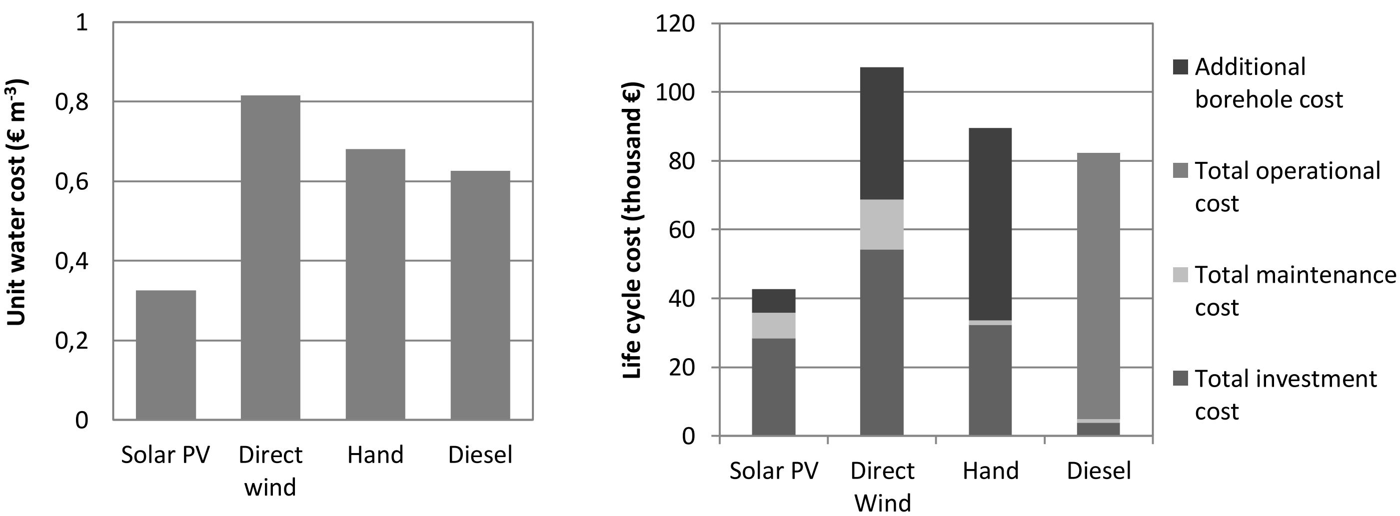


Figure 62: Unit water cost and life cycle cost of the different systems for the 100 m borehole class

Lastly, the unit water and life cycle costs of the different systems for the deepest borehole are presented in Figure 62. Again the solar PV system has the lowest cost. For the direct wind system, as stated before, the high number of units needed increases the investment and additional borehole drilling cost. The windmill water pumping system is the most expensive one for this depth. The life cycle cost of the hand pump is remarkable in Figure 62: when making abstract of the number of boreholes needed, solar PV systems and hand pumps are highly competitive for the 100 m head with a m³ cost of respectively € 0.27 against € 0.26. This is due to the high price of the Afripump, which is almost € 4000.

3.5. General discussion

3.5.1. Effectiveness and effectiveness limitations of water pumping systems

Based on the technical analysis only, it can be concluded with high confidence that electric wind water pumping for human drinking water supply is no reasonable option in rural Mozambique. The major reason is the multitude of relative expensive pumping systems needed for 1 borehole, among other reasons because of the low wind regimes in Mozambique. This constraint cannot be overcome with technical evolutions.

The effectiveness of direct wind mills is also low for high heads. The multitude of systems needed, including a multiplication of boreholes makes these installations no option as well for these specific applications. The low wind regimes in Mozambique are again a major none vulnerable obstacle. For smaller heads, the effectiveness difference between PV and direct wind mills is less pronounced and economic reasoning becomes more important.

The effectiveness of diesel pump and solar pumping systems are comparable, because they both generate sufficient energy for one borehole for the required capacity. The choice between the 2 systems should therefore be based rather on economic considerations.

Hand pumps are not effective because when the flow is insufficient, the number of systems including the number of boreholes, needs to be increased. This low effectiveness per borehole makes them little competitive with solar systems as well.

3.5.2. Cost-effectiveness

The investment costs are very different from one type of installation to another. Electric wind turbines are nearly 6 times the investment cost of PV systems. Independent of any maintenance costs they can be excluded as a reasonable investment for drinking water pumping in rural Mozambique.

Direct wind systems also show considerably higher investment costs than PV systems. Even when maintenance costs for PV would increase from a yearly 2 to an unlikely 10% of the investment cost, PV systems remain less expensive. Costs that can be taken into account with more difficulty are theft and the time for repair in case of major breakdowns. If these factors are important, than direct wind power installations might become more cost-effective still in the low head categories where the number of boreholes does not need to be increased. This would be especially true in the more windy coastal areas of Mozambique.

Hand pumps demand a lower investment per installation, but for the same capacity, up to 9 installations including boreholes are needed. The 6 to 8 additional boreholes make the investment more expensive than the PV solution. In the case borehole capacity is too low, and their number has to be increased anyway, hand pumps might become competitive with PV installations. For considerably smaller populations than the average of 1000 used in this study and where one hand pump would suffice for the need of 30 L per person, clearly the hand pump solution has to be preferred if there is no need for additional water for other means than purely domestic use.

3.5.3. Need for maintenance

The importance of maintenance does not to be proven anymore.

Maintenance systems are crucial for investments to be worthwhile. An important implicit assumption for all pumping systems is the existence of a minimal maintenance system. Without, even sometimes minor breakdowns can cause complete failure of the system. Investment in a maintenance system should be proportional to the investment in new pump installations.

Maintenance entails a complex system indeed. It includes spare part storage and procurement, and also the financial management. It includes communication and registration, technical capacity, transport means, etc.

Because of the high distances involved, a maintenance system should be decentralised as much as possible. This implies a system organised in tiers with the local caretaker of the installation at the most decentralised level. Depending on the size of the country and the availability of technicians, 2 (max. 3) additional tiers can be imagined, each with its specific capacities and tasks for maintenance. A combination of public and private organisation can be imagined, depending on the prevailing conditions in the country. In rural Mozambique, few private enterprises are present sufficiently close to the rural poor, which implies a relatively large responsibility for public authorities.

Upper tiers of the system should back-up and supervise the technically lower tiers. This calls for regular field visits and investments in transport and professional capacity. Maintenance cannot be based only on voluntary work by local caretakers.

Need for maintenance increases because of abuse and misuse. Theft of solar panels was already mentioned and causes important ‘maintenance’ costs. Sub-optimal maintenance leads to increased maintenance costs because early maintenance is a preventive factor for major breakdowns.

The theoretical mathematical models of maintenance discussed in Chapter 1 (Riha, et al., 1998) could not be applied due to simple lack of data. Far more field research will be needed in this area (see further). This would allow to optimise the maintenance system, to decide effectively on replacement of equipment and to plan the maintenance costs over the years.

The organisation of a maintenance system is not included in the costing study. Transport costs, professional training, storage of spare parts and so on might give a new perspective on maintenance costs, although it is unlikely to influence the comparison between the different systems.

3.5.4. Need for an integrated and performing monitoring system

A major drawback of this study is the use of mathematical models based on many assumptions instead of making use of real-life data. The high number of concomitant factors of diverse nature influencing the effectiveness and cost-effectiveness of the installations imposes the use of field data.

Such data can only be obtained when a performing monitoring system is put up. Monitoring should be part of the maintenance organisation. Every tier should collect standard data on the performance of the installations and this information should reach the higher levels of organisation. Regular visits to the installations by back-up maintenance teams should include the monitoring system in the supervision exercise. Data have to be centralised and analysed. This should result in improved yearly planning of maintenance activities and in a better overall system’s performance.

3.5.5. Important drawbacks in the study

The major drawback of the study was already mentioned: in absence of field data, assumptions have to be made. Every assumption has the inherent danger of being wrong, leading to erroneous conclusions. To mitigate the risk, a sensitivity analysis could be conducted in order to estimate the robustness of the conclusions. The different costs within the life cycle of the installations were displayed separately in the graphs. This provides already a visual impression of the relative contribution of each cost to the total life-cycle cost.

Some variables such as population size were kept constant. The wide variety of population sizes in rural communities might influence the results. Higher populations, if not already planned for connection to the general electrical grid, could benefit from simply a multiplication of the same installation. But on the other extreme, in very small villages a considerably different standard installation capacity should be considered. Under such conditions, hand pumps might become competitive with solar systems.

Absence of quality data on maintenance, performance and quality of installations might not alter the fundamental conclusions of this study, that solar energy systems have the biggest potential and cost-effectiveness. But without the appropriate field data, the overall system of drinking water supply to the rural poor cannot be improved.

An implicit assumption is the quality of the installations. All cost-effectiveness considerations, might become irrelevant in the case of poor quality installations. Solar panels might not have the optimal inclination or might be shadowed during important periods during the day, as has been observed in practice. Wind energy installations might be hampered by interference of its close environment such as big trees or buildings. Pumps could be poorly installed causing early irreversible breakdown, etcetera. Poor quality control on delivery of installation or even during the works is not exceptional in developing country conditions. Quality of the installation might therefore largely interfere with the effectiveness of installations and consequently influence the maintenance costs. In as far as these drawbacks are evenly distributed for any type of installation, it would not significantly influence the theoretical conclusions of the present study. It does however emphasize once more the need for real field data.

4. CONCLUSIONS

This study found that under the actual conditions and assuming that the various assumptions are correct, solar energy water pumping systems are the most cost-effective for rural Mozambique. The study provided various arguments for this conclusion.

Based on the renewable energy resources potential in Mozambique, namely solar irradiation and wind speed, the latter seemed less reliable and less abundant. Solar irradiation, according to the database of PV GIS, is between 4.5 and 7.0 kWh m^{-2} d^{-1}. The peak power needed ranged from 2.6 to 6.4 kW_p for borehole depths from 40 to 100 m. Wind speeds to the contrary were found to be quite low, surprisingly so for a country with such a long shore line. The average wind speed for Mozambique, based on daily RETScreen wind speed data from 2002 to 2012, is 3.86 m s^{-1}. When the wind speed is lower than 2.5 or 3 m s^{-1}, no water delivery is expected for both direct and indirect systems of the installation sizes under consideration in this study.

