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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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Science can amuse and fascinate us all, but it is engineering that changes the world.

Isaac Asimov

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Resumo

O aumento populacional que Moçambique tem verificado coloca desafios acrescidos à gestão e exploração de recursos naturais. Neste sentido, o acesso a água e energia eléctrica necessárias à irrigação são fundamentais ao desenvolvimento do sector agrícola e bem-estar das populações locais.

Neste trabalho o estudo incide numa plantação de cana-de-açúcar, Macuvulane I, localizada no distrito de Magude, província de Maputo, estando a exploração do regadio a cargo de uma associação de pequenos produtores. A irrigação é realizada por bombagem a partir do rio Incomati e, estando as bombas ligadas à rede eléctrica nacional, incorrem daqui custos energéticos avultados. Assim, determinadas as necessidades de água para esta cultura e local específicos e, tendo em consideração as características do sistema instalado, estima-se o consumo energético que assegura a correcta irrigação do regadio.

Dada a sua boa localização geográfica relativamente a incidência solar, a introdução de um parque fotovoltáico é uma opão bastante apelativa para o caso de estudo. É esperado que seja necessário um número extenso de painéis dado que se está a trabalhar com um dos maiores produtores de cana-de-açúcar em Moçambique. Para tal, são considerados 3 cenários: aplicação de 1, 2 ou 3 parques fotovoltáicos. Desta forma, será possível observar se um maior investimento remete para um retorno menor.

Feitos alguns cáculos, foram definidos 3 grupos semelhantes de painéis (510 painéis fotovoltáicos em cada). Analisados estes 3 casos, é possível obter uma ideia que os retornos serão valores entre os 10 a 20 anos, que revelam ser números plausíveis dada a importância da produção de cana-de-açúcar em Moçambique. Esperando que este seja um mercado no qual terá uma aposta no futuro como teve até agora, é mais que aceitável realizar investimentos com tais números de retorno.

Palavras-chave: Parques Fotovoltáicos, Irrigação Otimizada, Painel Fotovoltáico BlueSolar Monocrystaline, Investimento eficiente.

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.

Contents

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Nomenclature

Economical Analysis

Inv primary investment

PY payback years

Rev revenue - energy sold per year

Irrigation Needs

$A_{sprinkler}$ area covered by 1 sprinkler

D usable water soil storage

I_G gross irrigation

I_N net irrigation

k_u uniformity coefficient

P_e effective precipitation

S soil water storage

Crop Water Needs (FAO method)

α canopy reflection coefficient

Δ slope of the saturation vapour pressure temperature relationship

δ solar declination

γ psychrometric constant

λ latent heat vaporization

ω_s sunset hour angle

ρ_a mean air density at constant pressure

σ Stephan-Boltzmann constant

φ latitude

c_p air specific heat

d_r inverse relative distance Earth-Sun

e_a actual vapour pressure

G soil heat flux

J day of the year

N daylight hours

P_a atmospheric pressure

R_a extraterrestrial radiation

r_a aerodynamic resistance

R_n net radiation

R_s solar radiation

r_s bulk resistance

R_{nl} net longwave radiation

R_{ns} net shortwave radiation

R_{so} clear-sky solar radiation

T_{dew} dewpoint temperature

T_{max} maximum air temperature

T_{mean} mean air temperature

T_{min} minimum air temperature

u_2 wind speed

z altitude

Reservoir

Q_{in} reservoir inflow

Q_{out} reservoir outflow

V reservoir volume

Solar Energy

ΔT temperature difference

$coef_{\text{Pmax}}$ maximum power coefficient

I_{SC} short-circuit current

P_{MaxNOCT} maximum power on NOCT conditions

P_{out} output power by solar panel

T_{amb} ambient temperature

T_{pan} solar panel surface temperature

TSI total solar irradiance

V_{OC} open-circuit voltage

Pumps/Turbine

η machine efficiency

E energy

H_b hydraulic Head

P electric power

Q_P pump design duty

Weather Data

$Irrad$ solar irradiance

P_t precipitation

T temperature

Chapter 1

Introduction

According to the World Bank, about two-thirds of Mozambique's population live in rural areas [1]. 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 [1]. In 2019, the devastation to infrastructure caused by the Idai and Kenneth cyclones, further sent the country into a 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 a environmentally sustainable way. In fact, while water is obsequiously 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 theses nations, and is already under incredible strain [2].

Subsistence agriculture provides farmers with consumables for self-sustainability, but also allows some level of economic independence as the agriculture sector employs much of the population in rural areas. Of all the crops explored at national level, sugar cane has an outstanding weight in the country's exports. In fact, 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 [3]. 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 PV 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. All energy necessary for irrigation comes from the Mozambican electric grid and at the end of the season production, the energy produced by the photovoltaic panels is sold and cut down on the final price.

The application of batteries connected to the solar park was also studied but given the location high temperatures, this option was easily discarded.

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.

1.4 Thesis Outline

The current work is organized in 7 chapters and 2 appendixes.

Chapter 1 is dedicated to the subject introduction. An overview of the subject is presented as well as the objectives to be met.

Chapter 2 provides a brief overview on the sugarcane crop, and how it is explored in Mozambique.

Chapter 3 presents the case study. Starting with available local climate data, more precisely, temperature and precipitation series, the water duty of the crop is derived, followed by the analysis of the irrigation system, based on existing installed pump units and the infield data concerning the sprinklers. The operation of the pumps as well as their energy consumption is characterized.

Chapter 4 addresses the main purpose of this project, a photovoltaic system. Not only the solar panels are discussed, but also their full connection to an electric grid or straight attachment to the electric pumps.

Chapter 5 attempts to provide a superficial economical analysis, bearing in mind the difficulty in evaluating certain aspects in implementing these solutions relating to construction costs, for example.

Chapter 6 presents and discusses the results obtained.

Chapter 7 is dedicated to the conclusions reached in this work, some caveats on the available data, as well as some recommendations for future work.

Appendix A provides a detailed description of the methodology followed in determining the evapotranspiration of the sugarcane crop based on the FAO 56 guide.

Chapter 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 [4].

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 [4]. The crop life cycle can be divided into 4 distinct growth stages, Figure 2.1.

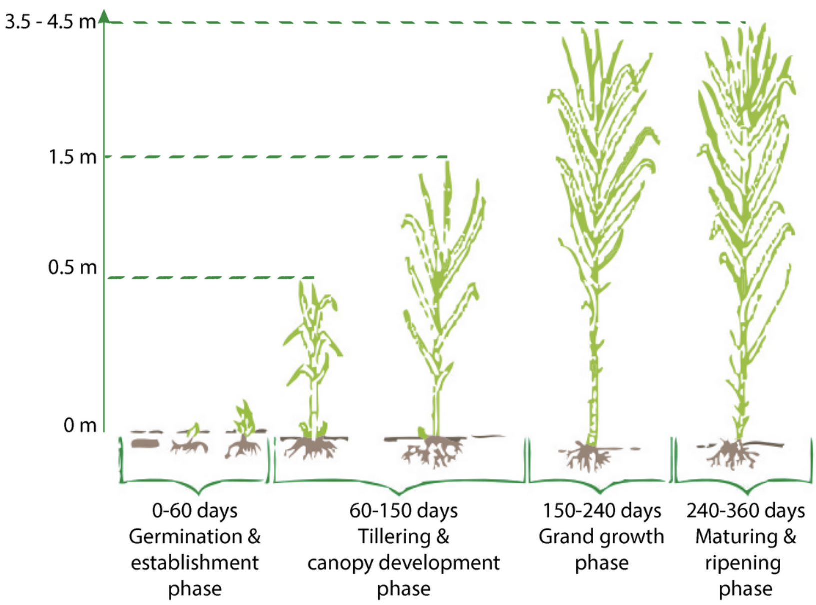

Figure 2.1: Sugar cane growth stages. Source: [5].

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 [4]. 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 [4].

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 begun 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, Figure 2.2.

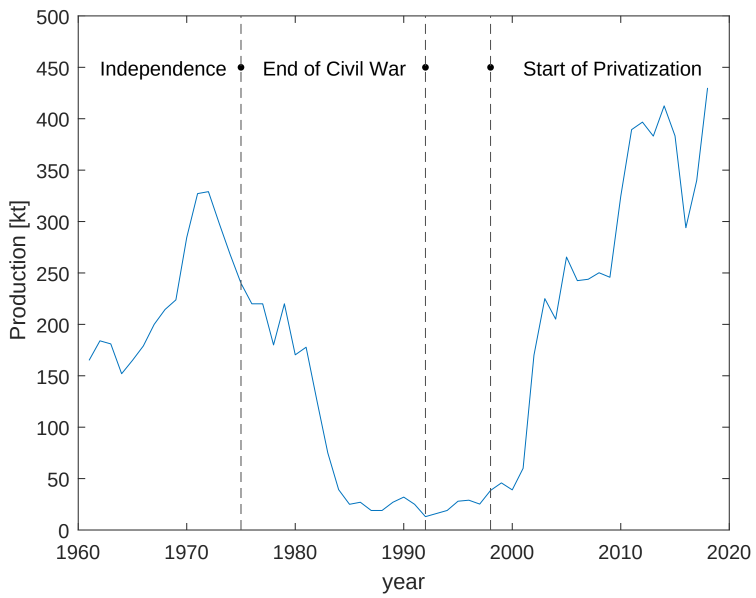

Figure 2.2: Sugarcane production in Mozambique (1961-2018) [source: FAOSTAT]

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 2.2. 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 [6]. 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 [6].

The geographical location of Mozambique makes it extremely favorable for sugar cane exploration. According to a MAFAP report dated from 2013 [7], between 2005 and 2010 sugar cane accounted, on average, to 20% of the total agriculture exports of Mozambique. In 2010, production represented nearly 3.84% 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 monopsony created by the demand and the oligopoly created by the supply act to discourage local farmers [7]. 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 [2].

Chapter 3

Case Study: Macuvulane I

Macuvalane I [1] 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. The layout of the plantation is presented in Figure 3.1.

Figure 3.1: Macuvulane I plantation layout.

The plantation is divided in blocks with block usage and respective area given in Table 3.1. A total of fourteen blocks are used for sugar cane exploration, whereas four of the remainder, while marked as unexplored (N.E.), are actually used for subsistence agriculture, as inferred from Google Earth.

[1] PT: Macuvulana I

The last block is reserved as a nursery for when the need arises to replant a new crop [2].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 of 194.24 ha as the area correspondent to the access roads between blocks is not accounted for.

Table 3.1: Macuvulane I block usage and area.

Sugar Cane				Other	
Block	Area [ha]	Block	Area [ha]	Block	Area [ha]
1	6.85	8	19.82	N.E.	0.68
2	15.54	9	19.77	N.E.	0.68
3	20.31	10	11.86	N.E.	0.51
4	10.67	11	17.40	N.E.	0.83
5	3.67	12	19.36	Nurseries	1.83
6	10.69	13	7.74		
7	19.38	14	11.18		
Total	–	–	194.24	–	4.53

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 [8]. Annual mean precipitation is around 1000 mm, and fluctuates greatly from the coast to interior regions and from north to south [8].

