Using Photovoltaic Panels with Pumped-Hydro Energy Storage for The Irrigation System of Sugar Cane Plantation at district of Magude-Mozambique

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Abstract

The population increase Mozambique has been experiencing, places additional challenges to the management and exploration of natural resources. In this regard, access to water and electric energy required for irrigation are fundamental to the development of the agriculture sector and well-being of local populations.

In this work, the study is focused on a sugarcane plantation, Macuvulane I, located in the district of Magude, province of Maputo, with a smallholders association in charge of the exploration of the plantation. Irrigation is done by pumping water from the Incomati river, and with the pumps connected to the national electric grid significant energetic costs incur. With the water requirements for both the crop and location in question determined, the energy consumption required to ensure a correct irrigation of the plantation is estimated.

Given its good geographic location in terms of solar incidence, the introduction of a photovoltaic park is a very appealing option for the case study. It is expected that an extensive number of panels will be needed as it is working with one of the largest sugarcane producers in Mozambique. For this, 3 scenarios are considered: application of 1, 2 or 3 photovoltaic parks. In this way, it will be possible to see if a greater investment leads to a lower return.

After some calculations, 3 similar groups of panels were defined (510 photovoltaic panels each). After analyzing these 3 cases, it is possible to obtain an idea that the returns will have values between 10 and 20 years, which reveal to be plausible numbers given the importance of sugarcane production in Mozambique. Expected that this is a market which will take a big part on the future as they have until now, it is more than acceptable to make investments with such return numbers.

Keywords: Photovoltaic Parks, Optimized Irrigation, BlueSolar Monocrystaline PV Panel, Efficient Investment, Microgeneration System.

1. Introduction

According to the World Bank, about two-thirds of Mozambique’s population live in rural areas [4]. Before 2016 the country had experienced accelerated economic growth, in part due to the increased importance of sectors like agriculture and industry, but this growth was later halted in light of the hidden debt the country had amassed [4]. In 2019, the devastation to infrastructure caused by the Idai and Kenneth cyclones, further sent the country into an economic crisis, putting at risk the well-being of the population.

In regard to natural resources, Mozambique is an extremely rich country, but lacks much of infrastructure required to explore them in an environmentally sustainable way. In fact, while water is obequiously abundant as the country has a important number of rivers, a direct consequence of the rise in population is the pressure exerted in the ecosystem.

In this work, the case study is focused on a sugar cane plantation in the district of Mugude in the Maputo province and the closest available body of water is the Incomati river, whose basin is shared between South Africa, Eswatini and Mozambique under the Tripartite Interim Agreement between these nations, and is already under incredible strain [7].

It is the high profitability of sugar that has motivated the construction and conversion of farmland into plantations, managed by a small number of companies that control this activity, or at times, by smallholders associations of local farmers. Either way, this activity is paramount to the general
well being as a means to raise populations out of poverty.

1.1. Motivation

Nowadays, one of the obstacles towards this economic independence that local populations are faced with is energy availability. Mozambique’s electric grid is still underdeveloped and the quality of supply is lacking. In fact, much of the country has no electric coverage even to fulfill basic needs and for many families and businesses the energy tariffs amount to unsustainable irrigation costs that act as barriers towards agriculture development. In light of this, there is an increased focus on the role of renewable energies in fostering opportunities and development. While solar and hydro resources are abundant, their exploration still presents a challenge to small farmer associations due to the high investment involved in such projects.

In order to ensure adequate crop yield, the irrigation system has to be able to deliver the required water duty, and despite the fact that the mean annual precipitation value for Magude is reasonably high, the bulk of precipitation occurs in summer months. So, while in these months the irrigation demands are higher, the critical months actually occur in winter, when despite the lower temperatures, the lack of rain causes an increased request of water availability which the Incomati river fulfills. However, pumping water is an energy intensive activity that lowers the profit margin of farmer associations and as a consequence threatens the economic sustainability of local populations.

It is thus self-evident the advantage of using the available resources to complement energy requirements. For the particular case of Magude, there are, at first glance, two technical viable possibilities to approach hydro-pumping, PV generation through photovoltaic panels and micro-hydro generation. For the development of this project, the first is addressed.

1.2. Topic Overview

As previously discussed, while the resources are abundant, exploring them is a whole different matter if one takes into consideration the lack of infrastructure and other issues typically associated with developing countries.