The electrical wind water pumping system turned out to be technically the least attractive. Based on the RETScreen wind speed data, 28 turbines (D=2m and η=30%) were needed for the 40 m borehole and this increases to 65 for the 100 m class. Using the Kestrel water delivery chart, only 5 m^3 d^{-1} can be pumped from the 40 m borehole at an average wind speed of 3.5 m s^{-1}, and higher mean wind speeds are needed for deeper boreholes. The latter fact makes use of electrical turbines as water pumping application difficult in a country with such wind regime.

The life cycle cost of a solar water pumping system was lower than for direct and electrical wind water pumping systems. This was due to a lower investment cost but also due to the fact that wind energy installation require extra boreholes for the estimated needed water supply (40 m^3 d^{-1}) in this study. Maintenance costs had presumably no influence on the ranking.

The study found that unit water cost of the solar system was lowest and varied between € 0.11 and € 0.33 for the three borehole classes while this was between € 0.29 and € 0.82 for the direct wind system. For the 40 m borehole class the unit water cost of the wind turbine system was € 0.55.

The high operational costs of diesel systems prevented these to be cost-effective: the unit water cost varied between € 0.46 and € 0.63. The low water delivery and hence the high extra borehole costs caused the hand pumping system not to be interesting either with unit water costs between € 0.38 and € 0.68.

Maintenance of solar systems was believed to be easier as installations, also for electrification, are already used in rural areas. The cost was also estimated less than for other installations.

Based on the results of this study, a PV water pumping system is advised to the *Renewable Energy for Rural Development* project of BTC in Mozambique as this turned out to be the most cost-effective. The rather theoretical approach of this study needs confirmation from a study under field conditions. The Belgian cooperation might actually invest in creating the conditions for a performing information and monitoring system that in the long run would pay back itself. Donor coordination can help to achieve this goal. Pulling resources together and unifying approaches would increase the quality of the installations and should lower costs due to advantage of scale.

5. FURTHER RESEARCH

As highlighted already in the discussion and conclusions, the most important failure of the water supply policy in rural Mozambique, is the absence of reliable routine data on installation and performance of the systems, both in technical and financial terms. It is clear that further research cannot be conducted by BTC or FUNAE alone, but they can participate in collaboration with other donors agencies and government institutions and private enterprises active in the water pumping sector.

Much of the further research needed, is of an operational nature and should serve decision makers in technical ministries like the Ministry of Energy, how to better organise itself in order to provide more water to more people in an affordable way. Therefore more information is needed on what the life-time of a water pump installation could be and what the maintenance costs are. How much can well-organised maintenance prolong the average life-time of an installation? How should a maintenance service country-wide be organised? How can one improve the actual system? How much does it cost?

5.1. Routine data collections

Basic data should be collected country-wide for different operational aspects.

The country should dispose of maps combining geological and groundwater levels for all areas. Such maps, with sufficient detail would greatly reduce the risk of borehole failure or low capacity, hence increase the cost-effectiveness of the installations.

A study on the actual quality of the pumping installations should be conducted. Sub-optimal installation quality increases the maintenance as well as the investment costs. Check list to estimate the quality of the installations could be developed. Real production of the existing installations should be measured and compared with the theoretical yield these installations should provide. This could also provide a good impression on the quality of the installations and evaluate some of the estimates on performance used in this study.

An evaluation of the borehole quality (maximum yield) and depth should be studied separately. Due to the cost of such exercise, a sample in each region could be taken. Such data could provide the necessary information needed to estimate the number of installations needed in a particular village with a given population. The averages used in this study cannot provide individual solutions per village.

Country-specific and daily wind speed and solar irradiation data should provide more reliable knowledge of the available resources in Mozambique. Also wind turbine installations on a large scale and extension of the electric net in rural areas might be a macro alternative for the individualized water pumping installations, with additional opportunities like lighting in the villages.

A routine data collection per borehole should allow calculating and monitor reliable indicators for life-expectancy and cost-effectiveness of installations. Routine data on investment and installation costs should be gathered, maintenance costs, but also maintenance frequency should be noted. Breakdowns and type of breakdown should be reported as well as the time between breakdowns and the moment reparations were realised (average duration of pumping system failures is an important performance indicator).

Donor coordination should allow the country to map all systems in place.

5.2. Experimental settings – operations research

This study modestly contributes to answering theoretical and practical questions on provision of sufficient drinking water for rural populations in Mozambique. But Interesting subjects for further research under field conditions remain.

One of the questions that could be asked is the interest of combining different types of installations in the same community. Is it useful to combine a PV water pumping system with hand pump systems as back-up? If the capacity of a PV unit is borderline for the given population, is it useful to foresee additional systems? Is it possible to add none-drinking water installations (open wells, rope pumps) without jeopardizing the health of the population? How do people behave under such conditions?

Also optimising the maintenance system remains an important challenge, and many interesting research questions can be forwarded on this subject. For example, how can a maintenance system be put up in the most effective way? What should be the technical capacity of caretakers at different levels? How should the spare parts supply and rapid response to breakdowns be organised? Who is paying what in this system? Actually the population is contributing through voluntary work and by paying for the water they consume. But is this enough? Can it buy technical capacity if it is not locally available? What should the government contribute through taxpayer money?

Despite the remaining questions to be answered, the results in this master thesis seem very useful for practical use in Mozambique. The theoretical robustness of the conclusions does provide operational answers for the project. The choice for solar energy installations can be taken with more confidence. The need for field data could help orient the project in investing more in the monitoring capacity of the Ministry of Water and in its ability to put up a performing country-wide maintenance system.

6. REFERENCES

Al-Smairan, M., 2012. Application of photovoltaic array for pumping water as an alternative to diesel engines in Jordan Badia, Tall Hassan station: Case study. *Renewable and Sustainable Energy Reviews,* Volume 16, pp. 4500-4507.

Alternative Energy News, n.d. *Wind Turbines - News and information about wind generator technologies and innovation.* [Online]
Available at: http://www.alternative-energy-news.info/technology/wind-power/wind-turbines/
[Accessed 13 April 2013].

American Water Works Association, 2006. *PE Pipe - Design and installation.* 1st ed. United States of America: American Water Works Association.

Araya, K. M., 2010. *Photovoltaics for community service facilities - Guidance for sustainability,* Washington: Africa renewable energy access program (AFREA).

Argaw, N., Foster, R. & Ellis, A., 2003. Renewable energy for water pumping applications in rural villages. *National Renewable Energy Laboratory*.

Atlabara, J., n.d. *African-water download section.* [Online]
Available at: http://www.african-water.com/african-water-pump-supply-and-services/download-grundfos.html
[Accessed 20 May 2013].

Badran, O., 2003. Wind turbine utilization for water pumping in Jordan. *Journal of wind engineering and industrial aerodynamics,* pp. 1203 - 1214.

Baumann, E., Montangero, A., Sutton, S. & Erpf, K., 2010. *WASH Technology Information Packages,* Copenhagen: UNICEF.

Belgian Technical Cooperation, 2009. *Technical & financial file: Renewable energy for rural development - Mozambique,* Brussels: s.n.

Bonsor, H. C. & MacDonald, A. M., 2011. *An initial estimate of depth to groundwater across Africa,* Nottingham: British Geological Survey.

Buschermohle, M. J. & Burns, R. T., n.d. *Solar-powered livestock watering systems,* Tennessee: Agricultural Extension Service - University of Tennessee.

Cengel, Y. A., Turner, R. H. & Cimbala, J. M., 2008. *Fundamentals of Thermal-Fluid Sciences.* 3rd ed. New York: McGraw-Hill.

Claesen, T. F., 2012. Millenium Development Goals water target claim exaggerates achievement. *European Journal - Tropical Medicine & International Health,* October(10), pp. 1178-1180.

Clark, R. N. & Vick, B. D., 2008. *Livestock water pumping with wind and solar power,* USA: ASABE.

Climatemps, 2008. *Climate & Temperature - Mozambique.* [Online]
Available at: http://www.mozambique.climatemps.com/
[Accessed 4 July 2012].

Cuamba, B. et al., 2006. A solar energy resources assessment in Mozambique. *Journal of Energy in Southern Africa - Vol 17 no 4,* pp. 76 - 84.

Cuamba, B. et al., n.d. Identification of areas with likely good wind regimes for energy applications in Mozambique.

Dankoff, W., 1995. A graphic guide to solar water pumping. *Home Power,* pp. 24-28.

de Jongh, J., 2008. *Diesel survey Cabo Delgado,* s.l.: s.n.

De Vos, A., 2012. *Duurzame energie en rationeel energiegebruik.* s.l.:Vakgroep elektronica en informatiesystemen - Faculteit toegepaste wetenschappen - Universiteit Gent.

Direcçao Nacional de Aguas, n.d. s.l.: s.n.

Drouin, T., 2005. *Rope pump vs. Nira AF-85, a Ghanian case study,* France: Rural water supply network (RWSN).

Enciso, J. & Mecke, M., n.d. Using renewable energy to pump water. *Extension, Texas water resources institue*.

Engineers Edge, 2000. *Centrifugal pumps.* [Online]
Available at: http://www.engineersedge.com/pumps/centrifugal_pump.htm
[Accessed 11 July 2012].

Erpf, K., 2005. Evaluation of rope pump prototypes of CARE in Pemba, Mozambique. *Rural water supply network*, 28 June.

FAO, 2007. *Mozambique factsheet,* s.l.: s.n.

Ferragens Maputo, 2012. *Depositos de agua* [Interview] (August 2012).

Focus Technology Co., Ltd., 2012. *product list - wind-solar hybrid water pump system for farm irrigation.* [Online]
Available at: http://poemoflight.en.made-in-china.com/product/RejEzSPZfvWu/China-Wind-Solar-Hybrid-Water-Pump-System-for-Farm-Irrigation.html
[Accessed 18 July 2012].

FUNAE, 2012. *Rede de Transmissão e de Distribuição da EDM.* Maputo: s.n.