Magude is located in the south interior region of the country and falls within the boundary of two distinct climate groups on the Köppen-Geiger classification, BSh to the west and Aw to the east, Figure 3.2.

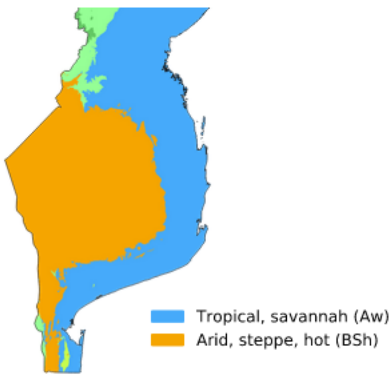

Figure 3.2: Köppen-Geiger classification map for south of Mozambique. (Adapted from Beck et al.)

[2]See ahead the discussion on the difference between virgin and ratoon cane.

3.1.1 Precipitation

As far as accurate and complete precipitation records for the region in question, the only data available [3] 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 [9], Table 3.2. Each of these stations is located roughly 60 km from Magude, Figure 3.3.

Table 3.2: Monthly precipitation recorded in two different stations near Magude, 1987.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
P(TM) [mm]	109.2	139.7	65.8	42.1	20.2	14.8	10.0	13.4	17.4	37.1	66.4	87.0
P(SM) [mm]	86.2	138.9	150.4	132.1	75.8	88.6	39.2	47.0	44.4	97.6	85.0	133.0

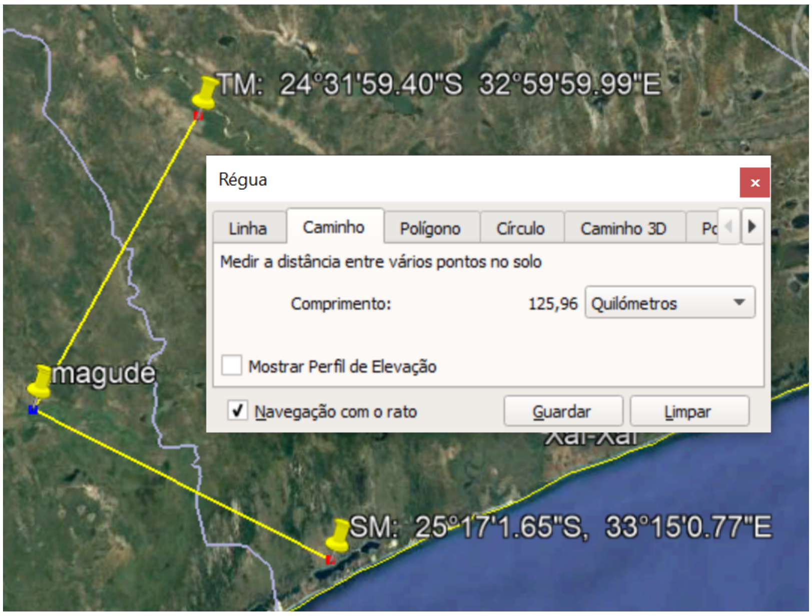

Figure 3.3: Location of TM and SM stations in relation to Magude.

Climate data for this region is hard to find and, since the precipitation series of table 3.2 are not recent and only refer to one year, additional sources were consulted, Weather Atlas (WA) [10] and Climate Data (CD) [11]. 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.

Table 3.3: Monthly average precipitation for Maputo (unkown period).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
WA [mm]	171.1	130.5	105.6	56.5	31.9	17.6	19.6	15.0	44.4	54.7	81.7	85.0
CD [mm]	160.0	132.0	91.0	55.0	28.0	17.0	19.0	15.0	38.0	63.0	75.0	88.0

[3]Station E-43 in Magude is equiped to measure precipitation but records are only available for the wet season.

Reportedly, these series refer to Maputo, located 100 km to the south of Magude, and are presumably monthly averages of a larger but unknown period of years, Table 3.3.

In order to identify precipitation trends, these four series, however not akin in origin, were plotted in the same graph as depicted in Figure 3.4.

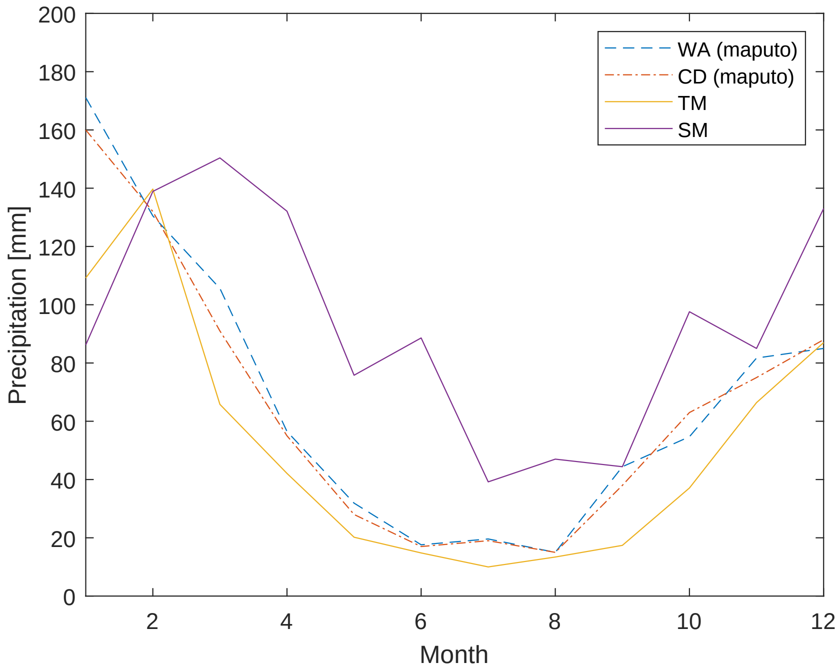

Figure 3.4: Precipitation series - 4 distinct sources.

The data from SM station was discarded because its time series does not conform with the observable trend. 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 3.4.

Table 3.4: Estimated monthly average precipitation in the region.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Precipitation [mm]	146.77	134.07	87.47	51.21	26.71	16.47	16.21	14.47	33.27	51.61	74.37	86.67

In the absence of recent actual records for a reasonable period of time, this composite series, from old data taken at a nearby station and two online sources will be assumed to portrait precipitation patterns in Magude.

From Figure 3.5, it is immediate that the months with higher mean precipitation values occur during the summer (south hemisphere).

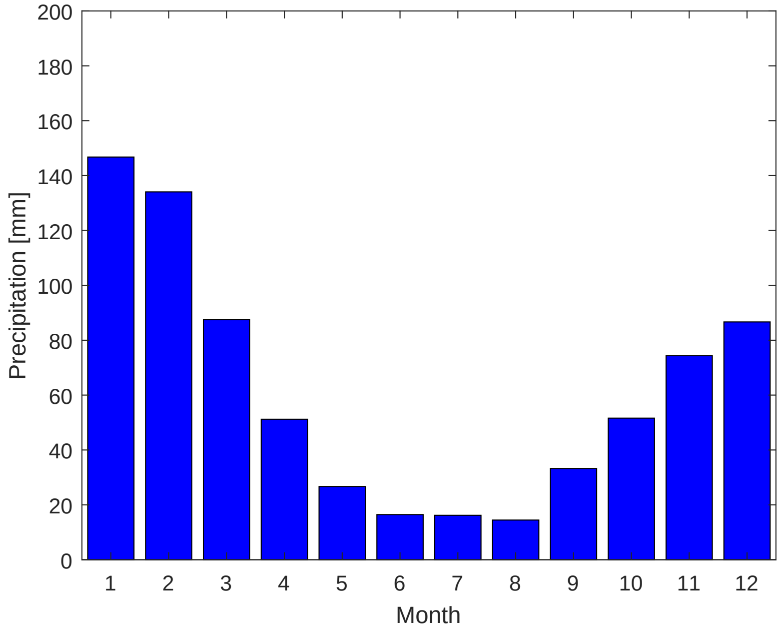

Figure 3.5: Estimated monthly average precipitation in Magude.

Adding the estimated monthly averages of Table 3.4 results in an annual mean precipitation for Magude of 739.23 mm. Comparing this value with the precipitation map of Figure 3.6, it is possible to conclude that the precipitation data used is accurate, since the mean of the three monthly average precipitation series resulted in a mean annual precipitation value that falls within the interval of expected annual precipitation in the region (650-750) mm.

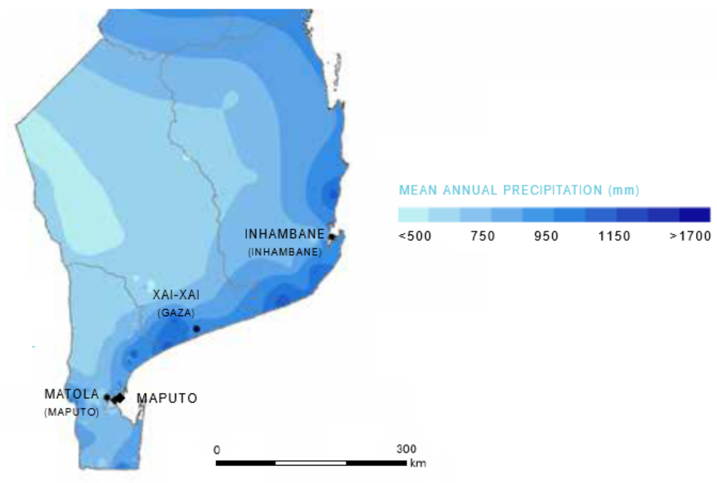

Figure 3.6: Precipitation map for south Mozambique. Adapted from [12].

3.1.2 Temperature

Due to the absence of publicly available temperature records, it was necessary to resort to the EU PVG online tool [4], 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 by month were obtained from the PVGIS-SARAH database, Figure 3.7.

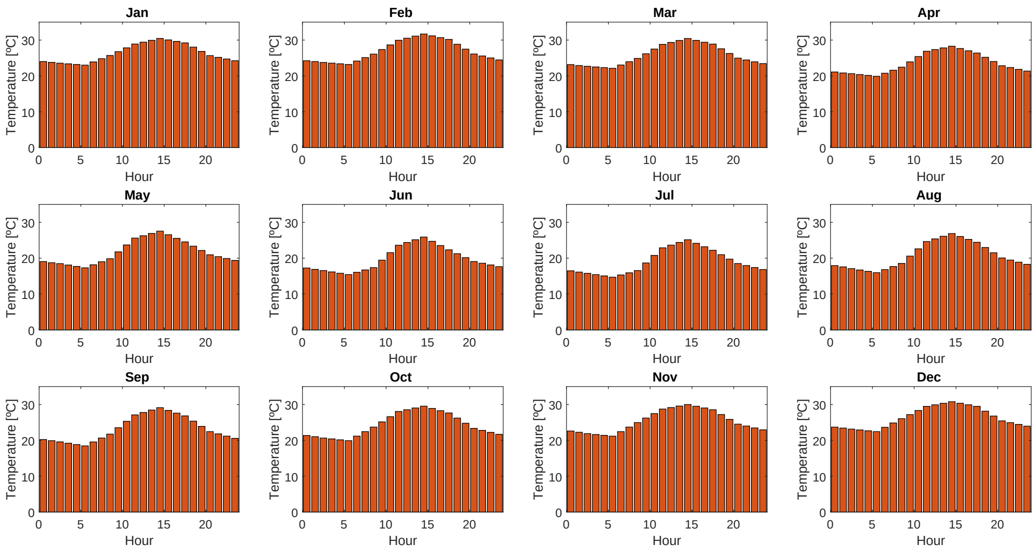

Figure 3.7: Daily average temperature by month.