Given the mentioned weight of the agriculture sector to the country’s development, it is natural to conclude that higher investment in agriculture and training towards better agricultural practices should be a top priority to combat poverty. Out of this necessity arose the concept associated with small scale irrigation projects (ISSPs) as a practical solution to tackle this problem. Moreover, in 2005, the EU and the AfDB, financed the construction, in Magude, of the Macuvulane I sugar plantation with a total command area of 187.9 ha. The irrigation is performed by sprinkler and the water is pumped from the Incomati River, located about 300 m north of the plantation. The pumping station is equipped with 3 groups of centrifugal pumps and induction motors connected to the electric grid. The plantation is divided in blocks and a smallholders association composed by small farmers is responsible for the distribution of tasks such as manual rotation of sprinklers, to ensure an evenly distribution of applied water across different blocks, otherwise ensure each plot assigned to a certain farmer or family is adequately maintained.

Naturally, in order to approach the problem of renewable powered irrigation, one must first look at the crop in question, the agricultural practices employed by the farmers and the association, the infield characteristics and the local climate and seasonal variance so as to characterize the water duty of the crop and develop an efficient irrigation scheme at the lowest possible cost. From the estimated water duty, the next step is to try to estimate the energy needs required for hydro-pumping. It should be noted that due to a number of issues, the information from the field is limited. For example, the need to estimate the energy requirements follows from a unavailability of energy bills.

This work focuses on the photovoltaic solution. It was first considered a scenario where the solar park is directly connected to the water pumps but, since the gross irrigation requirements are reached and a fixed irrigation system is designed, it was chosen to follow the path of microgeneration. This becomes quite advantageous since all estimated production values are based on previous years irradiances and not following this trail could lead to some months where not all water is delivered provoking some trouble in the optimized irrigation process.

1.3. Objectives

This work focuses on the effect of photovoltaic energy production in a major sugarcane plantation of Magude, Mozambique. The ideal option would be finding the correct number of solar panels which could eliminate the electric grid dependence, making it fully sustainable and avoiding big costs for the farmers.

To reach the above goal, it is firstly needed to evaluate how the system responds to different groups of solar parks. If it is concluded that the payback decreases with the addition of solar panels, then in a future work it’s a reliable option considering this fully-sustainable sugarcane plantation.
2. Sugarcane Crop

2.1. An overview

Sugarcane is the name given to several species of perennial tall grass that thrive in warm to temperate tropical regions of the world and are cultivated for their sucrose content, reaching between 2 to 4 meters in height [1].

Most commercial sugar cane is grown between 35ºN and 35ºS, in areas where there is adequate moisture and high incidence of radiation. Germination occurs at an optimum temperature range of 32ºC to 38ºC and optimum growth is achieved for mean daily temperatures of 22ºC to 38ºC. In order for active growth to occur, it requires a minimum temperature of approximately 20ºC, which occurs during warm long seasons. The ripening phase requires a lower temperature interval, 20ºC to 10ºC and is directly tied to sucrose content [1]. The crop life cycle can be divided into 4 distinct growth stages: Germination Establishment, Tiller ing Canopy Development, Grand Growth and Matura tion Ripening.

Higher yields depend on the length of the growing period, which is usually between 9 to 24 months, and on irrigation methods. The first crop (virgin) is usually followed by 2 to 4 ratoon crops [1]. The ratoon practice is common for many crops as it reduces the length of the germination phase shortening the total crop length. However, to ensure high yields, after a given number of ratoon crops, up to a maximum of 8 in some cases, the crop is replanted anew. As for soil needs, the best soils are those that are more than 1 m deep and well-aerated and with a pH in the range of 5 to 8.5, with the row spacing usually between 1.1 and 1.4 m [1].

While sugar cane exploration is mostly aimed at raw sugar production, it is also cultivated for other purposes such as biofuel production. In 2018, 26 million hectares of sugarcane were cultivated worldwide with an estimated production of 1.91 billion tonnes. It is the most cultivated crop by quantity in the world [FAO].

2.2. Exploration in Mozambique

In 1908, the commercial sugarcane sector in Mozambique began with the establishment of sugarcane estates and mills in the Zambezi and Buzi Valleys and, 6 years later, it was followed by the Xinavane plantation on the banks of the Incomati river. In the years preceding Mozambique’s independence, the outflow of knowledge and skills associated with the loss of the staff, mainly Portuguese, led the estates and mills production to sharply decrease. Moreover, the ensuing civil war (1977-1992) had detrimental effects on the sugarcane industry, leading most mills to cease their activity.