Fundo Nacional De Energia, 2012. Maputo: s.n.

Gesti Canuto, J. A., 2011. *Custo-effectivos de Agua em Moçambique,* Maputo: UNICEF.

Gipe, P., 2004. *Wind power - Renewable Energy for Home, Farm and Business.* 1st ed. Vermont: Chelsea Green Publishing Company.

Group URD, 2009. *Rope Pump: Experience in Chad,* s.l.: s.n.

Grundfos, 2012. *Grundfos Renewables - solar,* s.l.: s.n.

Grundfos, 2012. *Grundfos Renewables - wind,* s.l.: s.n.

Grupo de Agua e Saneamento, 2011. *Tabela Bombas Manuais.* [Online]
Available at: http://www.gas.org.mz/Media/Files/Tabela-Bombas-Manuais
[Accessed 17 August 2012].

Hansen, L., 2012. *Grundfos Interview* [Interview] (23 July 2012).

Howard, G. & Bartram, J., 2003. *Domestic water quantity, service level and health - executive summary,* sl: WHO.

Ironman Windmill, 1970 - 2013. *How water pumping windmills work.* [Online]
Available at: http://www.ironmanwindmill.com/how-windmills-work.htm
[Accessed 2 March 2013].

Kestrel Renewable Energy, 2012. *Water Pumping Solution.* [Online]
Available at: http://www.kestrelwind.co.za/content.asp?PageID=452
[Accessed 11 March 2012].

Kestrel Renewable Energy, 2012. *wind turbines - information sheet.* [Online]
Available at: http://www.kestrelwind.co.za/assets/wind%20turbines/kestrel%20e400n.pdf
[Accessed 27 March 2013].

KG Electric, n.d. *Solar water pumping applications - budget costs for equipment sets.* [Online]
Available at: http://www.kgelectric.co.za/commercial/budget-cost-submersible-pump-systems
[Accessed 2 April 2013].

Kijito Windpower, 2013. *Downloads.* [Online]
Available at: http://www.kijitowindpower.com/downloads.html
[Accessed 3 April 2013].

Lancashire, S., Kenna, J. & Fraenkel, P., 1987. *Windpumping Handbook.* sl:Intermediate Technology Publications Ltd..

Maps of World, 2012. *Political Map of Mozambique.* [Online]
Available at: http://www.mapsofworld.com/mozambique/mozambique-political-map.html
[Accessed 27 June 2012].

Maure, G. A., 2011. *Atlas de Ventos de Moçambique,* s.l.: FUNAE.

McSweeney, C., New, M. & Lizcano, G., 2010. *UNDP Climate Change Country Profiles - Mozambique,* s.l.: American Meteorological Society.

Meah, K., Ula, S. & Barrett, S., 2006. Solar photovoltaic water pumping: oppertunities and challenges. *Renewable and Sustainable Energy Reviews,* pp. 1162-1175.

Minister of Natural Resources Canada, 1997 - 2012. *RETScreen Plus,* Canada: s.n.

Ministério das Obras Públicas e Habitação - Direcção Nacional de Águas, 2012. *Inquérito de base - estudo institucional,* Maputo: s.n.

Monteith, J. & Unsworth, M., 1990. *Principles of Environmental Physics.* second ed. London: Edward Arnold.

Moore, K., 2008. Pumping water with the wind: modern historic technology. *Home Power,* pp. 88 - 93.

Nampusuor, P. & Mathisen, S., 2000. Report on the performance of Afridev and Nira handpumps on the upper regions community water project, Ghana. *GWSC/CIDA*, 5 September.

National Renewable Energy Laboratory (NREL), 2012. *Dynamic maps, GIS data, & Analysis Tools.* [Online]
Available at: http://www.nrel.gov/gis/re_potential.html
[Accessed 21 March 2013].

Ohio Department of Natural Resources, 2011. *Understanding your water well.* [Online]
Available at:
http://www.dnr.state.oh.us/ContentApproval/GWPPMetaDataButtonScript3227/pubs/fs_div/fctsht62/tabid/4149/Default.aspx
[Accessed 28 March 2013].

Polinder, S., Toet, H., Panneman, M. & van Beeck, E., 2011. *Methodological approaches for cost-effectiveness and cost-utility analysis of injury prevention measures,* s.l.: World Health Organization.

Practical Action, 2010. Technical brief: Solar (photovoltaic) water pumping. *practical action - technology challenging poverty*.

Purdue University, 2010. *The process of draw-down during pumping.* [Online]
Available at: https://engineering.purdue.edu/~h2o/COURSES/1/section5.htm
[Accessed 12 December 2012].

PVGIS European Communities, 2001 - 2007. *Interactive Maps.* [Online]
Available at: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa#
[Accessed 20 March 2013].

Ragheb, M., 2012. *Wind shear, roughness classes and turbine energy production.* [Online]
Available at: http://www.mragheb.com/NPRE%20475%20Wind%20Power%20Systems/index.htm
[Accessed 15 July 2011].

Ramos, J. & Ramos, H., 2008. Sustainable application of renewable sources in water pumping systems: Optimized energy system configuration. *Energy Policy,* Volume 37, pp. 633-643.

Ratterman, W., Cohen, J. & Garwood, A., 2007. *Solar pumping systems - introductory and feasibility guide,* Portland: Green Empowerment.

Rhebergen, W., 2012. *WE consult* [Interview] (24 July 2012).

Riha, J., Mangenot, L., Halbwachs, H. & Attéméné, G., 1998. *Reflections on the economy of maintenance,* Abijan: gtz.

Ronsse, F., 2011-2012. *Procestechniek.* s.l.:Vakgroep Biosysteemtechniek- Faculteit Bio-ingenieurswetenschappen - Universiteit Gent.

Roox, I., 2013. VN goochelen met cijfers om milleniumdoelstelling te halen. *De Standaard*, 17 May, pp. 18-19.

Royer, J., Djiako, T., Schiller, E. & Sada Sy, B., 1998. *Le Pompage Photovoltaïque - Manuel de cours à l'intention des ingénieurs et des techniciens,* Québec - Canada: IEPF/ Université d'Ottawa/ EIER/ CREPA.

RWSN, 2012. *Rope pump (Mozambique).* [Online]
Available at: http://www.rwsn.ch/prarticle.2005-10-25.9856177177/prarticle.2005-10-26.2582788867/prarticle.2008-12-04.2105225472/prarticle.2009-02-05.7483602003/prarticle_view
[Accessed 17 July 2012].

RWSN, 2012. *RWSN - Afridev Pump.* [Online]
Available at: http://www.rwsn.ch/prarticle.2005-10-25.9856177177/prarticle.2005-10-26.2582788867/prarticle.2008-12-04.2105225472/prarticle.2009-02-06.9581575564/
[Accessed 17 July 2010].

SARWP, 2009. Technical design and operational guide. In: *Rural water pipeline handbook for Saskachewan.* s.l.:s.n., p. Unit six.

Southern Cross Industries, 2013. *Agricultural - Windmills.* [Online]
Available at: http://southx.bloem-online.com/southern-cross-products/agricultural
[Accessed 26 April 2013].

Southern Cross Windmills, 2013. *Pumping tables.* [Online]
Available at: http://www.southx.co.za/windmill.htm
[Accessed 20 March 2013].

Thomas, M., 1996. *Water pumping: the solar alternative,* United States of America: Sandia National Laboratories.

United Nations, 2012. *The millenium development goals report,* New York: s.n.

van der Velden, M., 2013. *UNICEF Wash program* [Interview] (20 March 2013).

Verhoest, N., 2011. *Groundwater flow.* Ghent: s.n.

Vervaeren, H., 2013. *Renewable Energy Sources I - Wind Energy* [Interview] (10 April 2013).

von Bargen, N., 2013. *Quotation RA Collectoren - Solar pumps.* Durban: Stewarts&Lloyds.

Washington State University, 2013. *Irrigation in the Pacific Northwest - Pipe Water Velocity and Minimum Pipe Diameter.* [Online]
Available at: http://irrigation.wsu.edu/Content/Calculators/General/Pipe-Velocity.php
[Accessed 19 January 2013].

WaterAid, 2002. *Groundwater Quality: Mozambique,* s.l.: British Geological Survey.

Waters & Farr, 2005. *Dimensions Of Polyethylene Pipes And Bosspipe.* [Online]
Available at: http://www.watersandfarr.co.nz/dimensions.asp
[Accessed 27 December 2012].

WHO, 2011. *Global health observatory data repository - country statistics.* [Online]
Available at: http://apps.who.int/ghodata/?vid=14200&theme=country
[Accessed 9 July 2012].

WILO SE, 2013. *Online Catalogue.* [Online]
Available at:
http://productfinder.wilo.com/en/DE/productrange/000000100003f7c300020023/fc_range_description
[Accessed 5 March 2013].

World Weather and Climate Information, 2010. *Average weather and climate of Mozambique.* [Online]
Available at: http://www.weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-in-Mozambique
[Accessed July 2012].