3.1.3 Irradiance

Simultaneously to section 3.1.2, irradiance values were also collected from the same database. Being this a project based on photovoltaic panels, the sun becomes their main power supply. Its hourly and daily averages of solar irradiance by month were presented on Figure 3.8.

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 [13], where the reference evapotranspiration, ET_o, which only incorporates climate parameters and is computed for a reference crop is then corrected with a crop coefficient K_c, that incorporates data about the crop, agricultural and irrigation practices, etc, to yield the desired crop evapotranspiration E_c. With this

[4] https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html

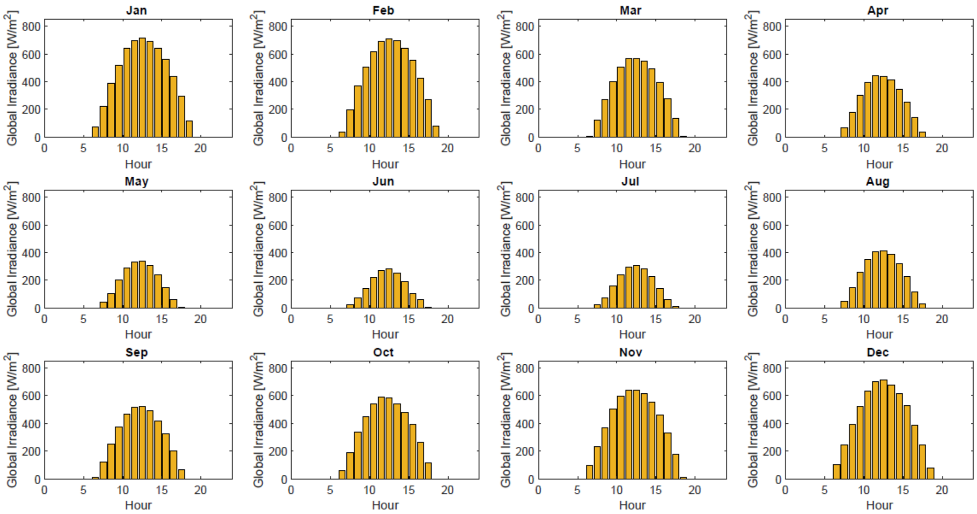

Figure 3.8: Daily average irradiance by month.

value computed, some adjustments are performed and the final water requirements estimated.

A detailed explanation of the method used to determine both the ET_o and ET_c as well as the results obtained can be consulted in Appendix A.

3.2.1 Effective Precipitation

The USDA through its SCS provides a handbook, in which chapter 2 entitled 'Irrigation Water Requirements', [14] gives the basis for estimating the effective monthly precipitation.

The resulting equation for estimating effective precipitation is:

$$\mathsf{P_e} = \mathsf{SF}\big(0.70917\mathsf{P_t}^{0.82416} - 0.11556\big)\big(10^{0.02426\,\mathsf{ET_c}}\big) \tag{3.1}$$

where

P_e : average monthly effective precipitation [in]
P_t : monthly mean precipitation [in]
ET_c : average monthly crop evapotranspiration [in]
SF : soil water storage factor

with the soil water storage factor defined as

$$\mathsf{SF} = (0.531747 + 0.295164\,\mathsf{D} - 0.057697\,\mathsf{D}^2 + 0.003804\,\mathsf{D}^3) \tag{3.2}$$

The value for D (usable water soil storage) is unknown but supposing 50.8 mm (2 in) as the document suggests, results in SF = 0.9217.

Note: The quantities D, P_t, ET_c and P_e have their units expressed in inches. After computing P_e, the conversion to mm is performed.

3.2.2 Net Irrigation Requirements

Finally, the net irrigation requirements, I_N [mm] are computed from equation 3.3

$$I_N = ET_c - P_e \tag{3.3}$$

3.2.3 Gross Irrigation Requirements

In order to determine the monthly average gross irrigation requirements, I_G [mm] , it is necessary to take the net irrigation requirements and 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 [15], after which the resulting value is increased by 10% to account for losses and other water usage, equation 3.4.

$$I_G = 1.1\frac{I_N}{K_u} \tag{3.4}$$

3.2.4 Normalized Results

The water requirements, for both types of agriculture practice, virgin and ratoon, assuming that plantation occurs in June, with all the assumptions previously discussed are presented in Tables 3.5 and 3.6, respectively.

Table 3.5: Water requirements for virgin sugar cane with plantation starting in June.

Month	ET_o[mm]	K_c	ET_c[mm]	P_t [mm]	P_e [mm]	I_N [mm]	I_G [mm]
June	77.2383	0.7250	55.9977	16.4667	10.0782	45.9195	56.1238
July	85.2581	0.7500	63.9436	16.2000	10.0772	53.8664	65.8367
August	107.8324	0.9375	101.0929	14.4667	9.6604	91.4324	111.7508
September	129.7011	1.1500	149.1562	33.2667	25.0325	124.1237	151.7068
October	145.5976	1.2500	181.9970	51.6000	40.3954	141.6016	173.0686
November	144.5500	1.2500	180.6875	74.3667	55.8526	124.8349	152.5759
December	150.2842	1.2500	187.8553	86.6667	64.9185	122.9368	150.2561
January	137.2697	1.2500	171.5871	146.7667	98.8343	72.7529	88.9202
February	126.0869	1.2500	157.6087	134.0667	88.6782	68.9305	84.2484
March	117.6411	1.2500	147.0514	87.4667	59.8262	87.2252	106.6086
April	90.8942	1.2500	113.6178	51.2000	34.5110	79.1068	96.6861
May	86.0830	1.2033	103.5837	26.7000	18.3285	85.2551	104.2007
June	77.2383	1.0917	84.3210	16.4667	10.7260	73.5950	89.9495
July	85.2581	1.0000	85.2581	16.2000	10.5608	74.6973	91.2967
August	107.8324	0.9000	97.0492	14.4667	9.5749	87.4743	106.9130
September	99.4375	0.8000	79.5500	33.2667	21.4794	58.0706	70.9752
Total	1768.2	–	1960.4	819.6	568.5	1391.8	1701.1

Table 3.6: Water requirements for ratoon sugar cane with plantation starting in June.

Month	ET_o[mm]	K_c	ET_c[mm]	P_t [mm]	P_e [mm]	I_N [mm]	I_G [mm]
June	77.2383	0.7250	55.9977	16.4667	10.0782	45.9195	56.1238
July	85.2581	0.8750	74.6008	16.2000	10.3162	64.2847	78.5702
August	107.8324	1.1758	126.7893	14.4667	10.2221	116.5672	142.4711
September	129.7011	1.2500	162.1263	33.2667	25.7568	136.3695	166.6738
October	145.5976	1.2500	181.9970	51.6000	40.3954	141.6016	173.0686
November	144.5500	1.2500	180.6875	74.3667	55.8526	124.8349	152.5759
December	150.2842	1.2500	187.8553	86.6667	64.9185	122.9368	150.2561
January	137.2697	1.2500	171.5871	146.7667	98.8343	72.7529	88.9202
February	126.0869	1.2143	153.1074	134.0667	87.8046	65.3027	79.8144
March	117.6411	0.9792	115.1942	87.4667	55.7781	59.4161	72.6196
April	48.4769	0.8125	39.3875	51.2000	29.3129	10.0746	12.3134
Total	1269.9	–	1449.3	819.6	489.3	960.1	1173.4

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, the determined gross water requirements are normalized to a year in Table 3.7.

Table 3.7: Normalization of the water requirements for both types of sugar cane practice.

Practice	Crop duration [days]	I_G [mm/(crop cycle)]	I_G [mm/year]
Virgin Cane	480	1700	1382
Ratoon Cane	320	1174	1339

Without information relative to infield practices, specifically, how many years go by before re-plantation 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.

As was discussed in Appendix A, several factors influence water requirements, but Figure 3.9 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.

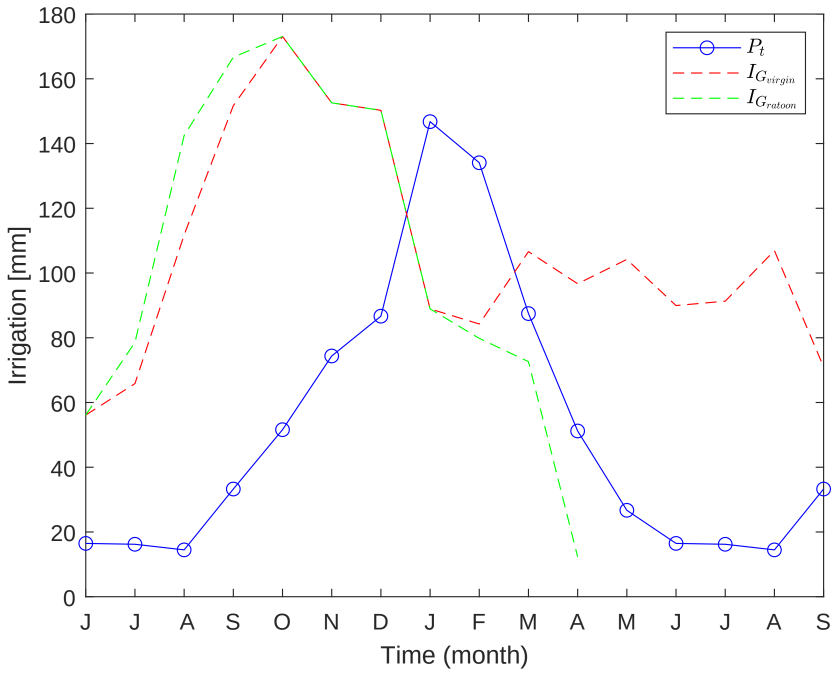

Figure 3.9: Gross irrigation requirements vs precipitation for the duration of the crop cycle.

3.3 Irrigation System

The irrigation system is composed by pumps, valves, drag-lines and sprinklers. A schematic of the hydraulic network is presented in Figure 3.10.

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, Figure 3.11.