By 1992, at the end of the civil war, the Mozambican government focused on the rehabilitation of the sugarcane industry, and the results were nothing more than expected given the excellent agricultural conditions for cane production and the abundance of labour in rural areas. The sugarcane activity in Mozambique has seen major increases in output during the past few years, jumping the production from 240,000 tons in 2007 to nearly 450,000 tons in 2018 Figure ?? . This information related to food and agriculture data was provided by FAOSTAT, a specialized agency of the United Nations that leads international efforts to defeat hunger.

Although the total cost of raw sugar is 260 per ton (production costs + insurance), it enters the European market at 335 per ton. Due to existing beneficial trade agreements, exporting to the European market constitutes a profitable business for the Mozambican sugar industry.

In 2005, the Macuvulane plantation was built as part of a three-phase expansion program (with over 15 sugar cane out-grower associations) implemented by the owners of AdX with the Government of Mozambique and the African Development Bank as funding agencies [9]. As far as funding modalities for this expansion program, the financing options fall between the concession of grants or loans. While the costs of the first and second phases are mainly tied to the establishment of the plantations, namely through land leveling, installation of the irrigation systems, training of the workforce and plantation of sugarcane, the third phase is financed through a loan, whereby smallholder associations are obliged to repay the costs of the first phases. In the case of Macuvulane, the expansion project seems to be the result of a development strategy by the Mozambican government, because the first two phases did not incur costs to either the smallholders or the company, rather, they were gifted by the government [9].

The geographical location of Mozambique makes it extremely favorable for sugar cane exploration. According to a MAFAP report dated from 2013 [8], between 2005 and 2010 sugar cane accounted, on average, to 20% of the total agriculture exports of Mozambique. In 2010, production represented nearly 3.8% of the total cultivated area of the country, being dominated by four commercial industries located in the provinces of Maputo and Sofala. As mentioned, the lucrative activity benefits from preferential trade agreements with the EU. In a market structure such as this, the monopoly created by the demand and the oligopoly created by the supply act to discourage local farmers [8]. In fact, the report cites that policy decisions and the EU trade agreement have no meaningful impact for local sugarcane farmers. Moreover, the
lack of strong farmer associations results in an “unbalanced bargaining power” between farmers and sugarcane millers.

Another drawback that impacts the profitability of these associations is tied to the significant costs that pumping water for irrigation represent, raising further obstacles that thwart opportunities at development. An additional source of concern related to intensive agriculture is the pressure this activity exerts on local ecology when performed in a non environmentally sustainable way. Magude is traversed by the Incomati river, whose delta is already under great strain, with the extension of upstream irrigation for sugar cane cited as posing significant problems in the delta downstream [7].

3. Case Study: Macuvulane I

Macuvulane I is a sugar cane plantation built in 2005, as a SSIP, located in the district of Magude, province of Maputo, at coordinates (-25.028 S, 32.652 E) in Mozambique and a total area of 194.24 ha. It should be noted that the command area for irrigation mentioned in the infield specifications, 187.9 ha, is slightly decreased, in relation to the total area reported above as the area correspondent to the access roads between blocks is not accounted for.

3.1. Climate Characterization

Mozambique’s climate is mostly tropical humid with two distinct seasons, a humid season (summer) and a dry season (winter). The humid season is typically warm and rainy, starting in October and lasting till March, whereas the dry season starts in April, ends in September and is usually colder and less rainy [5]. Annual mean precipitation is around 1000 mm, and fluctuates greatly from the coast to interior regions and from north to south [5].

3.1.1 Precipitation

As far as accurate and complete precipitation records for the region in question, the only data available belongs to Trigo de Morais (TM) and São Martinho (SM), at coordinates (25.17 S, 33.15 E) and (24.32 S, 33.00 E), respectively, for the year of 1987 [10]. Each of these stations is located roughly 60 km from Magude.

Climate data for this region is hard to find and, since the precipitation series of TM and SM are not recent and only refer to one year, additional sources were consulted, Weather Atlas (WA) [3] and Climate Data (CD) [2]. However, the accuracy of the data from these online sources cannot be verified in regard to exact location and time span for which the measurements were taken.