7. APPENDICES

Appendix A

Appendix B

Appendix C

Appendix D

Appendix A

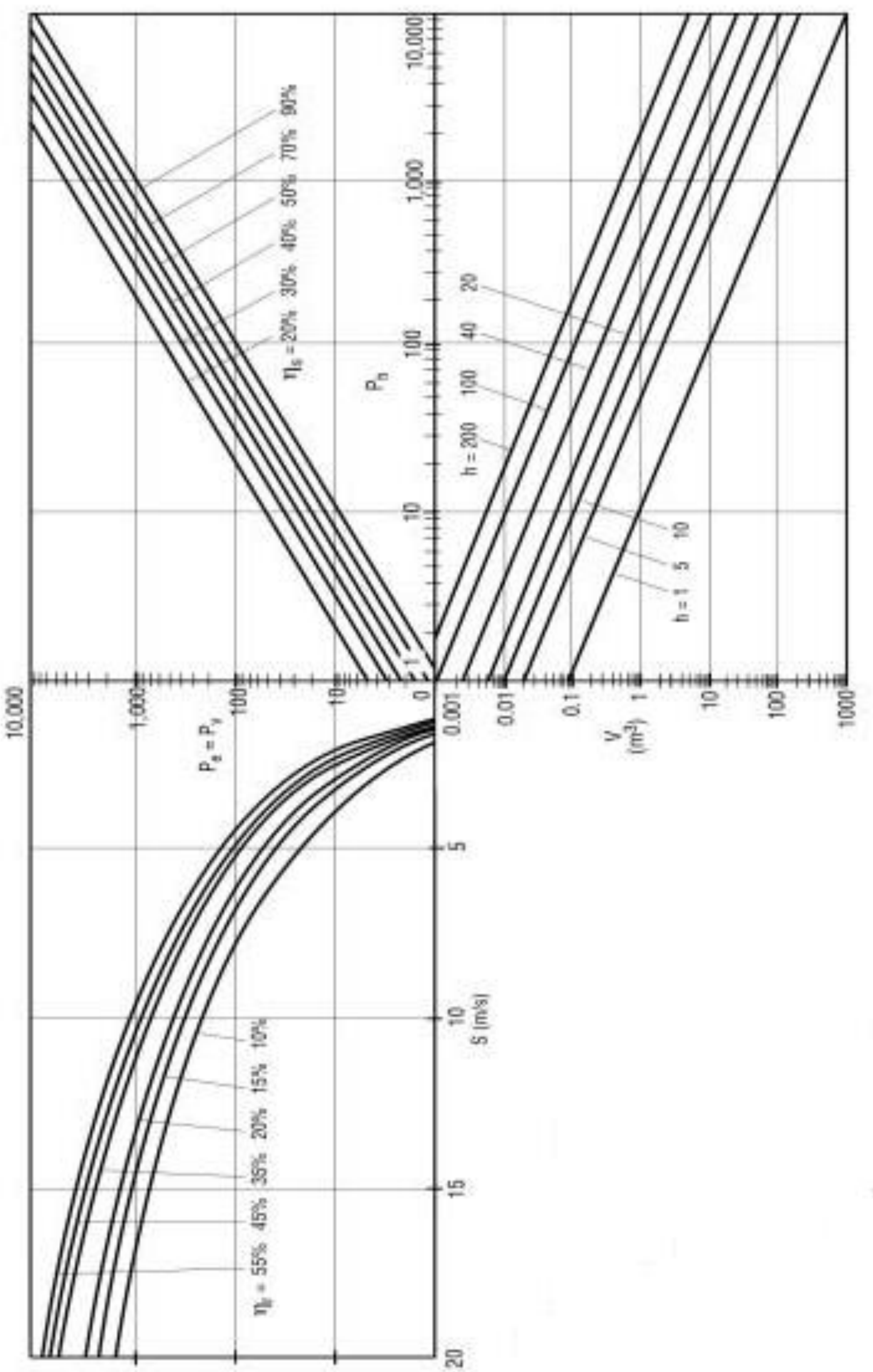


Figure 1: Nomogram for a wind water pumping system (Argaw, et al., 2003)

Appendix B: Used data locations in Mozambique

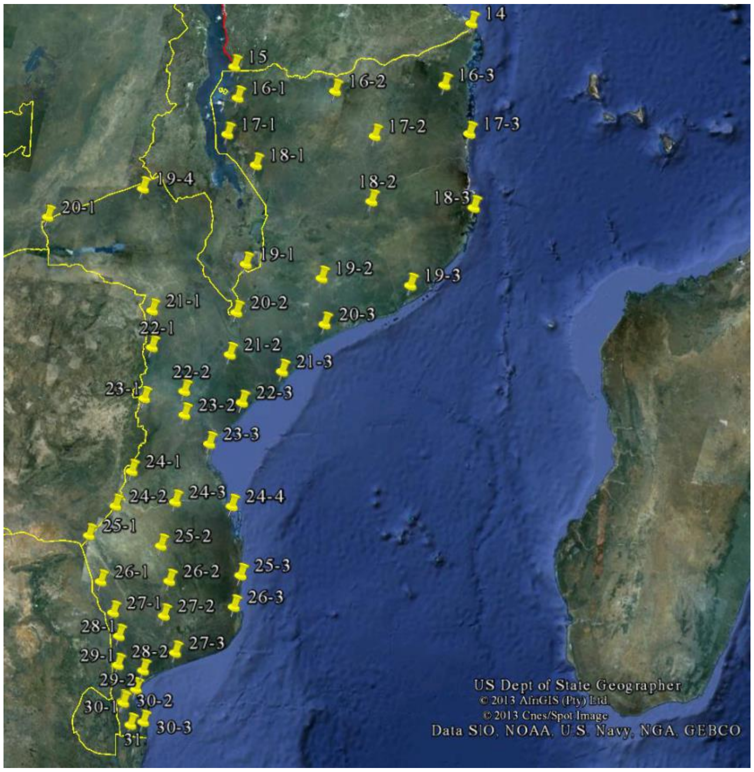


Figure 2: Selected PV GIS data locations in Mozambique

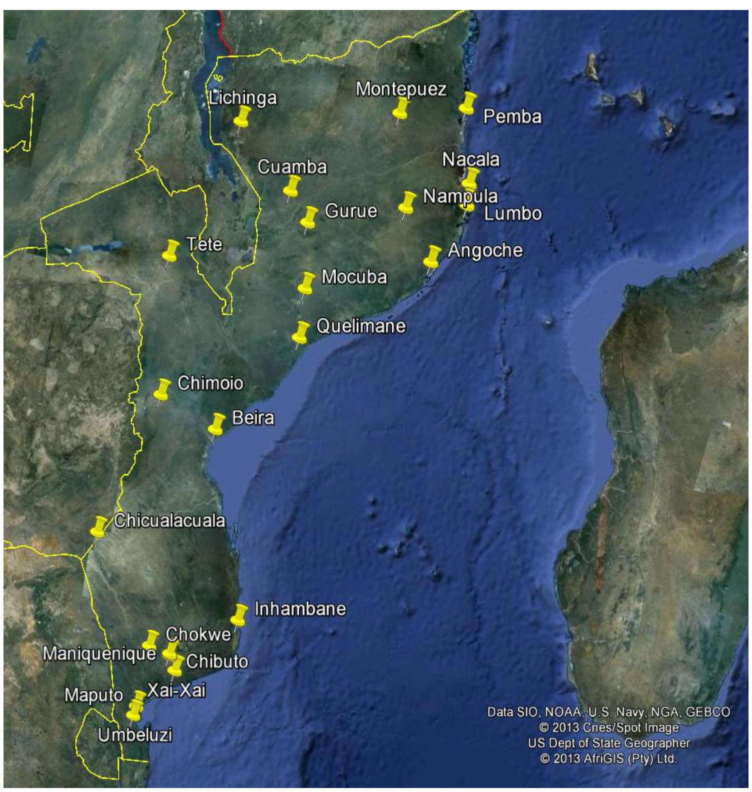


Figure 3: RETScreen data locations in Mozambique

Appendix C: Daily energy figures for the 70 and 100 m borehole categories

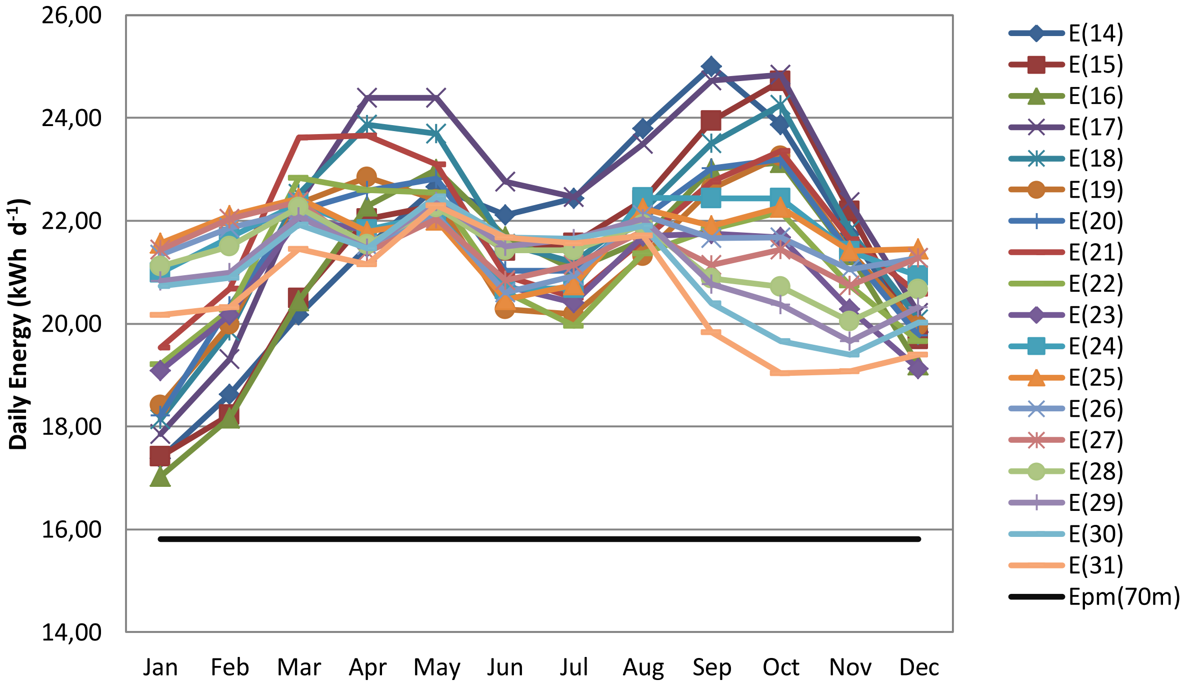


Figure 4: Daily energy from 4.4 kW$_p$ optimally inclined PV installation for different locations in Mozambique and the pump-motor energy requirement for the 70 m borehole category