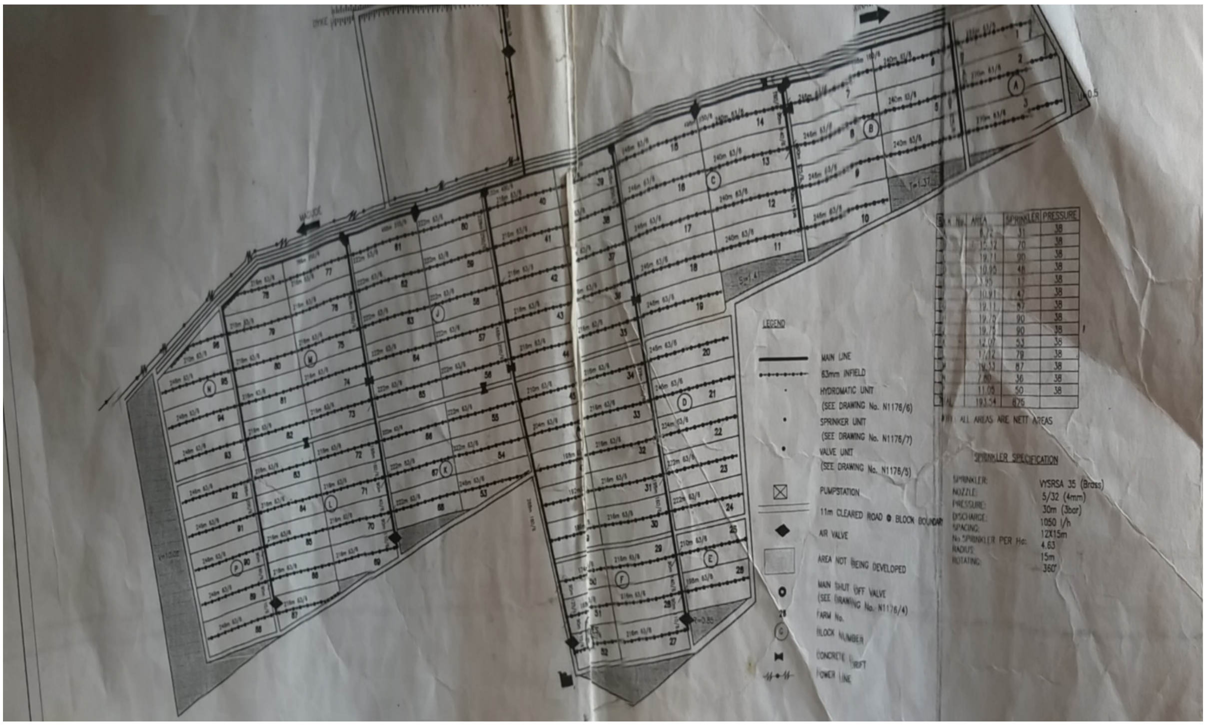

Figure 3.10: Macuvulane I hydraulic network (2005).

Figure 3.11: Installed pump and motor units.

The design duty of the pumps, Q_p and the nominal power of the motors, P are summarized in Table 3.8.

Table 3.8: Characteristics of installed units.

Unit	Q_p [l/s]	P [kW]
1	97.2	90
2	97.2	90
3	207.0	132
Total	401.4	312

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.

Table 3.9 shows the distribution of sprinkler units as well as the command area for irrigation per block.

Table 3.9: Sprinkler distribution per block.

Block	Area [ha]	Sprinklers	Block	Area [ha]	Sprinklers
1	6.85	31	8	19.82	90
2	15.54	70	9	19.77	90
3	20.31	90	10	11.86	53
4	10.67	48	11	17.40	79
5	3.67	17	12	19.36	87
6	10.69	47	13	7.74	36
7	19.38	87	14	11.18	50
Total	–	–	–	194.24	875

Table 3.10: Infield Specifications

Cycle Length (days)	6
Design no. Sprinklers/ha	2.57
Default Stand Time (hrs)	12
Sprinkler Gross Application (mm/hr)	4.1
Sprinkler Net Application (mm/hr)	3.3
Sprinkler Operating Pressure (kPa)	330
Pump Design Operating Pressure (kPa)	600
Gross Application (mm/cycle)	49
Net Application (mm/cycle)	39
Net Irrigation Requirement (mm/year)	1366
Target Cycles (no. Per year)	35

According to information obtained on site, and presented in Table 3.10, 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. From Figure 3.10, one knows each sprinkler covers an area with radius of 15 m, so rewriting the design duty of the sprinklers results in 481 l/hr.

However, Figure 3.10 also shows that each sprinkler has a discharge of 1050 l/hr for an operating pressure of 300 kPa (3 bar). The slight change in pressure cannot possibly explain this discrepancy, so one is led to believe that some error exists somewhere in the infield specifications.

Furthermore, from Table 3.10, one year of irrigation translates into 2520 hours (35 cycles, each with the duration of 6 days with 12 hours of irrigation per day), and considering the total command area, a net irrigation of 1366 mm/year means 1.0185×10^6 l/hr, leading to a required number of 970 sprinklers if each sprinkler discharges 1050 l/h. Therefore, since the total number of sprinklers in the plantation is 875, Table 3.9, they have to be rotated somehow to cover the entire field. Moreover, given that the pumps are able to output 401.4 l/s, they would be able to feed all of the sprinklers simultaneously (in terms of flow alone not considering pressure constraints). However, in the scenario where the larger pump is not working, only a fraction of sprinklers can be activated simultaneously. Even if this was not the case, given that irrigation of each plot is performed by a given smallholder or group of them, it is likely that a rotation scheme of some sort, connected to a cycle length of 6 days (presumably from Monday to Saturday), concerning sprinkler usage is in place. Since this is not known, no particular irrigation scheme will be devised.

Similarly, doubt remains on the actual duration of one cycle, as it is defined in Table 3.10, since a sprinkler net application of 3.3 mm/hr, over a period of 12 hours results in 39 mm. In the same table, 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.

In the next chapter, the prospect of installing a photovoltaic park, highly dependent on sunshine intensity and duration, either producing an automatic irrigation system or even a microgeneration one. For this purpose, the plantation could be divided into several areas, each corresponding to a 12 hour shift.

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 in table 3.10 of 1366 mm/year, which is derived from:

Net Application: 39 mm/cycle

Target cycles per year: 35

Net Irrigation Req.: $39 \times 35 = 1366$ mm/year

Comparing this value with that obtained in the normalized water requirement results (1360 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. Some possible causes for this discrepancy are discussed in the results section.

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, as described in Appendix A, 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[5].

And perhaps, more importantly, a starting point for estimating the monthly energy consumption now exists, something that would be immediate with access to energy bills. Lastly, a new photovoltaic system can now be designed, if so wished, to cover the demand of specific months, for example months when energy demand peaks, designing in essence a self-supply system, assuming that such a thing is possible at all.

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, from Table 3.10, for the original designed system (3 pumps), since the cycle duration lasts 6 days (Monday to Saturday),it can be assumed that a given association of blocks comprising 1/6 of the total plantation area, $A' = 31.3$ 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} [m^3/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 $I_N = 1366$ mm/year. Then, the rationale behind the pumps design duty, Q_{tot} is understood:

$$Q_{tot} = \frac{I_N \times \frac{A}{6} \times 10^4}{35 \times 12 \times 3600} = 283 \, \text{l/s} \tag{3.5}$$

Now, the water duty in terms of the net irrigation requirements does not take into account the discussion about the uniformity coefficient associated with irrigation by sprinklers, but even if this was ignored, it is highly likely that a margin was added to this value, considering that choosing a group of pumps to be associated such that the design duty would match this value would prove nearly impossible, and, on top of that, a higher value of flow may be advantageous, given not only the desired operating point that must

[5] Information from infield.

ensure stability and efficiency, but also, the fact that the system was probably oversized as considering the pumps are installed in parallel (see next section). The loss of one unit would not affect substantially Q_{tot}. This being said, it's understandable that the designer went from $Q_{tot} = 283$ l/s to $Q_{tot} = 401$ l/s.

3.3.3 Pump Operation

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 [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 [m^3/s], the head pressure it needs to overcome H [m], the fluid specific weight, γ [N/m^3], (in this case water) and the overall efficiency, η, as given by equation 3.6

$$P = \frac{\gamma \, Q \, H}{\eta} \tag{3.6}$$

3.3.3.1 H-Q Curves

The characteristic curves of the pumps could not be obtained from local inspection, but from Figure 3.11, it is possible to gather that the pumps are connected in parallel. In an arrangement such as this, the design of the system is aimed at ensuring the required total value of water duty, in this case $Q_{\text{tot}} = 2Q_1 + Q_3$ where the sub indexes 1/2 and 3 denote the smaller and larger pumps, respectively, when 1 or 2 pumps are not enough to ensure Q_{tot}.

Figure 3.12 is intended to show the approximate behavior of the pumps and system, bearing in mind that the curves do not represent the installed pumps, as they could not be measured.

This type of curves, known as steadily decaying, are the most encountered type, as they lead to very stable systems. As for the system curve, generally the head increases with the flow in a quadratic form, as the pipe circuit offers increased resistance to an increase demand in Q.

In general, the curve that describes the change in head, H of the pump as a function of flow, Q can be modeled by a quadratic function given by equation 3.7.

$$H = A + B\,Q - C\,Q^2 \tag{3.7}$$

Then, supposing that the smaller pumps are each represented by $H_{1/2}$ (blue), their parallel association is given by H_{p12} (green), where the parallel association of 2 equal pumps is obtained by rewriting equation 3.7 in equation 3.8.

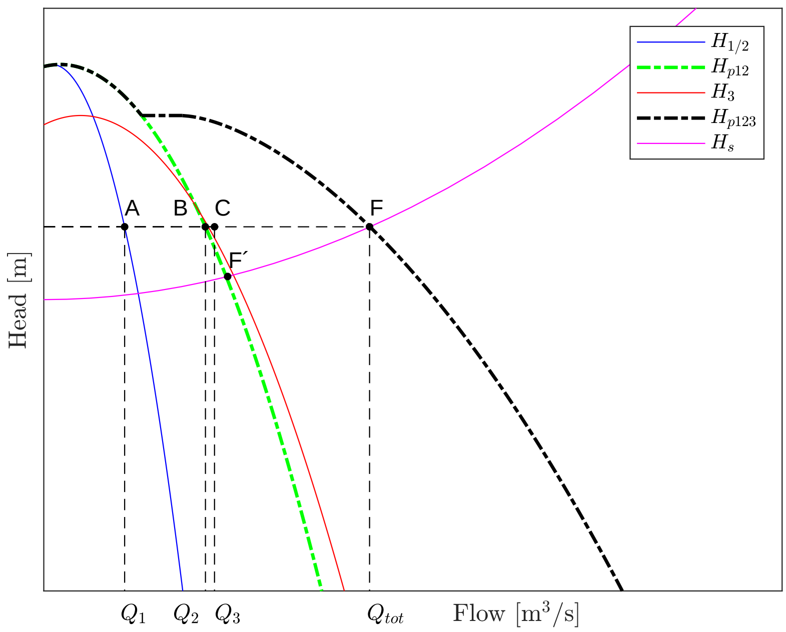

Figure 3.12: Example of parallel association of pumps.

$$H_p = A + \frac{B}{2}\,Q - \frac{C}{4}\,Q^2 \tag{3.8}$$

The larger pump, which is knocked out, could be represented by H_3 (red), as its design flow Q_3 is approximately $Q_2 = Q_1 + Q_1$, Table 3.8, i.e, its curve should be close to H_{p12} (green). By design, the 3 pumps work in parallel, H_{p123} (dashed black) and the system would be represented by something like H_s (pink) given by equation 3.9.

$$H_s = A + B\,Q^2 \tag{3.9}$$

Thus, the operating point would be defined by F, and while the real shape of the curves is unknown, Table 3.8 gives the design duty of the pumps, here expressed in cubic meters per second, and since from Table 3.10 the design operating pressure is also known, P = 600 kPa and equivalent to a water column with a pressure head H = 61.19 m, the points F (0.401,61,19), A (0.097, 61,19) and C (0.207, 61,19), are known.