The data from SM station was discarded because its time series does not conform with the other 3 trends. This is not hard to understand since this station is located at the coast, with a distinct Köppen-Geiger group (Aw), and therefore no longer in the boundary of the two previous discussed groups. Nonetheless, even considering that two of the sets are actual measurements from 1987 and the other two are averages for an unknown period, since the remaining three data sets are reasonably in accordance to each other, these were averaged to yield the results of Table 1.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm)</td>
<td>146.77</td>
<td>134.07</td>
<td>87.47</td>
<td>51.21</td>
<td>26.71</td>
<td>16.47</td>
<td>16.21</td>
<td>14.47</td>
<td>33.27</td>
<td>51.61</td>
<td>74.37</td>
<td>86.67</td>
</tr>
</tbody>
</table>

3.1.2 Temperature and Irradiance

Due to the absence of publicly available temperature records, it was necessary to resort to the EU PVG online tool, which allows for the consultation of several solar databases for the African continent. For the region of Magude, the hourly daily averages of air temperature and irradiance by month were obtained from the PVGIS-SARAH database, two major factors on the production of photovoltaic energy.

3.2. Water Requirements

When planning an irrigation system, the first step lies in determining the crop water requirements. These will depend on the type of crop in question and, naturally, on some intricate relation with the local climate. Often, in more detailed studies, the type of soil is also taken into account but this will not be the case here.

The methodology adopted to determine the crop water requirements is that of guide 56 of FAO [6], where the reference evapotranspiration, ET₀, which only incorporates climate parameters and is computed for a reference crop is then corrected with a crop coefficient Kᵢ, that incorporates data about the crop, agricultural and irrigation practices, etc, to yield the desired crop evapotranspiration Eᵢ. With this value computed, some adjustments are performed and the final water requirements estimated.

3.2.1 Effective Precipitation

The USDA through its SCS provides a handbook, in which chapter 2 entitled 'Irrigation Water Re-

### 3.2.2 Net and Gross Irrigation Requirements

Once found the net irrigation requirements, gross values can be reached only being needed to apply a uniformity coefficient, which accounts for the fact that water is not distributed evenly, for this case study, the value assumed was $K_u = 0.9$, considering [12], after which the resulting value is increased by 10% to account for losses and other water usage.

### 3.2.3 Normalized Results

With all the assumptions previously discussed, the water requirements for both types of agriculture practice starting in June, virgin and ratoon, were obtained.

As the total length of the crop varies greatly according to the agriculture practice, 480 days for virgin cane and 320 days for ratoon cane, a normalization to a year was required in order to carry out a better comparison between these 2 types.

Without information relative to infield practices, specifically, how many years go by before replantation of the crop occurs, i.e., how many years is ratoon practiced until a virgin crop is planted, it is convenient for the work ahead, for example in determining energy needs associated with irrigation, to consider an annual crop with fixed length, instead of considering a given number of cycles of 320 days followed by a cycle of 480 days, and so on. Consequently, the annual mean water requirement is assumed to be the average of the normalized gross irrigation requirements, i.e, 1360 mm/year.

Evapotranspiration owns several factors which influence water requirements, but Figure 1 shows how irrigation accompanies the change in precipitation for the duration of each crop, and in line with what one may have expected, higher levels of precipitation generally imply a decrease in water requirements, and, although more abundant precipitation occurs during the summer, when temperature is also higher, leading to increased evapotranspiration, the crop has entered its end stage requiring less water.

### 3.3. Irrigation System

The irrigation system has a hydraulic network composed by pumps, valves, draglines and sprinklers. The pumping station is located approximately 300 m north of the plantation on the right bank of the Incomati river and is equipped with 3 groups of centrifugal pumps and respective induction motors that feed the same pipeline (2 of 97.2 l/s flow and 90 kW Power, while the other has 207 l/s flow and 132 kW Power).

Due to unknown issues, the larger group is disabled and it is not known what measures are being taken, if any, to correct the resultant water deficiency, because as it is discussed ahead, the two smaller pumps cannot guarantee the delivery of the required water duty in critical months.

According to information obtained on site, a given sprinkler is able to apply 49 mm/cycle (gross application), and since each cycle lasts for 6 days, with a default stand time of 12 hours (per day), the design duty of each sprinkler is 0.6806 mm/hr for a operating pressure of 330 kPa.Knowing each sprinkler covers an area with radius of 15 m, the design duty of the sprinklers results in 481 l/hr.

Doubt lies on the actual duration of one cycle, since a sprinkler net application of 3.3 mm/hr, over a period of 12 hours results in 39 mm. The units for this value come in mm/cycle, which implies a duration of 12 hours for each cycle (default stand time) instead of the length of the cycle (6 days). Either way, if this new value for the duration of the cycle is assumed to be correct, the sprinkler discharge becomes 2886 l/h, which seems impossible given that the sprinkler is only supposed to be able to apply 1050 l/h, as corroborated by a search for the model of the sprinkler, VYSRSA 35 (Brass). 4 mm. Nonetheless, the pumps are unable to feed the entirety of sprinklers and a manual rotation for a work shift of 12 hours is assumed.