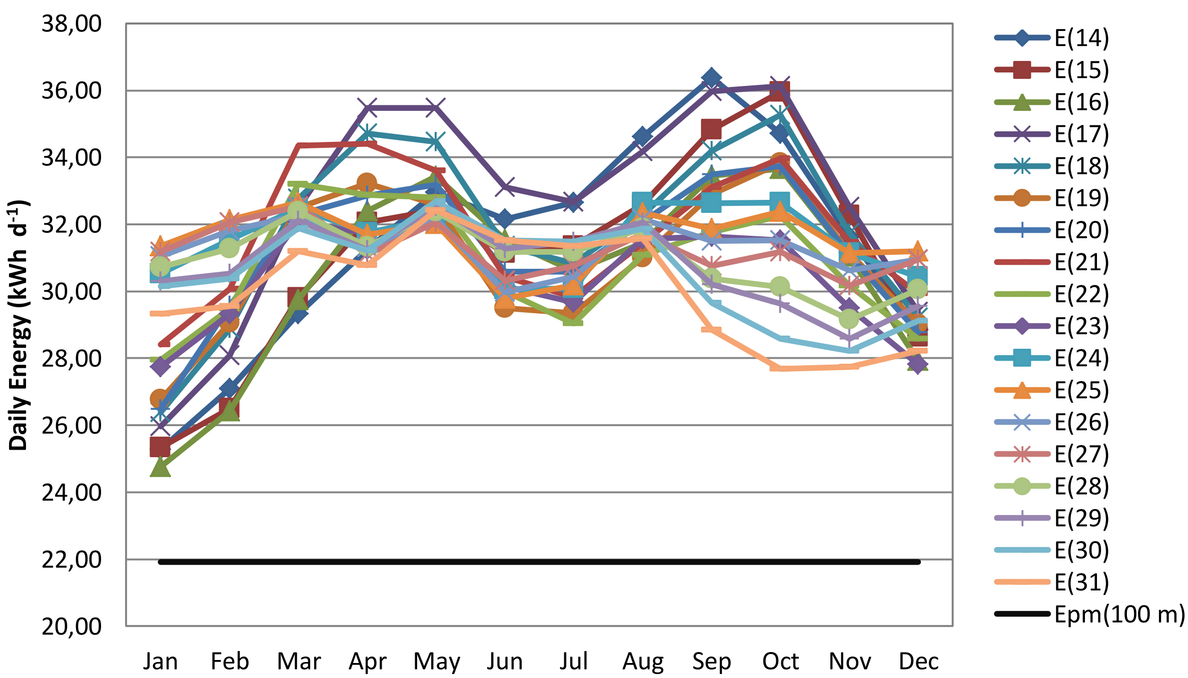


Figure 5: Daily energy from 6.4 kW$_p$ optimally inclined PV installation for different locations in Mozambique and the pump-motor energy requirement for the 100 m borehole category

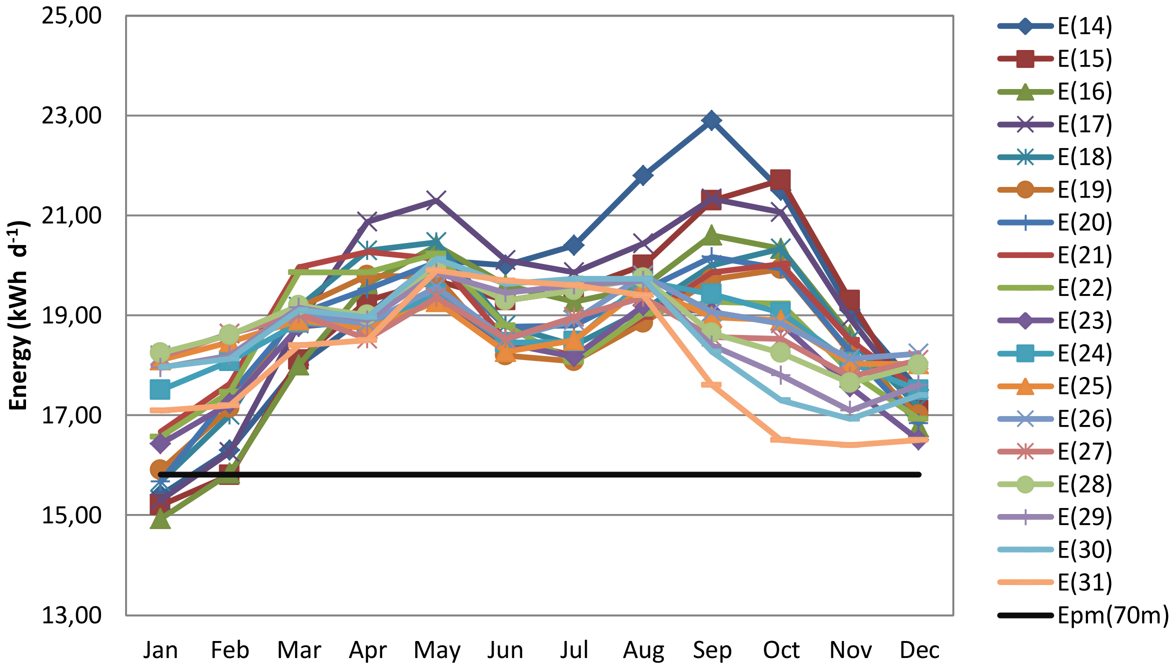


Figure 6: Daily energy production from 4.4 kW$_p$ optimally inclined grid-connected PV installation for different locations in Mozambique and the pump-motor energy requirement for the 70 m borehole category

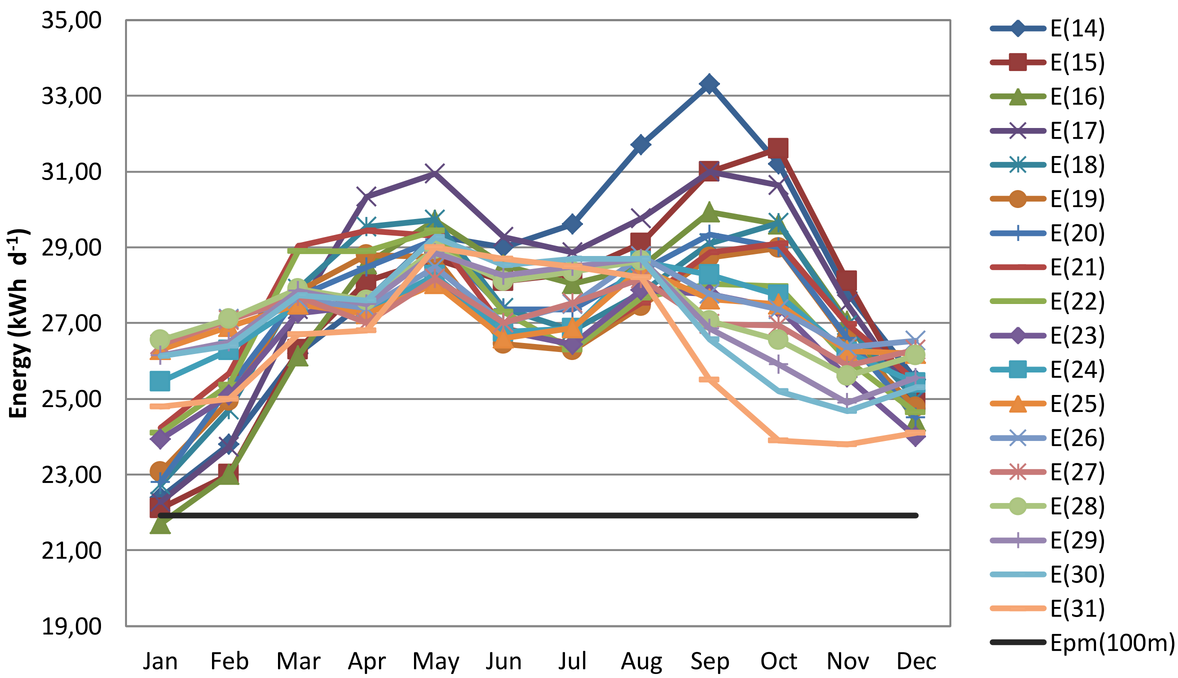


Figure 7: Daily energy production from 6.4 kW$_p$ optimally inclined grid-connected PV installation for different locations in Mozambique and the pump-motor energy requirement for the 100 m borehole category

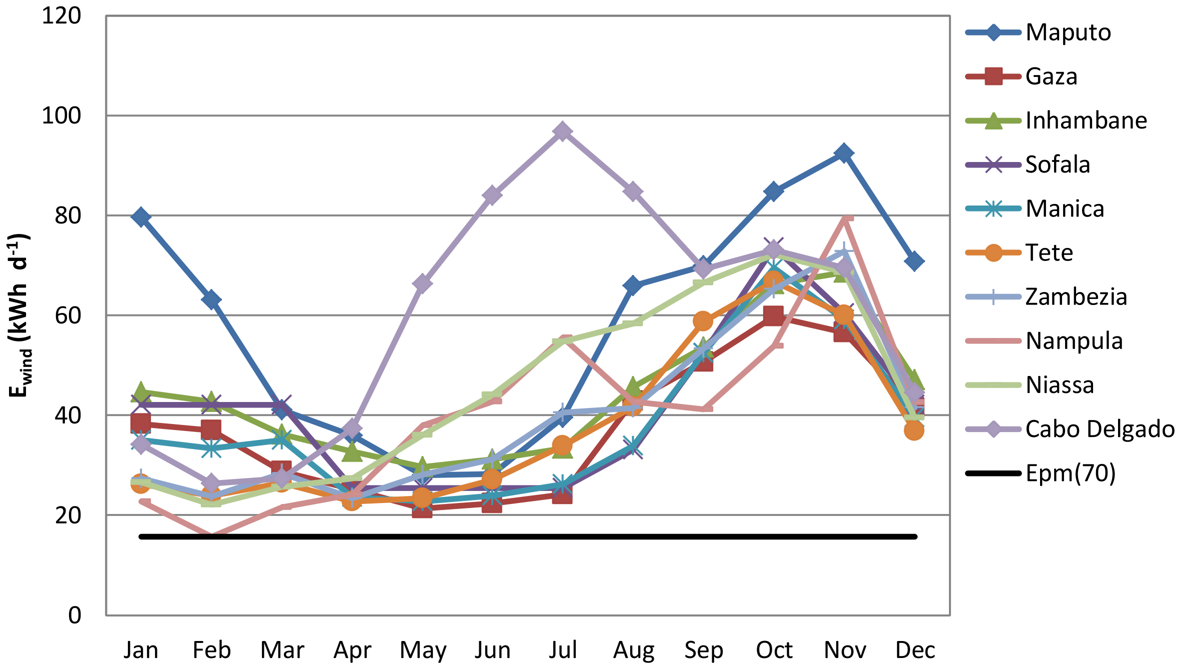


Figure 8: Daily energy from 45 wind turbines (D=2m, η=30%) based on mean daily RETScreen wind speed data for every province in Mozambique and pump-motor energy requirement for the 70 m borehole category