The situation where the larger pump (3) is knocked out shows the operating point move to F'. One immediate advantage of the parallel association of the 3 pumps is that the total flow can be adjusted by connecting or disconnecting units from operation without compromising the overall system, as the head can be maintained by the remaining units, since $H_{\text{tot}} = H_1 = H_2 = H_3$. However, since the configuration of the system can change, as a result of actuating the several valves present throughout the plantation, the head will change according to the system characteristics [16].

One then sees how a parallel configuration allows for a greater flexibility, and redundancy in order to tackle hardware failure (case in point), allowing the system to maintain operation with just 2 units. However, in the next section, the prospect of disconnecting one unit (or having it fail) is revisited in terms of efficiency, but without the H-Q curves of both the system and the association of pumps it is not possible to determine an operating point. In theory, the 3 pumps were chosen so that the operating point F also coincides with the pump's best efficient point (BEP) but since the efficiency curve is also unknown, the only thing that can be said is that the new operating point F' implies a decrease in efficiency. [16].

3.3.3.2 Required Work Hours

Considering the command area, A = 187.9 ha, and the design duty of the pumps Q_p^i [l/s], where i is the number of pumps working, the water duty per hectare, W_i [$\mathrm{l\,s^{-1}\,ha^{-1}}$] is given by equation 3.10:

$$\mathrm{W}_i = \frac{Q_p^i}{\mathrm{A}},\ i = \{2, 3\} \tag{3.10}$$

or alternatively, expressing the water duty as $\mathrm{m^3\,hr^{-1}\,ha^{-1}}$,

$$\mathrm{W}_i^{'} = \mathrm{W}_i \times \frac{3600}{10^3},\ i = \{2, 3\} \tag{3.11}$$

Now, considering that the original net irrigation requirements, $\mathrm{I}_N^0 = 1366\,\mathrm{mm/year}$ can also be expressed as $\mathrm{I}_N^0 = 13660\,\mathrm{m^3\,ha^{-1}\,year^{-1}}$, the estimated required work hours of the pumps, T_i^0 [hr], are given by equation 3.12.

$$T_i^0 = \frac{\mathrm{I}_N^0}{W_i^{'}},\ i = \{2, 3\} \tag{3.12}$$

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 given, as defined by equations 3.10, 3.11 and 3.12 are given in Table 3.11.

Table 3.11: Water duty and work hours for different pump arrangements.

Pumps	Q_p^i [l/s]	W_i [$\mathrm{l\,s^{-1}\,ha^{-1}}$]	$\mathrm{W}_i^{'}$ [$\mathrm{m^3\,hr^{-1}\,ha^{-1}}$]	T_i^0 [hr]
2	194.4	1.0346	3.7245	3667.6
3	401.4	2.1300	7.6680	1776.8

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. Table 3.12 gives the work hours for different pump arrangements $\mathrm{T}_i^{v/r}$, for the two types of agriculture practices and for the computed gross irrigation requirements, as defined by equation 3.13.

$$\mathrm{T}_i^{v/r} = \frac{\mathrm{I}_G^{v/r}}{\mathrm{W}_i^{'}},\ i = \{2, 3\} \tag{3.13}$$

Table 3.12: Required pump work hours for both types of sugarcane.

	Virgin Cane				Ratoon Cane			
Month	I_G [mm]	T_1 [hr]	T_2 [hr]	T_3 [hr]	I_G [mm]	T_1 [hr]	T_2 [hr]	T_3 [hr]
June	56.1238	301	151	73	56.1238	301	151	73
July	65.8367	354	177	86	78.5702	422	211	102
August	111.7508	600	300	145	142.4711	765	383	185
September	151.7068	815	407	197	166.6738	895	448	217
October	173.0686	929	465	225	173.0686	929	465	225
November	152.5759	819	410	198	152.5759	819	410	198
December	150.2561	807	403	195	150.2561	807	403	195
January	88.9202	478	239	116	88.9202	478	239	116
February	84.2484	452	226	110	79.8144	429	214	104
March	106.6086	572	286	139	72.6196	390	195	94
April	96.6861	519	260	126	12.3134	66	33	16
May	104.2007	560	280	135	–	–	–	–
June	89.9495	483	242	116	–	–	–	–
July	91.2967	490	245	119	–	–	–	–
August	106.9130	574	287	139	–	–	–	–
September	70.9752	381	191	92	–	–	–	–
Total	1701.1	9135	4567	2212	1173.4	6301	3151	1526

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

3.3.3.3 Required Units

Since the two smaller pumps are equal, one of them working twice as long is exactly the same as 2 working for half as long, i.e., $T_1 \simeq T_2$, Table 3.12. This is not exactly true, as a change in flow will affect the efficiency of the system, but the H-Q curves are unknown. The choice then lies on how to design the irrigation system, based on whether or not irrigation can be made automated, and how are the tasks assigned to the workers. The solution that can guarantee adequate irrigation for shifts of 12 hours a day is that of Table 3.13.

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.

3.4 Energy Consumption

In principle, the energy requirements incurring from irrigation needs could be accurately estimated from energy bills, where averages could be performed for each month over a large periods of years.

Table 3.13: Required number of pumps to deliver the estimated gross irrigation.

	Virgin Cane			Ratoon Cane		
Month	#P	#P	#P	#P	#P	#P
June	1	2	3	1	2	3
July	1	2	3	-	2	3
August	-	2	3	-	-	3
September	-	-	3	-	-	3
October	-	-	3	-	-	3
November	-	-	3	-	-	3
December	-	-	3	-	-	3
January	-	2	3	-	2	3
February	-	2	3	-	2	3
March	-	2	3	-	2	3
April	-	2	3	1	2	3
May	-	2	3	–	–	–
June	-	2	3	–	–	–
July	-	2	3	–	–	–
August	-	2	3	–	–	–
September	-	2	3	–	–	–

Since no energy bills were available, energy consumption had to be indirectly estimated from the installed capacity of the motors powering the pumps and the frequency of irrigation, which implies knowing the water requirements of the crop, and preferably, how they change on a given time interval (or step), in accordance to the climate. This was the main motivation behind the previous sections.

That being said, for the original system, the results of energy consumption, E_i^o [MWh] given by equation 3.14, are presented in Table 3.14.

$$\mathrm{E}_i^o = P_i \times \mathrm{T}_i^o,\ i = \{2, 3\} \tag{3.14}$$

Table 3.14: Energy consumption for different pump arrangements with original net requirements.

Pumps	P_i [kW]	T_i^0 [hr]	E_i^0 [MWh]
2	180	3667.6	660.17
3	312	1776.8	554.36

Considering the results of Tables 3.12, energy consumption results, given by equation 3.15 for both types of agriculture practices are presented in Table 3.15.

$$E_i^{v/r} = P_i T_i^{v/r},\ i = \{2, 3\} \tag{3.15}$$

Table 3.15: Estimated monthly energy consumption for virgin and ratoon sugarcane.

	Virgin Cane		Ratoon Cane	
Month	E_2^v [MWh]	E_3^v [MWh]	E_2^r [MWh]	E_3^r [MWh]
June	27.12	22.77	27.12	22.77
July	31.82	26.71	37.97	31.88
August	54.01	45.34	68.85	57.80
September	73.32	61.55	80.55	67.62
October	83.65	70.21	83.64	70.21
November	73.74	61.89	73.74	61.89
December	72.62	60.96	72.62	60.96
January	42.97	36.07	42.87	36.07
February	40.72	34.18	38.57	32.38
March	51.52	43.25	35.09	29.46
April	46.73	39.23	5.95	4.99
May	50.36	42.27	–	–
June	43.47	36.49	–	–
July	44.12	37.04	–	–
August	51.67	43.37	–	–
September	34.30	28.79	–	–
Total	822.12	690.14	567.08	476.05

3.5 Energy Efficiency

As the load of the system may change, according to the number of pumps or sprinklers active at one time, so do P, Q and H, which actively demonstrates that the efficiency is not constant. For this reason, the operating point of the system, is given by the interception in the (H,Q) plane of the pump characteristic curve H = H(Q) with the cure that expresses the height in elevation of the installation as a function of Q [17].

However, as discussed before, the H-Q curves and the efficiency curve of the pumps are unknown. Assuming the system is working at the design point, (F) in Figure 3.12, the combined efficiency of the unit (pump + motor) can be roughly evaluated solely from P and Q, as expressed by equation 3.16.

$$\eta = \underbrace{\frac{\gamma}{H}}_{k} \frac{Q}{P} \tag{3.16}$$

Thus, if it can be assumed that both the fluid (hence γ), and the head of the installation H remain constant after the loss of the larger unit, that is, which is the same as saying that the system curve H_s in Figure 3.12 is horizontal and that point F moves to point B instead of F', the overall decrease in efficiency is given by equation 3.17.

$$\Delta\eta_{\,3\rightarrow 2} = \frac{\eta_3 - \eta_2}{\eta_3} = 1 - \frac{Q_2}{Q_3}\frac{P_3}{P_2} = 0.1597 \tag{3.17}$$

Alternatively, the impact on efficiency can be estimated by determining the relative decrease in energy consumption ΔE if the larger pump were to be repaired, as given by equation 3.18.

$$\Delta E_{\,2\rightarrow 3} = \frac{E_2^o - E_3^o}{E_2^o} = \frac{660.17 - 554.36}{660.17} = 0.1603 \tag{3.18}$$

Consequently, the failure of the larger pump has a deleterious effect on the annual costs, since it made it so that the arrangement with the 3 working delivered a higher value of flow per unity of power. This can be verified by comparing the efficiency of both arrangements. Referring to Table 3.10, a head (at the duty point) of P $= 600$ kPa can be converted to H $= 61.19$ meters head, and since the specific weight of water is $\gamma = \rho\, g = 9800$ N/m^3, the efficiency can be computed from equation 3.16.

$$\eta_2 = \frac{\gamma\, Q_2\, H}{P_2} = \frac{9800 \times 97.2 \times 10^{-3} \times 61.19}{90 \times 10^3} = 64.76\,\%$$
$$\eta_3 = \frac{\gamma\, Q_3\, H}{P_3} = \frac{9800 \times 401 \times 10^{-3} \times 61.19}{312 \times 10^3} = 77.07\,\%$$

With the larger pump knocked out, the remaining two need to work for a longer period to ensure the crop water requirements, and since these have a lower Q/P ratio, the energy expenditure increases if measures were put in place to compensate the loss of the larger pump. It is unknown how the association is dealing with the problem, although it is advisable to effectuate a repair.