### 3.3.1 Water Duty

In previous sections the water requirements were computed based on the FAO 56 guide approach. However, a value for the net requirements is given obtained by infilled information, 1366 mm/year, which is derived from: Net Application (39 mm/cycle), Target Cycles per Year (35) and Net
Irrigation Requirements \((39 \times 35 = 1366 \text{mm/year})\).

Comparing this value with that obtained in the normalized water requirement results \(1360 \text{mm/year}\), might strike one as odd, as the gross irrigation, judging by the application of some uniformity coefficient (as it was done), should not coincide with the original design net irrigation requirements.

Even so, what is important is that, independent of the validity of the assumptions made (which can be revised provided more information exists in the future), the lengthy computations to obtain the water requirements now allow for the estimation of the monthly water requirements, implying that a more efficient irrigation system with adjustable cycle duration and intervals can be designed, instead of just suspending irrigation for two weeks when precipitation in the region reaches 70 mm\(^4\).

### 3.3.2 Water Scheduling

Doubts remain in the irrigation scheme adopted for the plantation, specifically which groups of blocks have their lines activated at the same time and how are the sprinklers rotated between them. However, for the original designed system \(3\) pumps, since the cycle duration lasts 6 days \(\text{(Monday to Saturday)}\), it can be assumed that a given association of blocks comprising \(\frac{1}{6}\) of the total plantation area, \(A' = 31.3 \text{ha}\) is irrigated each day. This would depend both on the configuration of the hydraulic network, location of valves and lines in relation to the blocks and their area, and so on.

If this is indeed true, then the design duty of the pumps \(Q_{tot} \text{[m}^3\text{/s]}\) would be constrained by the number of cycles per year \(35\) required for each group of blocks with area \(A'\) and the water duty of the crop, assumed in the original system to be \(I_N = 1366 \text{mm/year}\). Then, the rationale behind the pumps design duty, \(Q_{tot}\) is understood:

\[
Q_{tot} = \frac{I_N \times 4}{35 \times 12 \times 3600} = 2831/\text{s} \quad (1)
\]

### 3.3.3 Pump Operation and Required Work Hours

Pumps are mechanical machines that move certain fluids by converting electric energy into hydraulic energy. In the present case, centrifugal pumps are installed and attached to induction motors which provide the required rotational energy to the fluid.

The hydraulic power \(P [\text{W}]\) of a turbomachine is the power available at the shaft of that machine, in the case of a pump, the power it needs to absorb, which is dependent on its imposed design flow \(Q \text{[m}^3\text{/s]}\), the head pressure it needs to overcome \(H \text{[m]}\), the fluid specific weight, \(\gamma \text{[N/m}^3\text{]}\), (in this case water) and the overall efficiency, \(\eta\), as given by equation 2

\[
P = \frac{\gamma Q H}{\eta} \quad (2)
\]

By design, all 3 units work simultaneously, but accounting for the lost unit, the water duty and the estimated work hours of the pumps are calculated.

Moreover, as it is costume for these sort of projects, the system is oversized in a way that only for critical months, when precipitation values decline and energy demand increases, all pumps work simultaneously. Thus, for most of the year, the 2 smaller pumps suffice to meet the water requirements, whereas in a small number of months, all of them are required.

Thus, if as suggested by the data from the in-field specifications, the duration of a cycle or day of work is equal to 12 hours, it can be concluded that, for some months, in order to ensure the required water duty \(I_N\), 1 or 2 pumps are not enough (1 month of 30 days with workable 12 hour days has 360 hours).

While it is known that the larger pump is disabled, and that the irrigation system can get by with only 2 pumps working for some months, this has a deleterious effect on the annual costs, because the pump in question made it so that the arrangement with the 3 working delivered a higher flow per unity of power.

Optimization of the Irrigation System

Since gross irrigation values where reached previously for both sugarcane types, and also due to all uncertainties which have come up with the irrigation process, there is high necessity for the development of a new one. A cycle was assumed to be a 12 hour irrigation process which would cover equal parts of the total area.

\[
A_{\text{sprinkler}} = \pi \cdot r^2 = \pi \cdot 15^2 \simeq 706.85 \text{m}^2
\]

Number of Sprinklers \(= \frac{187.9 \times 10^4}{706.85} \simeq 2652\)

With a total of 875 sprinklers available, the maximum usage for equal cycles will be 663, covering 25% of the plantation area. Assuming this, the system will require 18273600 l/cycle, which leads to a total of 17.76 cycles on a worst case scenario \(\text{(June)}\).