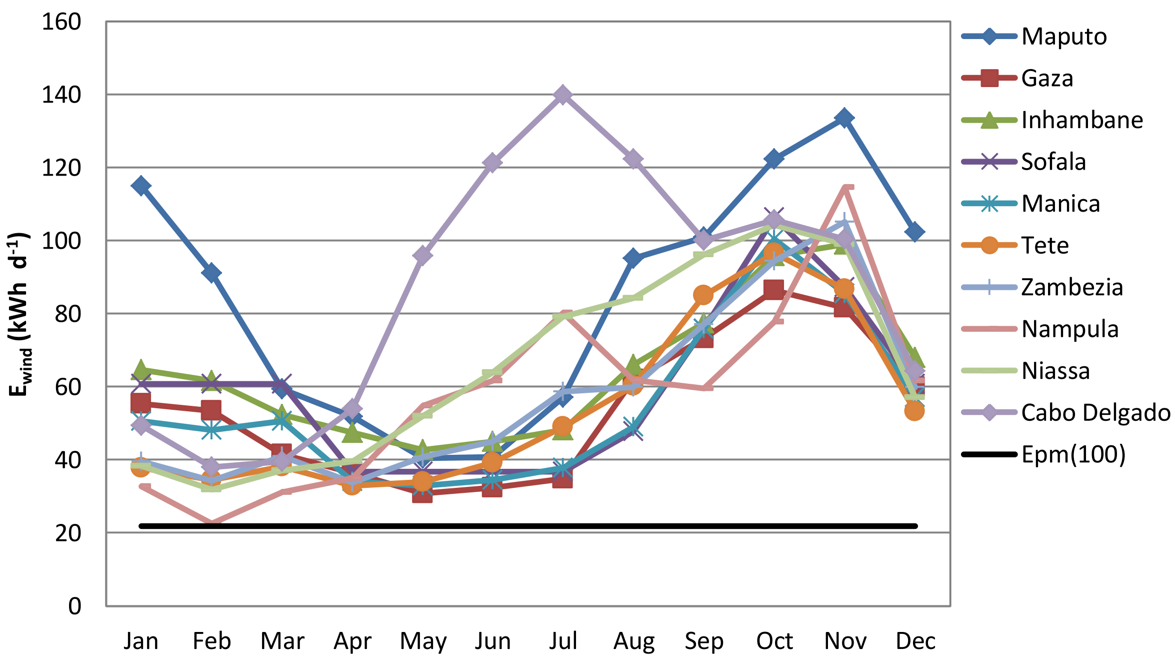
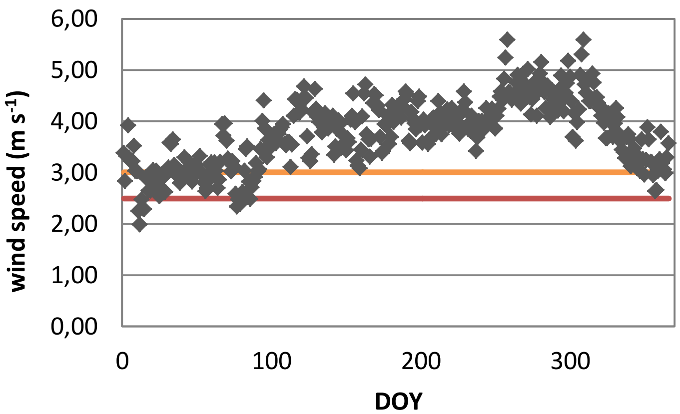


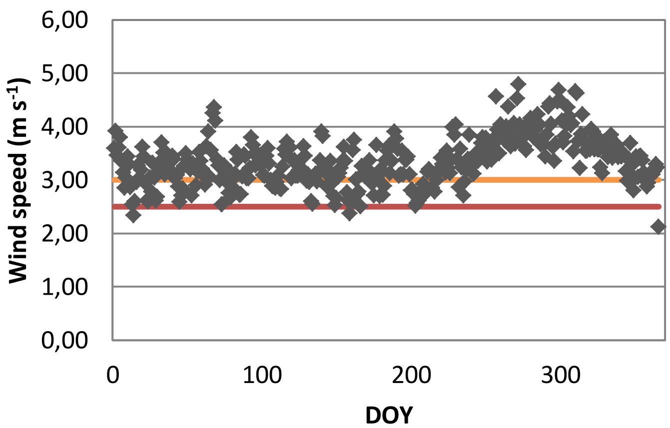
Figure 9: Daily energy from 65 wind turbines (D=2m, η=30%) based on mean daily RETScreen wind speed data for every province in Mozambique and pump-motor energy requirement for the 100 m borehole category

Appendix D: RETScreen daily average wind speed data from 2002 to 2012 for different locations in Mozambique (Minister of Natural Resources Canada, 1997 - 2012)



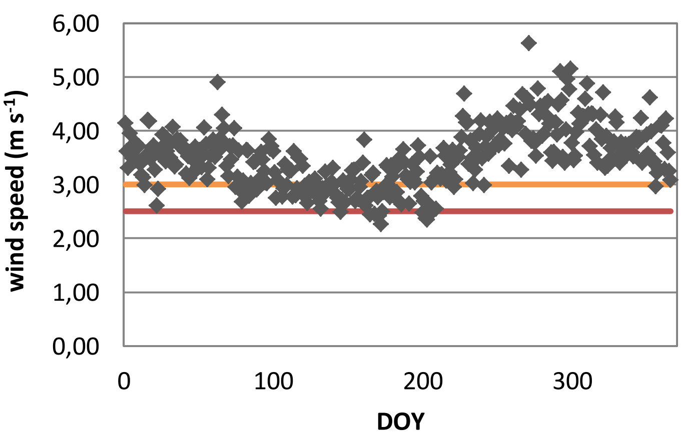
Minimum	1.99
Maximum	5.59
Mean	3.76
% under 2.5 m s^{-1}	2.7
% under 3 m s^{-1}	12.9
Days under 2.5 m s^{-1}	10
Days under 3 m s^{-1}	47

Figure 10: Average daily wind speeds and main parameters for Angoche and threshold wind speed of 2.5 and 3 m s^{-1}



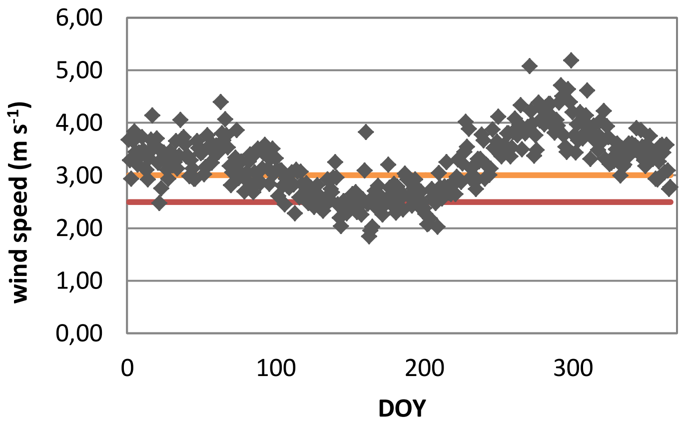
Minimum	2.11
Maximum	4.79
Mean	3.35
% under 2.5 m s^{-1}	0.8
% under 3 m s^{-1}	22.2
Days under 2.5 m s^{-1}	3
Days under 3 m s^{-1}	81

Figure 11: Average daily wind speeds and main parameters for Beira and threshold wind speed of 2.5 and 3 m s^{-1}



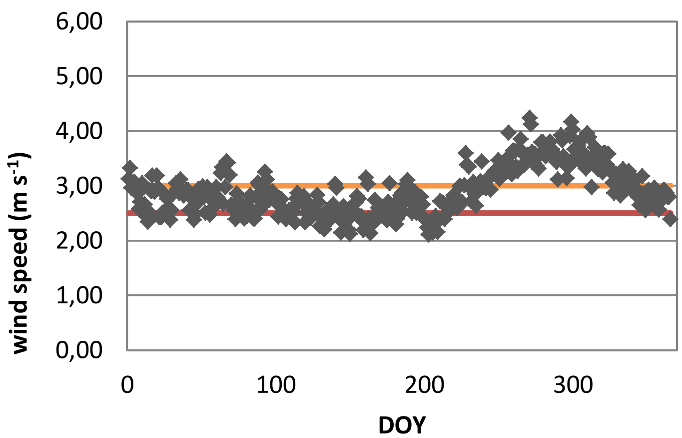
Minimum	2.27
Maximum	5.63
Mean	3.50
% under 2.5 m s^{-1}	2.2
% under 3 m s^{-1}	20.3
Days under 2.5 m s^{-1}	8
Days under 3 m s^{-1}	74

Figure 12: Average daily wind speeds and main parameters for Chibuto and threshold wind speed of 2.5 and 3 m s^{-1}



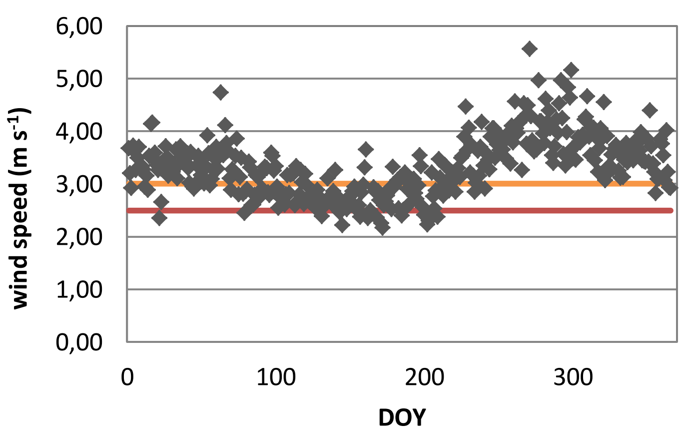
Minimum	1.83
Maximum	5.19
Mean	3.22
% under 2.5 m s^{-1}	12.6
% under 3 m s^{-1}	37.5
Days under 2.5 m s^{-1}	137
Days under 3 m s^{-1}	46