3.6 Energy Costs

Since no consumption records are available, the estimation of energy costs can be performed assuming an agriculture tariff for monthly recorded consumption exceeding 500 kWh, Table 3.16. In the following, a current exchange rate of R = 0.013 is assumed when converting Metical (MT) to Euro (EUR).

Table 3.16: Presumed energy tariff. [Source: EDM]

Variable Tariff V_t		Fixed Tariff F_t	
[Mt/kWh]	[€/kWh]	[Mt/month]	[€/month]
6.39	0.0831	257.97	3.356

From the estimated energy consumption in the original scenario, Table 3.14, here converted to kWh, the estimated energy costs, C_i^0 €] can be obtained by equation 3.19 and are presented in Table 3.17.

$$C_i^o = R \times (V_t \times E_i^o \times 10^3 + 12 \times F_t),\;\; i = \{2, 3\} \tag{3.19}$$

Table 3.17: Energy cost for different pump arrangements with original net requirements.

Pumps	P_i [kW]	E_i^0 [MWh]	C_i^o [€]
2	180	660.17	54 881
3	312	554.36	46 091

If a distinction between crops is assumed and the results of Table 3.15 considered, the energy costs are computed from equation 3.20 and presented in Table 3.18.

$$C_i^{v/r} = R \times (V_t \times E_i^{v/r} \times 10^3 + n \times F_t),\ i = \{2, 3\} \tag{3.20}$$

where n is the duration of the crop cycle in months, 16 and 11 for virgin and ratoon cane practices, respectively.

Table 3.18: Monthly energy costs for virgin and ratoon practices.

	Virgin Cane		Ratoon Cane	
Month	C_2^v [€]	C_3^v [€]	C_2^r [€]	C_3^r [€]
June	2306.8	1945.1	2290.0	1928.3
July	2696.8	2272.4	3191.2	2684.8
August	4540.0	3819.8	5756.6	4838.3
September	6144.1	5166.4	6728.2	5654.0
October	7001.7	5886.3	6984.9	5869.5
November	6179.0	5195.7	6162.2	5178.9
December	6085.9	5117.5	6069.1	5100.7
January	3623.5	3050.4	3606.7	3033.6
February	3435.9	2892.9	3241.1	2726.7
March	4333.6	3646.5	2952.3	2484.3
April	3935.2	3312.1	531.2	451.9
May	4236.9	3565.3	–	–
June	3664.8	3085.1	–	–
July	3718.9	3130.5	–	–
August	4345.8	3656.8	–	–
September	2903.0	2445.6	–	–
Total	69 152	58 188	47 514	39 951

Without access to the energy bills for validation this is merely a reasonable and well-fitted guess. The costs are being estimated based on the assumption that the tariff adhered to is that for "low voltage agriculture". However, from [3], since in 2011 there were only 55 affiliated agriculture consumers based on EDM reports, this is unlikely.

In 2010, new legislation came into effect that introduced a medium voltage agriculture tariff, but given that the Macuvulane I plantation was built in 2005, five years prior, it is doubtful at best that an update on the equipment in order to accommodate a new voltage level (and new tariff) was performed.

3.7 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.

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

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

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

$$663 \times 0.6381\,\text{l/s} = 423\,\text{l/s} = 25380\,\text{l/min} = 1522800\,\text{l/h} = 18273600\,\text{l/cycle}$$

by the water pumps. Considering a worst case scenario, October for Virgin Cane, the 173.0686 should be delivered as:

$$\frac{187.9 \cdot 10^4 \times 173.0686}{18.2736 \cdot 10^6} = 17.76 cycles$$

where numerator means 'Total Water Necessary' and denominator means 'Water delivered per cycle'. Following the same logic, both tables 3.19 and 3.20 where filled up:

Since the plantation is divided in 4 parts, a circular and continuous irrigation allows it to perform this type of optimization, where in some months less water is delivered but in others, the excess of it, compensates it.

3.7.1 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.

Table 3.19: Cycles Otimization for Virgin Cane

Month	Gross Irrig. Req. [mm]	Cycles	Cycles (Rounding Up)	Cycles (Optimized)
June	56.1238	5.76	6	5
July	65.8367	6.76	7	6
August	111.7508	11.48	12	11
September	151.7068	15.56	16	15
October	173.0686	17.76	18	18
November	152.5759	15.64	16	15
December	150.2561	15.28	16	15
January	88.9202	9.12	10	9
February	84.2484	8.64	9	8
March	106.6086	10.96	11	11
April	96.6861	9.92	10	10
May	104.2007	10.68	11	10
June	89.9495	9.24	10	9
July	91.2967	9.4	10	9
August	106.9130	10.96	11	11
September	70.9752	7.28	8	7
Total	1701.1	167.04	181	169

Table 3.20: Cycles Otimization for Virgin Cane

Month	Gross Irrig. Req. [mm]	Cycles	Cycles (Rounding Up)	Cycles (Optimized)
June	56.1238	5.76	6	6
July	78.5702	8.08	9	8
August	142.4711	14.64	15	14
September	166.6738	17.12	18	17
October	173.0686	17.76	18	18
November	152.5759	15.68	16	16
December	150.2561	15.44	16	15
January	88.9202	9.12	10	9
February	79.8144	8.20	9	8
March	72.6196	7.44	8	8
April	12.3134	1.28	2	1
Total	1173.4	120.52	127	120

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, figure 3.13.

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:

$$\text{Total Power} = \frac{132}{0.956} + 90 \times 2 = 318\text{kW}$$

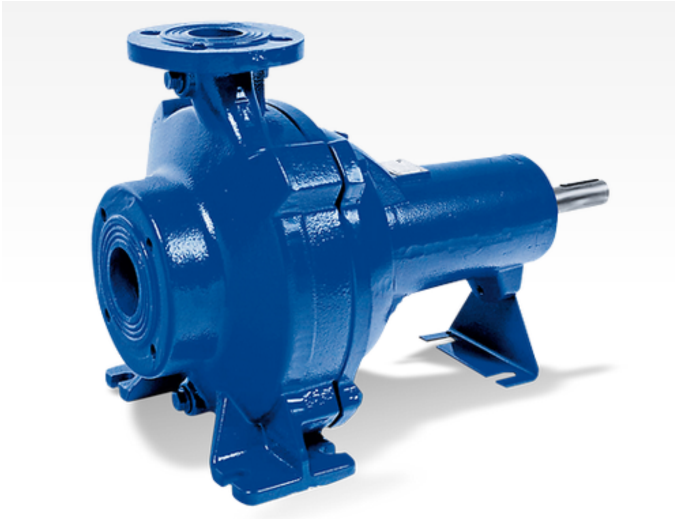

Figure 3.13: Sewatec K 200-402G 3EN 315M 04.

3.7.1.1 Spent Energy

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

Table 3.21: Energy Required for Virgin Cane Seasonal Irrigation

Month	Cycles (Optimized)	Energy Required [MWh]
June	5	19.080
July	6	22.896
August	11	41.976
September	15	57.240
October	18	68.688
November	15	57.240
December	15	57.240
January	9	34.344
February	8	30.528
March	11	41.976
April	10	38.160
May	10	38.160
June	9	34.344
July	9	34.344
August	11	41.976
September	7	26.71
Total	169	644.904

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 re-

Table 3.22: Energy Required for Ratoon Cane Seasonal Irrigation

Month	Cycles (Optimized)	Energy Required [MWh]
June	6	22.896
July	8	30.528
August	14	49.608
September	17	64.872
October	18	68.688
November	16	61.056
December	15	57.240
January	9	34.344
February	8	30.528
March	8	30.528
April	1	3.816
Total	120	457.920

peated 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 3.23.

Table 3.23: Energy Required for each month.

Month	Energy Required (MWh)
January	34.344
February	30.528
March	41.976
April	38.160
May	38.160
June	34.344
July	34.344
August	41.976
September	57.240
October	68.688
November	57.240
December	57.240
Total	534.24

Chapter 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.

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

4.1.1 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 *BlueSolar Monocrystalline*, represented in figure 4.2. Table 4.1 identifies the most relevant specifications of that panel, so are the P-U and U-I characteristic curves of the panel represented in the figure 4.1.

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) condi-

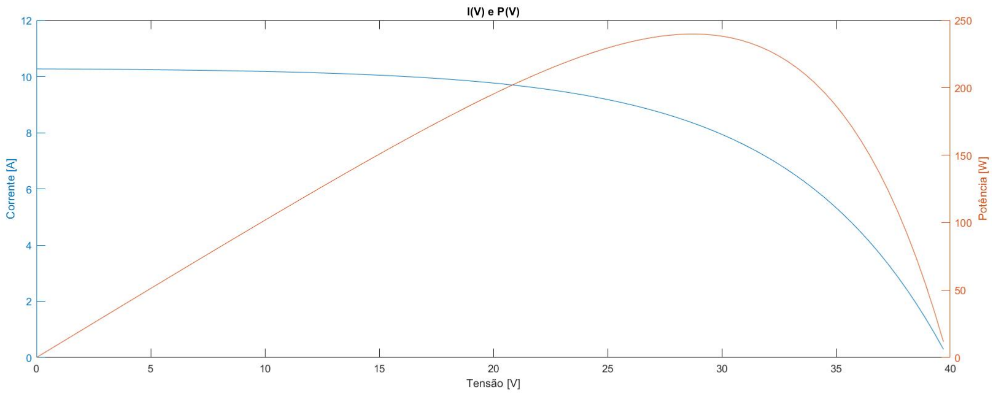

Figure 4.1: P-U and U-I curves characteristic of the *BlueSolar Monocrystalline solar panel.*

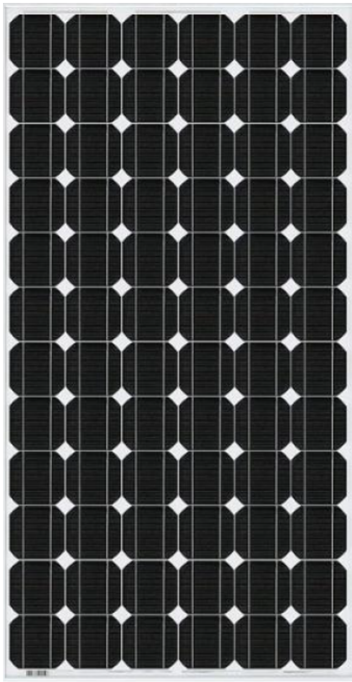

Figure 4.2: *BlueSolar Monocrystalline* 305W.