Since the plantation is divided in 4 parts, a circular and continuous irrigation allows it to perform

\[\text{Information from infield.}\]
this type of optimization, where in some months less water is delivered but in others, the excess of it, compensates it.

### 3.3.4 Additional Unit

As referred previously, since the larger group is disabled, the acquisition of a new one is mandatory in order to fulfill the requirements of the optimized irrigation cycle. Considering the 663 sprinklers usage, the missing flow becomes:

\[
\text{Missing Flow} = 423 - 97.2 \times 2 = 228.66 \text{l/s}
\]

KSB, Klein Schanzlin Becker, is a reliable and well experienced store in Pumps, Valves and Services. With their collaboration, the Sewatec K 200-402G 3EN 315M 04 was recommended as the best fit for the missing part of the water delivery group. This 132 kW rated power machine delivers the 228 l/s needed for the irrigation designed at an efficiency of 95.6%. Combining these pumps in series, it is gathered a total of 318 kW on the hydraulic network.

### 3.3.5 Spent Energy

Once found the requested motor units, energy calculations for both sugar canes can finally be reached.

Although it is dealt with 2 type of sugarcanes, it’s helpful fixing values for the required energy from January to December in order to facilitate an annual economic analysis, which will be further executed.

Since the ratoon type does not last 12 months, the focus is turned towards the virgin cane. When repeated the months, it is selected the greater one, this allows the requirements to have some slack. All calculations will be based on the following table 2.

### 4. Photovoltaic Energy

Once gathered all field information and focusing on the irrigation system planification, a photovoltaic investment should be studied as a mid-long term solution. In a world where clean energy is evolving, is available anywhere and has no moving parts required, this option stands out. Since in some months the precipitation is less abundant, irradiance becomes the next target.

This chapter aims to present a proposal for both types of sugarcane. An ideal solution would either deliver to the electrical machines the power necessary for all cycles every month, or produce as much as energy spent during the total process so it can be sold in a state of microgeneration.

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy Required (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>34.344</td>
</tr>
<tr>
<td>February</td>
<td>30.528</td>
</tr>
<tr>
<td>March</td>
<td>41.976</td>
</tr>
<tr>
<td>April</td>
<td>38.160</td>
</tr>
<tr>
<td>May</td>
<td>38.160</td>
</tr>
<tr>
<td>June</td>
<td>34.344</td>
</tr>
<tr>
<td>July</td>
<td>34.344</td>
</tr>
<tr>
<td>August</td>
<td>41.976</td>
</tr>
<tr>
<td>September</td>
<td>57.240</td>
</tr>
<tr>
<td>October</td>
<td>68.688</td>
</tr>
<tr>
<td>November</td>
<td>57.240</td>
</tr>
<tr>
<td>December</td>
<td>57.240</td>
</tr>
<tr>
<td>Total</td>
<td>534.24</td>
</tr>
</tbody>
</table>

Moving on to the projection, the South African market was the main focus since most of the equipment needed for the construction of a photovoltaic park is bought here, mainly Mozambique. Not only the accessibility of these products were taken into account, but also their Power/Price ratio.

#### 4.1. Photovoltaic Equipment

**Solar Panel and Inverter**

After analyzing a large number of panels and doing an economic study of the Power/Price ratio, it was possible to identify an economically suitable solar panel that would fit the needs of this project (59.6 MWh). Note that the annual/seasonal energy requirement is very high, so low power panels (100W, 150W, etc.) were put aside since it would result in an even larger number of them. The chosen panel was then the 305W *BlueSolarMonocrystalline*.

Calculations were carried out in order to determine the energy that each panel could produce. It was considered a system performance according to the NOCT (Nominal Operating Cell Temperature) conditions. These are standard operational conditions of solar cells which assume a 800 W/m², 20ºC ambient temperature and wind speed of 1 m/s, with the PV module at placed at a tilt angle of 45º leading to a feasible approach of real-world conditions. Once found its output power, energy originates of a sum of the 12 hours of operation with the highest efficiency (7:00 am to 7:00 pm exclusive, coinciding with the 12 hour cycle of the water pumps).