Figure 13: Average daily wind speeds and main parameters for Chicalacuala and threshold wind speed of 2.5 and 3 m s^{-1}



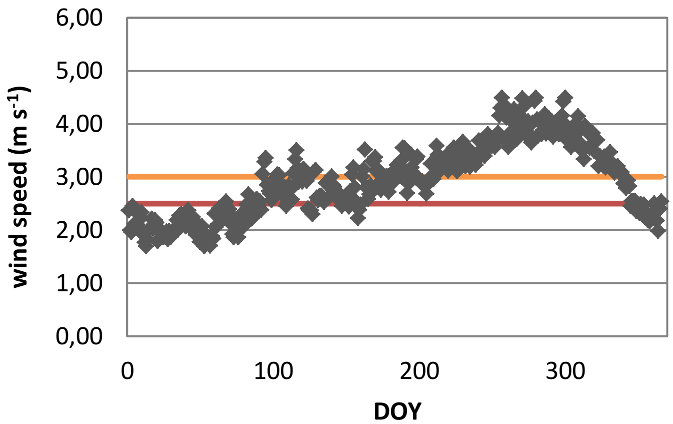
Minimum	2.10
Maximum	4.23
Mean	2.90
% under 2.5 m s^{-1}	18.1
% under 3 m s^{-1}	65.2
Days under 2.5 m s^{-1}	66
Days under 3 m s^{-1}	238

Figure 14: Average daily wind speeds and main parameters for Chimoio and threshold wind speed of 2.5 and 3 m s^{-1}



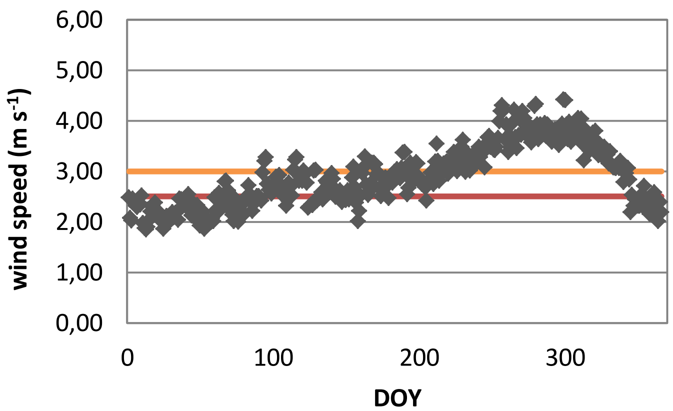
Minimum	2.16
Maximum	5.56
Mean	3.32
% under 2.5 m s^{-1}	5.5
% under 3 m s^{-1}	32.3
Days under 2.5 m s^{-1}	20
Days under 3 m s^{-1}	118

Figure 15: Average daily wind speeds and main parameters for Chokwe and threshold wind speed of 2.5 and 3 m s^{-1}



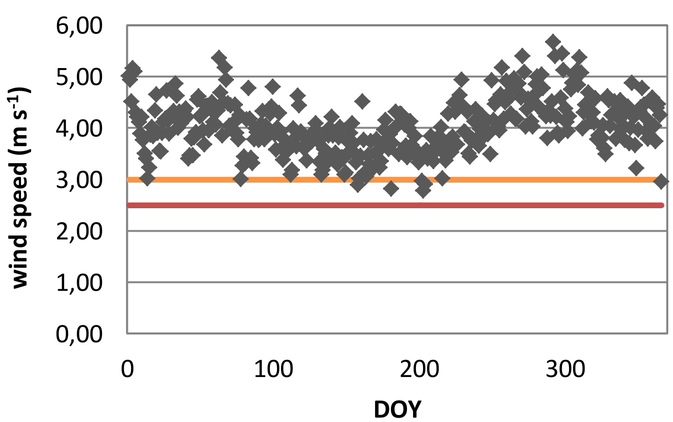
Minimum	1.69
Maximum	4.49
Mean	2.93
% under 2.5 m s^{-1}	31.0
% under 3 m s^{-1}	52.9
Days under 2.5 m s^{-1}	113
Days under 3 m s^{-1}	193

Figure 16: Average daily wind speeds and main parameters for Cuamba and threshold wind speed of 2.5 and 3 m s^{-1}



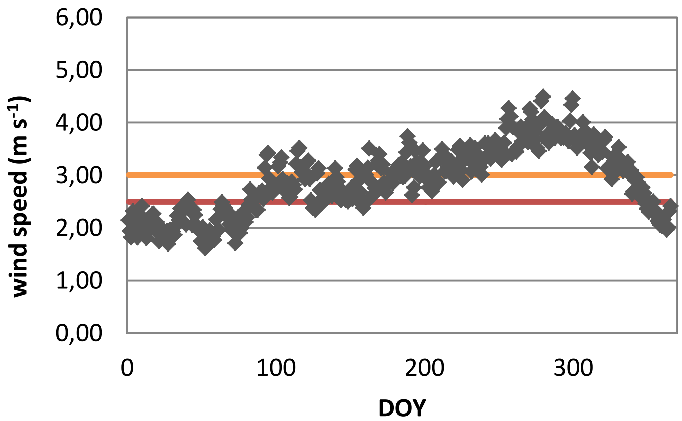
Minimum	1.84
Maximum	4.42
Mean	2.89
% under 2.5 m s^{-1}	32.3
% under 3 m s^{-1}	60.0
Days under 2.5 m s^{-1}	118
Days under 3 m s^{-1}	219

Figure 17: Average daily wind speeds and main parameters for Gurue and threshold wind speed of 2.5 and 3 m s^{-1}



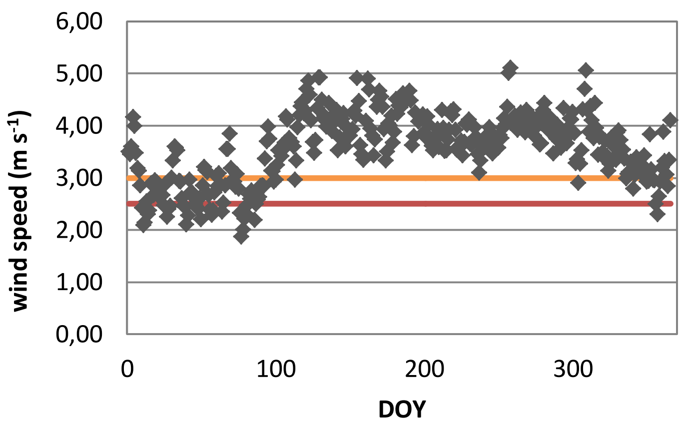
Minimum	2.78
Maximum	5.67
Mean	4.04
% under 2.5 m s^{-1}	0.0
% under 3 m s^{-1}	1.6
Days under 2.5 m s^{-1}	0
Days under 3 m s^{-1}	6

Figure 18: Average daily wind speeds and main parameters for Inhambane and threshold wind speed of 2.5 and 3 m s^{-1}



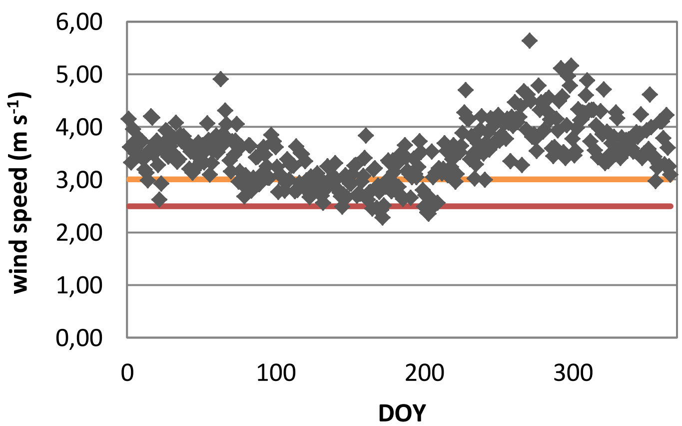
Minimum	1.60
Maximum	4.49
Mean	2.90
% under 2.5 m s^{-1}	29.9
% under 3 m s^{-1}	53.2
Days under 2.5 m s^{-1}	109
Days under 3 m s^{-1}	194

Figure 18: Average daily wind speeds and main parameters for Lichinga and threshold wind speed of 2.5 and 3 m s^{-1}



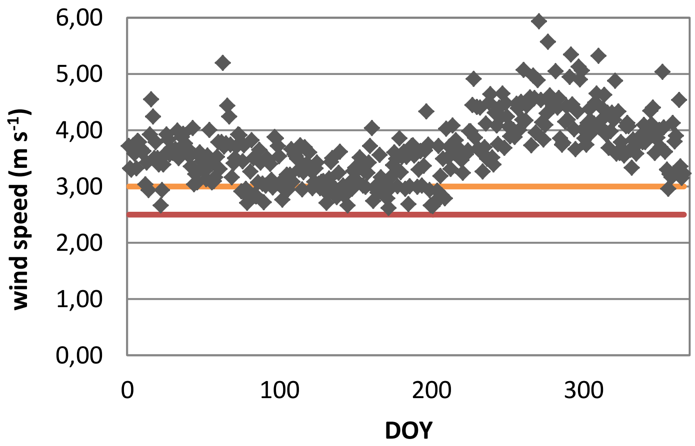
Minimum	1.87
Maximum	5.11
Mean	3.57
% under 2.5 m s^{-1}	8.2
% under 3 m s^{-1}	23.0
Days under 2.5 m s^{-1}	30
Days under 3 m s^{-1}	84

Figure 19: Average daily wind speeds and main parameters for Lumbo and threshold wind speed of 2.5 and 3 m s^{-1}