Table 4.1: Partial *Datasheet* of BlueSolar Monocrystalline.

BlueSolar Monocrystalline	
Net Weight	18kg
Nominal Power	305W
Nominal Power [NOCT]	225W
Nominal Power Coefficient [%]	-0.45/ºC
Max-Power Voltage	32.5V
Max-Power Current	9.38A
Open Circuit Voltage	39.7V
Short-Circuit Current	10.27A
Nr. of cells in series	60
Maximum System Voltage	1000V
Dimensions	1640×992×35mm

tions. These are standard operational conditions of solar cells which assume a 800 W/m^2, 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. After, the output power of 1 panel was calculated through the following equations:

$$T_{pan} = T_{amb} + TSI \times \frac{45 - 25}{800} \tag{4.1}$$

$$\Delta T = T_{pan} - 45 \tag{4.2}$$

With knowledge of the panel temperature, it is possible to determine the panel output power value. Through the equation 4.3, these values were determined for all hours of an entire year.

$$P_{out} = P_{MaxNOCT} \times \frac{TSI}{800} \times (1 - coef_{Pmax}) \times \Delta T \tag{4.3}$$

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), leading to the daily produced energy. Adding all the days of the month, the monthly energy data produced by a panel for each month is graphically displayed in the figure 4.3.

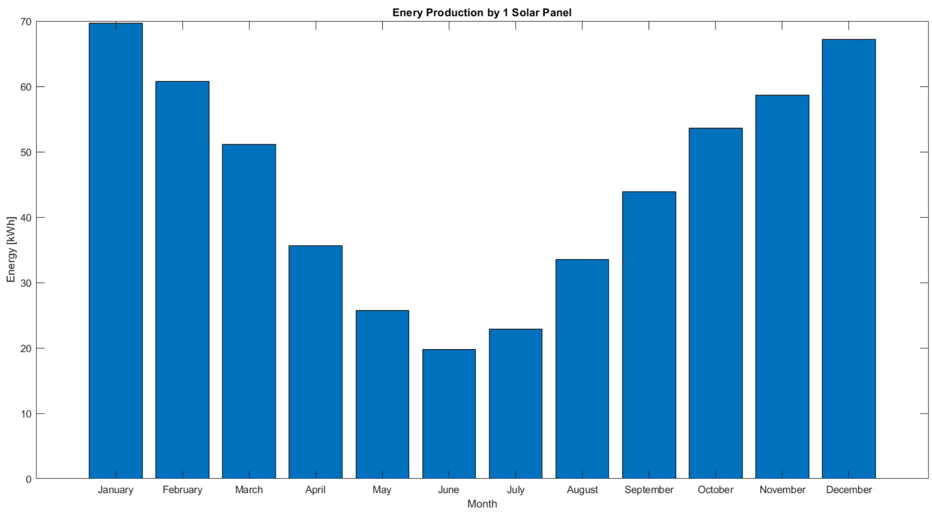

Figure 4.3: Energy produced by 1 panel every month.

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 payback 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 is chosen a modular assembly of inverters, exemplified in figure 4.4. This assembly makes it possible to divide the total number of panels into smaller groups, which becomes particularly advantageous since if there is a fail in a certain group of panels, it is possible not only to locate the problem, as the inverter has a monitoring function, but also to disable only that group, not compromising the other groups that can continue to producing normally. In addition, it allows a more varied range of inverters to choose from.

If only one inverter was used, it would have to support the voltage and current of a large number of panels, so it would have to be a very specific inverter since there is no a wide variety that supports such high voltages and currents. Microinverts were also an option, but for a high number of panels this choice is not practical, has higher cost and increased labour hours.

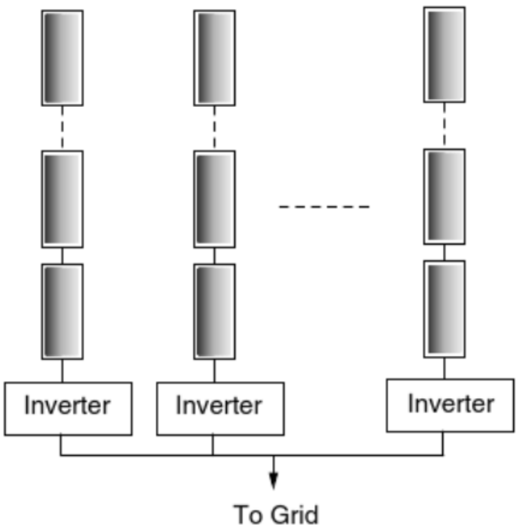

Figure 4.4: Modular assembly of inverters.

The size of the many groups of panels is dimensioned from the open circuit voltage, Voc, and short-circuit current, Isc, characteristic of these panels. For x panels in series, there is a corresponding voltage of $x \times Voc$. For x panels in parallel, there is a corresponding current of $x \times Isc$. For example, for a 5x5 panel group (5 rows of 5 panels), of Voc = 2V and Isc = 0.5A, the inverter must support $5 \times 2V = 10V$ voltage, and $5 \times 0.5A = 2.5A$ of current. Transposing this to the case study, it is necessary to divide all panels of Voc = 39.7V and Isc = 10.27A, into groups so that an inverter available in the South African market can support the total voltage and current of that group.

The market for inverters in South Africa was then analyzed, and it was concluded that inverters with

Figure 4.5: WEG inverter from the CFW11 range of 280 kW, 600V and 357A input.

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, represented in figure 4.5. Using this specific model, there is the possibility of grouping our panels in 3 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 inverter also has a built-in transformer, which reduces the output voltage and current, so that the pump can withstand them. The representation of the group is shown in Figure 4.6.

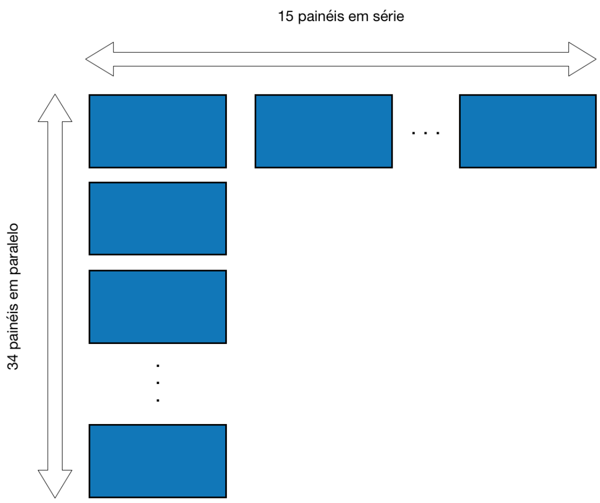

Figure 4.6: Group of 510 panels. 34x15

The area occupied by the groups of panels was also taken into account. Although there are doubts towards the question 'Where should we install the solar panels?', it was assumed the area represented on figure 4.7 belongs to Macuvulane and has no significant appliance. First, through *Google Maps*, the available terrain area was determined and marked in red down below.

Figure 4.7: Available area to install photovoltaic Panels.

It was estimated, through the scales provided in *Google Maps*, that the area highlighted is about 147300m^2.

Some estimates were made in order to determine the area occupied by the groups of panels. From [18] the ideal tilt of the panel is 29º. Knowing the dimensions of the panels, present in the table 4.1, and for the referred 29º inclination, it is possible to calculate for panels in series, through trigonometry, the horizontal extension, x, represented in the figure 4.8. It turns out that x = 1,43m. However, the panels have to be spaced apart, as if they are not, there is a risk of covering each other, reducing energy production. Thus, considering the worst case of solar inclination - 20º - it is possible to calculate the distance between panels in series, y, also represented in the figure 4.8, again using trigonometry. y = 2,17m was obtained. Therefore, it is concluded that the distance that each panel "occupies" when connected in series is x+y = 3,60m.

As for the distance between panels in parallel, it is known that it does not need to be as high as the distance between panels in series, and it is even advisable to be small, so it was considered to be 0,1m. Thus, the distance that each panel connected in parallel occupies is 0.992 + 0.1 = 1.092m. The representation of this distance is shown in the figure 4.9.

Finally, it is possible to determine the area each group occupies. The 34x15 groups occupy an area of $(15 \times 3.60 + 1.43) \times (34 \times 1.092 + 0.992)$ = 2113 m^2, which makes a total area of 6339m^2, much less than the 147300m^2 available, so there won't be any problems with the area of occupation of the panel groups.

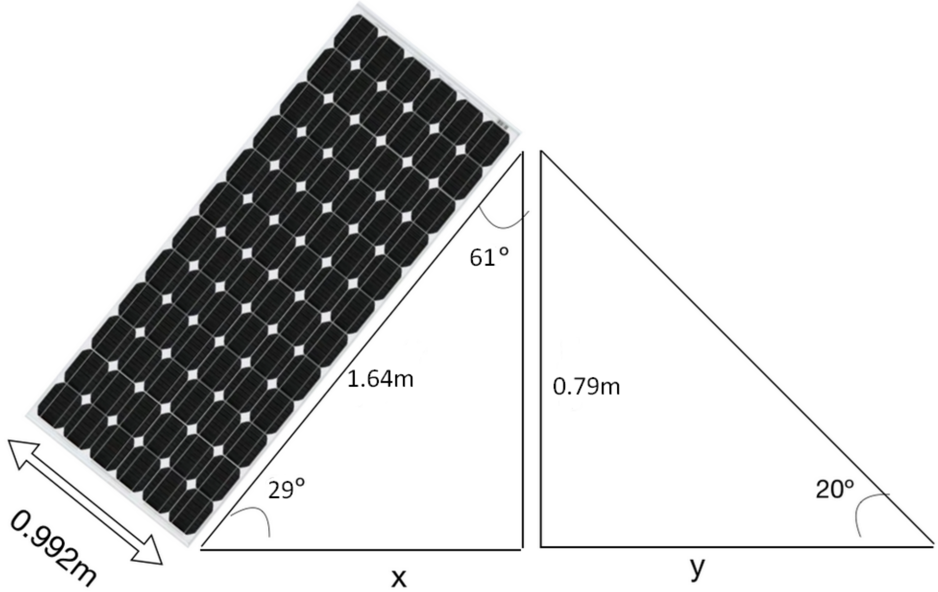

Figure 4.8: Representation of calculated distances and angles in order to determine the distance between panels in series.