In this case, there is no target of energy production each month. As microgeneration is considered, the main purpose is to find different groups of photovoltaic panels and observe how the pay-
back evolves. With this being said, it is uncertain if a bigger group does or not lead to a reduction of the payback, since it demands a bigger investment.

The energy produced by the photovoltaic panels is in DC, and since the pumps are AC, it is necessary to carry out the DC/AC conversion. This conversion is done through an inverter. Since a large amount of panels (and energy) will be needed, it was chosen a modular assembly of inverters.

The market for inverters in South Africa was then analyzed, and it was concluded that inverters with high voltages, currents and power would have to be chosen. The inverter that stood out was the WEG CFW11 with 280 kW, 600V and 357A. Using this specific model, there is the possibility of grouping our panels in sets of 510 (34 rows of 15 panels). Summing a single planification, it is reached a total of 595.5V and 349.18A, which is well-suited for the chosen inverter.

The area occupied by the groups of panels was also taken into account, but by Google Maps it was proved 3 sets of 510 solar panels could easily fit in unused territory.

4.1.1 Batteries
In a scenario where microgeneration is not considered, batteries would be a very important factor to be studied when introduced in topics related to photovoltaic energy. Also, the usual hot climate of Mozambique is also inadvisable for the use of this type of material. Therefore, it is convenient to follow the microgeneration path since there would be a balance between saving energy on batteries and selling it to the electric grid.

4.1.2 Cabling
The cabling allows the connection between all the equipment used and referred to in the previous subsections. Cables are required for connections like: Inter - panel, Panel - Inverter, Inverter - AC combiner, Panels - Ground.

5. Economic Analysis
With the intent of making this project viable, it is mandatory to analyse different options and choose wisely the one that suits better for investors and owners of these smallholder associations.

Some assumptions were made: fixing a 12-month energy requirement, Table 2, considering microgeneration instead of direct connection from PV Panels to Electric Pumps (This way, water not delivered due to missing irradiance can be avoided). Not done these hypothesis, this analysis would get too complex and confusing.

The approach made, even if chosen not to be followed, allows a better understanding of how a photovoltaic project could help on annual profits, after proposed an initial investment. It is ensured the energy requirements are stable and allow both type of sugarcanes a proper development.

5.1. Main Investment Pricing
For this Analysis, 3 scenarios were considered: 1, 2 and 3 groups of 34x15 solar panels.

The number of panels for the different situations are not random, as some simulations had to be performed in order to find a number of photovoltaic panels which could produce as much energy as needed for the entire month. Although 1530 (3 groups) does not complete the required 1735, these scenarios can demonstrate a good perspective of how the system evolves with the addition of solar panels.

<table>
<thead>
<tr>
<th>Table 3: Equipment and Electricity Prices.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
</tr>
<tr>
<td>Panels (€/unit)</td>
</tr>
<tr>
<td>Inversors (€/unit)</td>
</tr>
<tr>
<td>Cables (€/m)</td>
</tr>
<tr>
<td>New Pump (€/unit)</td>
</tr>
<tr>
<td>Agricultural Tariff (€/kWh)</td>
</tr>
<tr>
<td>Flat rate (€/month)</td>
</tr>
<tr>
<td>Sale price (€/kWh)</td>
</tr>
</tbody>
</table>

5.2. Return Years
In order to observe the payback evolution, some calculations were followed equally on each case:

- Price of Main Investment: panels, inverters, cabling and new pump;
- Revenue: energy sold to the electric grid each year;

This way, Table 4 was filled in and expected results were presented.

<table>
<thead>
<tr>
<th>Table 4: Return Years for the 3 studied scenarios.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>Return Years</td>
</tr>
</tbody>
</table>

6. Results & discussion
6.1. Work Overview
Work had to be divided in different steps with the aim of progressing in the project on a sequence of correlated ideas. These steps are described down below:

- 1. Study of Crop Information: Inspection on both types of sugarcanes (Virgin and Ratoon) and their different crop levels during cultivation;
• 2. Weather Data: Study of Irradiation, Precipitation and Temperature, Inspection of the FAO Penman-Monteith Equation, Calculation of Effective Precipitation;

• 3. Irrigation System: Computation of Gross Irrigation Requirements, Study of Previous Irrigation System, Planning of New Irrigation System with Optimized Cycles;

• 4. Pumping Station: Investigation of Available Water Pumps, Choosing new Water Pump, Calculation of required time and energy;

• 5. Photovoltaic Park: Selection of Solar Panels, Inverters, AC Combiner Box, Cabling and Grounding, Study of PV Panel production, Measurement of Space occupied by Groups of Panels;

• 6. Economic Analysis: Inspection of 3 different types of investments while opting through a microgeneration solution;

6.2. Relevant Results

6.2.1 Water Requirements

Table 5 presents all values related to water irrigation requirements via the FAO Penman-Monteith Method, estimation of effective precipitation and calculation of net irrigation. Following the ratoon/virgin cycle having different lengths, and remaining uncertainty for the beginning of both cultures, the estimations were normalized to the duration of 1 year.