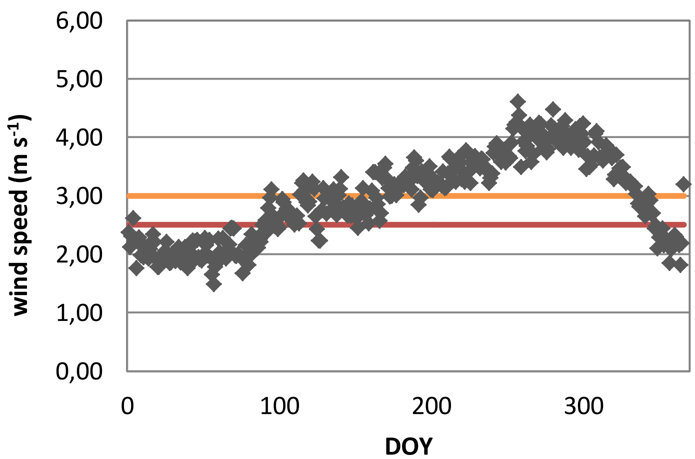
Minimum	2.27
Maximum	5.63
Mean	3.50
% under 2.5 m s^{-1}	2.2
% under 3 m s^{-1}	20.0
Days under 2.5 m s^{-1}	8
Days under 3 m s^{-1}	74

Figure 20: Average daily wind speeds and main parameters for Maniquenique and threshold wind speed of 2.5 and 3 m s^{-1}



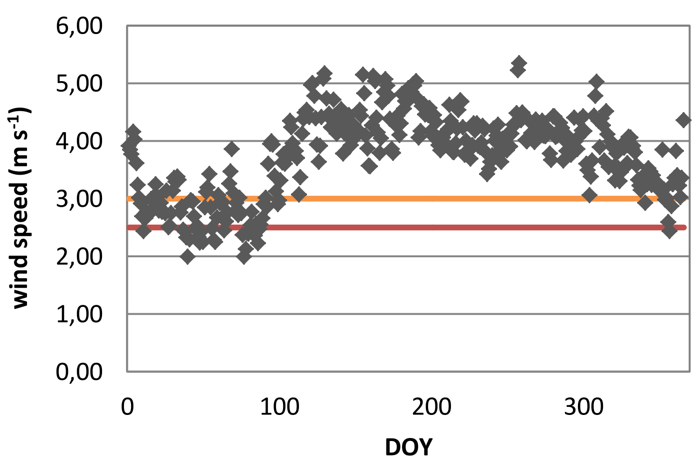
Minimum	2.61
Maximum	5.93
Mean	3.66
% under 2.5 m s^{-1}	0.0
% under 3 m s^{-1}	13.4
Days under 2.5 m s^{-1}	0
Days under 3 m s^{-1}	49

Figure 21: Average daily wind speeds and main parameters for Maputo and threshold wind speed of 2.5 and 3 m s^{-1}



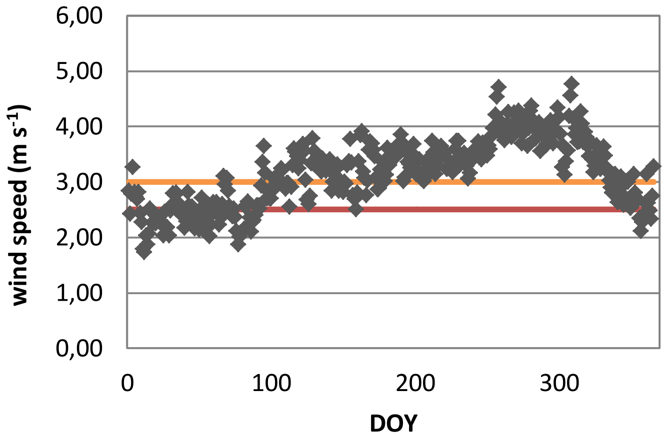
Minimum	1.48
Maximum	4.61
Mean	2.96
% under 2.5 m s^{-1}	31.5
% under 3 m s^{-1}	49.6
Days under 2.5 m s^{-1}	115
Days under 3 m s^{-1}	181

Figure 22: Average daily wind speeds and main parameters for Montepuez and threshold wind speed of 2.5 and 3 m s^{-1}



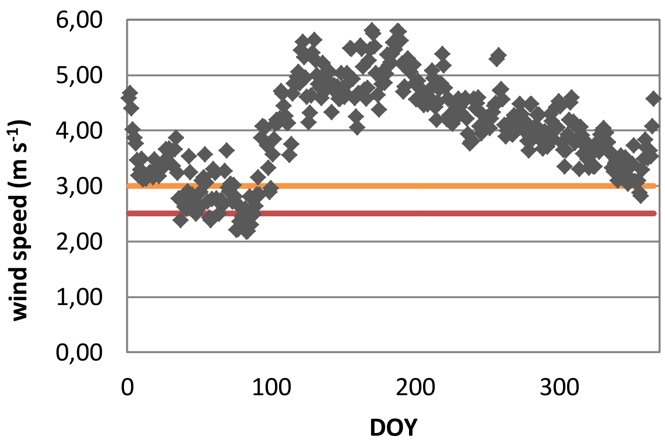
Minimum	1.99
Maximum	5.35
Mean	3.74
% under 2.5 m s^{-1}	6.9
% under 3 m s^{-1}	19.7
Days under 2.5 m s^{-1}	25
Days under 3 m s^{-1}	72

Figure 23: Average daily wind speeds and main parameters for Nacala and threshold wind speed of 2.5 and 3 m s^{-1}



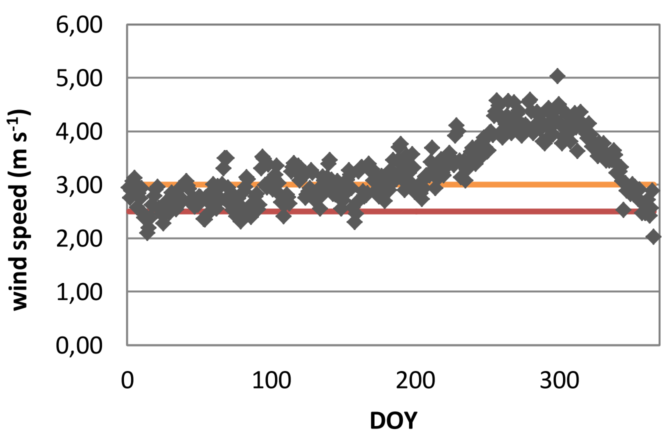
Minimum	1.73
Maximum	4.76
Mean	3.15
% under 2.5 m s^{-1}	17.5
% under 3 m s^{-1}	38.4
Days under 2.5 m s^{-1}	64
Days under 3 m s^{-1}	140

Figure 24: Average daily wind speeds and main parameters for Nampula and threshold wind speed of 2.5 and 3 m s^{-1}



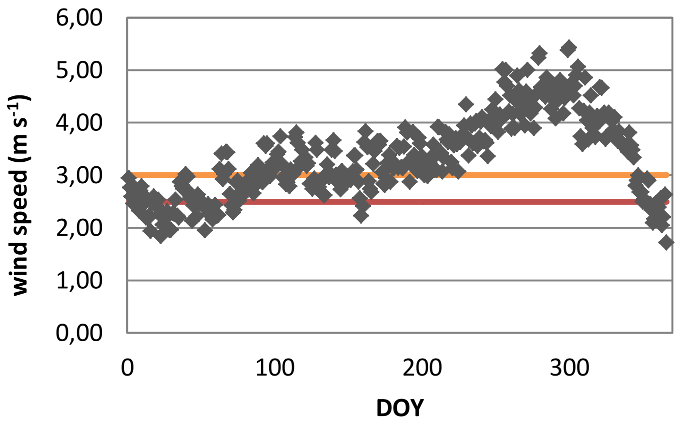
Minimum	2.17
Maximum	5.80
Mean	4.01
% under 2.5 m s^{-1}	3.8
% under 3 m s^{-1}	13.2
Days under 2.5 m s^{-1}	14
Days under 3 m s^{-1}	48

Figure 25: Average daily wind speeds and main parameters for Pemba and threshold wind speed of 2.5 and 3 m s^{-1}



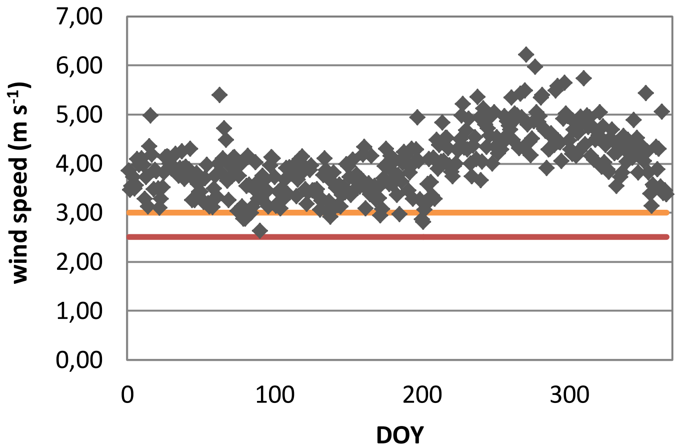
Minimum	2.02
Maximum	5.02
Mean	3.23
% under 2.5 m s^{-1}	6.9
% under 3 m s^{-1}	42.7
Days under 2.5 m s^{-1}	25
Days under 3 m s^{-1}	156

Figure 26: Average daily wind speeds and main parameters for Quelimane and threshold wind speed of 2.5 and 3 m s^{-1}



Minimum	1.71
Maximum	5.43
Mean	3.32
% under 2.5 m s^{-1}	15.9
% under 3 m s^{-1}	38.9
Days under 2.5 m s^{-1}	58
Days under 3 m s^{-1}	142

Figure 27: Average daily wind speeds and main parameters for Tete and threshold wind speed of 2.5 and 3 m s^{-1}



Minimum	2.62
Maximum	6.21
Mean	4.01
% under 2.5 m s^{-1}	0.0
% under 3 m s^{-1}	2.5
Days under 2.5 m s^{-1}	0
Days under 3 m s^{-1}	9

Figure 28: Average daily wind speeds and main parameters for Umbeluzi and threshold wind speed of 2.5 and 3 m s^{-1}