Following the ratoon/virgin cycle having different lengths, and remaining uncertainty for the beginning of both cultures, the estimations on Table 5 were normalized to the duration of 1 year.

From Table 5, the average water requirement is 1360 mm/year, which is extremely close to the value obtained by Infield Specifications, but not disregarding the fact that both have different meanings, since the first relates to gross irrigation and the second one to net irrigation. Due to precariousness, it is considered this similarity to be a surplus by inaccurate climate date, with the aim of always delivering at least the required water. The main focus stays on the gross irrigation requirements, since it expresses the quantity of water that needs to be extracted, leading to better Energy and Cost Requirements computations. There is the importance of creating an over-sized system which allows the culture to maintain its progression in case of the appearance of a failure in one of the machines.

6.2.2 Energy Requirements

This topic focus on concerning about the working hours of the pumps. Initially, there were 3, but the one with higher Flow/Power ratio is said to be unavailable, having no knowledge if it is due to internal damage or even a choice by the smallholder association workers to not use it. Even though it was verified the 2 smaller pumps were enough in most of months, it is unavoidable the acquisition of a 3rd pump in order to secure all water needed is delivered. Therefore, it is also designed a brand new irrigation system for each month which facilitates the farmers job and to facilitate annual energy calculations, Table 2.

6.3. Solution

After simulating 3 different scenarios, close to 30%, 60% and 90% photovoltaic park with energy available to sustain the most demanding month (June), all payback values are considered to be viable. From Scenario A to B the payback had a reduction of 5.2%, while from B to C a reduction of 9.3%. This comes from the fact of the additional pump becoming smaller compared to other equipment investment (solar panels, inverters, cabling), throughout the addiction of extra photovoltaic panels groups.

It is reasonable to say the 3 scenarios have results which could become solutions of this project. The payback values are located between the 13 and 16 years, ones that practical being this a culture that has been practiced since 1908 and is expected to maintain its rhythm the next many years approaching. It is a decision that will be based on the budget available, if seen as a feasible one.

7. Conclusions

7.1. Achievements

Although some infield specifications were presented, still a part of important information kept unknown. This lead to the procedure of the FAO water irrigation guide based on two different types of cultures, with no starting month, provoking some assumptions since the early studies. All these natural energy sources (precipitation, irradiance, temperature) were used in order to obtain the maximum benefit and reduce energy costs.

Some information was provided, although sometimes insufficient. Reportedly, when precipitation reached 70 mm in a day, irrigation would get suspended for 2 weeks becoming this an ineffective irrigation method since it is not linear and weather temperature can take a big part on this suspension. For this reason, a new irrigation plan was designed to ensure the culture was well treated.

For the photovoltaic park, the chosen solution will rely on the budget available since all 3 cases are viable. The assembly cost of the entire park and new pump are already included in the values displayed on the Economic Analysis Chapter. Bearing in mind this is a culture that will last as
many years as it has proceeded since created in Mozambique, the bigger the photovoltaic park, the better the return is every year.

7.2. Future Work
A few straightforward ideas for future developments include:

- For a better precision on estimations by the FAO Penman-Monteith Equation, a better knowledge on assumed weather parameters would be helpful, as knowing the type of sugarcane being developed and its starting month;

- Knowing sprinklers are rotated by hand, a new method of automatic rotation could be investigated in order to have a more concise and simultaneous irrigation system;

- Usage of hydro-power incoming from the Incomati River, where water is extracted. Solar and Hydro Energy Production can be studied as complementary sources;

- Utilization of distributed reservoirs of water across the field. This will help saving water in months with extra precipitation, enabling the irrigation system to rest some days;

- Related to the photovoltaic park, a direct connection from solar panels to pumps could look up to. A suggestion would be finding how much hours per month the park would be able to deliver the required energy for an adequate irrigation, subtracting on the total hours per month previously found;

References