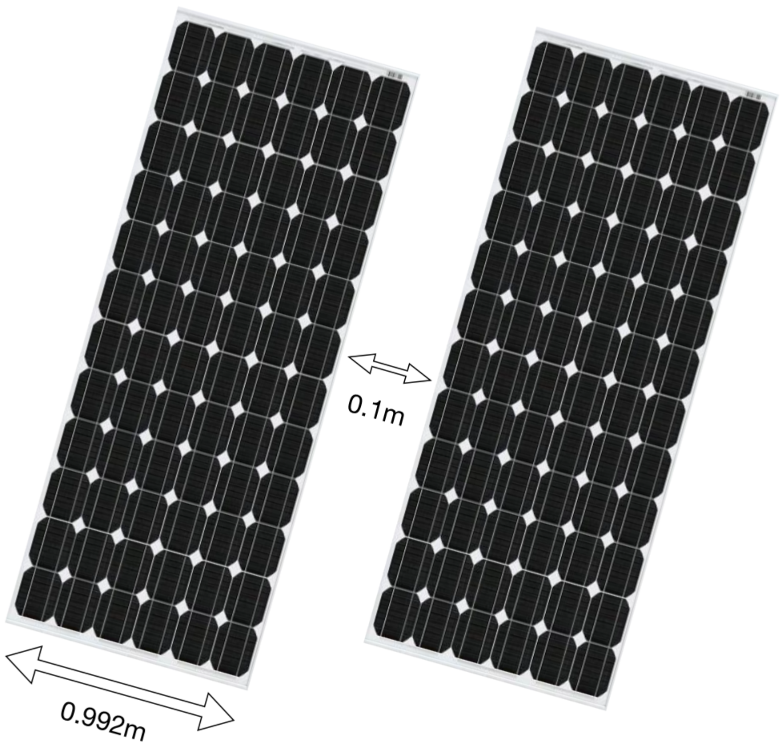

Figure 4.9: Representation of the distance between panels in parallel.

4.1.2 *AC Combiner Box*

The role of the combiner box is to bring the output of several solar strings together. It greatly simplifies the connection between series inverter and AC power distribution cabinet or boost transformer. Simple and clear internal structure make reasonable wiring. High reliability and simple maintenance.

In order to connect the 3 inverters to the electric grid, an *AC Combiner Box* is needed, which allows to combine the voltages and currents of these 3 inverters, in a single bus. The *AC Combiner Box* has yet another advantage - it introduces fuses for each of the connections, improving safety in case of a system short-circuit.

The *AC Combiner Box* chosen was a SolarBOS AC Combiner with 4 inputs, 600V and 400A maximum *input*, figured in 4.10. Even though only 3 buses are used, a fourth one might be useful if in the future there is the desire to introduce a new group of panels. With renewable energies evolving each day, this should always be considered as a possibility.

Figure 4.10: AC Combiner Box SolarBos with 4 inputs of 600V and 400A maximum.

4.1.3 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. Hot weather means high temperatures under the hood, which accelerates corrosion inside the battery, also causing water to evaporate out of the battery's liquid electrolyte. Decreased battery capacity, a weakened ability to start an engine and, ultimately, shorter battery life.

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.

4.1.4 Cabling

The cabling allows the connection between all the equipment used and referred to in the previous subsections. The cables required for the following connections were taken into account:

- Inter - panel;
- Panel - Inversor;
- Inversor - AC combiner;
- Panels - Ground.

It should be noted that it was considered that the connection to the electricity network is already assembled and operating in perfect condition. The inter-panel connection was estimated depending on the cable that was needed for the series connections and for the parallel connections. For the serial connection, it was assumed that the cable would travel, between 2 panels, the distance y of the figure 4.8, calculated previously, that is, $3(2.17 \times 15)m$. As for the parallel connection, it was considered that the amount of cable needed was the distance between panels in parallel, estimated at 0.1m (figure 4.9), $3(0.1 \times 34)$. The total value of the inter-panel connection results from the sum of the amount of cable in the series connection with the parallel connection: 107.85m.

As for the panel-inverter connection, it was assumed that it was short, in order to avoid energy losses, so it was decided to place the inverters 0.5m from the panels.

The inverter-AC combiner link was estimated to be the width of each group approximately 2.17×15, which makes 33m. Thus, the total value of the call is $33 \times 3 = 99m$.

As for the *grounding* of the panels, that is, the panels-ground connection, it was estimated by rows of panels (parallel), adding the width of each row to the length of 2 panels (beginning and end of the row). In figure 4.11, this estimate is explained visually. Note that only 3 panels are portrayed per representative facility.

It should be noted that, even though it's not the aim of this project, some future work might opt out on connecting the photovoltaic panels directly to the electric pumps, progressing towards a self-sustained system. Therefore, for the development of the current work, it's only required the connection between the panels and the inverters, given that the location of the electric grid is unknown, a group of 34x15 combines on a total of $34 \times 0.992 + 2 \times 1.64 + 3 \times 0.5 = 38.508m$.

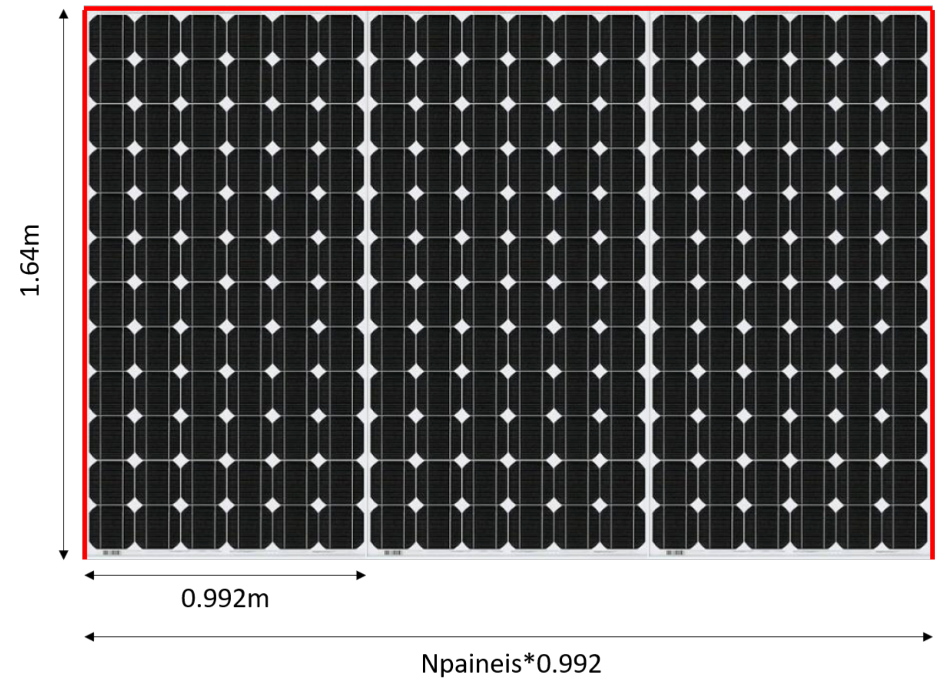

Figure 4.11: Representation of the estimated cable needed to connect panels to earth, in red.

Chapter 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 had to be made, for example:

- fixing a 12-month energy requirement, Table 3.23;
- 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

Bearing in mind what was mentioned above, the financial analysis is now carried out, which shows all the calculations made for 3 power supply situations for the system in question:

- **A** – 1 group of 34x15 (510 panels);
- **B** – 2 groups of 34x15 (1020 panels);
- **C** – 3 groups of 34x15 (1530 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. With equation 5.1, table 5.1 was fulfilled.

$$\text{Number of Panels} = \frac{\text{Required Energy}}{\text{Energy produced by 1 panel}} \tag{5.1}$$

Table 5.1: Estimated number of panels to fulfill each month.

Jan.	Feb.	Mar.	Apr.	May	June	July	August	Sept.	Oct.	Nov.	Dec.
494	503	815	1071	1485	1735	1499	1253	1353	1262	975	852

Although 1530 does not complete the required 1735, these 3 situations can demonstrate a good perspective of how the system evolves with the addition of solar panels.

Now, the parameters that will influence the respective monetary value for each dimensioning are highlighted:

Table 5.2: Price of needed material.

Panels (€/unit)	Inversors (€/unit)	Cables (€/m)	AC Combiner Box (€/unit)	New Pump (€/unit)
284.41	14112.26	17.69	590.90	18728.17

In order to carry out this balance, it is necessary to take into account both the electricity tariff in Mozambique with regard to the agricultural tariff for consumption above $500kWh$, as also for the sale price of energy, illustrated in the table 5.3, in accordance with Table 3.16.

Table 5.3: Mozambique Electric Energy Tariff, December 2020.

Agricultural Tariff (€/kWh)	Flat rate (€/month)	Sale price (€/kWh)
0.0831	3.356	0.040

Given the dimension of the proposed photovoltaic parks, and being recognized as one of the largest sugarcane plantations in Mozambique, it is expected that the return value of such investment will involve values in the tens of years.

All the factors, whether for investment in material, or for purchase and sale prices to the electricity network, the different cases can be duly analyzed. Once again, it should be noted that the values relative to irradiance are from PVGIS-SARAH database, which may cause fluctuations in sales from photovoltaic parks in subsequent years. The annual cost values will be fixed as an irrigation scheme was designed to optimize delivery, never compromising the water levels to be distributed during its production.

5.1.1 Scenario A

Scenario A is considered as the reference case: a group of 510 panels of the photovoltaic system sized so as to satisfy about 1/3 of the energy needs for the worst month of the year, which in this case is June.

With this, you have:

$$510 \text{ PV Panels} \times 284.41€ = 145049.1€$$

Using a single inverter, as mentioned in the section Photovoltaic Equipment, it's obtained:

$$1 \text{ inverter} \times 14112.16€ = 14112.16€ \tag{5.2}$$

Equation 5.2: Price of Inverters - A.

Then, for cabling, the necessary length was estimated to make the connection between the panels and the inverter. The length of cable needed to *grounding* the panels was also estimated. The different lengths are shown in the table 5.4.

Table 5.4: Estimated distances - A

Inter-panel (m)	Panel-Inverters (m)	Grounding (m)
35.95	0.5	37.01

That is, without the *grounding*, we get a total length of:

$$35.95 + 1 = 36.95\text{m}$$

Bearing in mind that the *grounding* of the panels is made with copper and that the price of copper is 4.49€/m, the cost of the cables is:

$$36.95\text{m} \times 17.69€ + 37.008\text{m} \times 4.49€ = 819,82€$$

Finally, the energy that can be sold and that must be purchased from the grid was calculated. Although there are questions about which type of sugarcane is cultivated, it is considered the 12 months that require the most energy, giving a better perspective of the annual income. These values can be checked in the table 5.5.

As referred before, the use of an *AC Combiner Box* is only taken into account when there's need to connect different inverters, which is not the case in study. In future work it remains an option, but right now it will continue not being considered.

In table 5.6, the values of the various parameters relating to the initial investment and the annual value of the energy balance are represented.

It can be noted that the cost of energy to be purchased includes a flat rate for each month ($3.77€\times 12$).

Table 5.5: Energy balance, respective cost and profit - A

	Energy to buy (MWh)	Cost (€)	Energy to be sold (MWh)	Balance (€)
January	34.344	2853.99	35.523	-1433.07
February	30.528	2536.88	31.016	-1296.24
March	41.976	3488.21	26.098	-2444.29
April	38.160	3171.10	18.187	-2443.62
May	38.160	3171.10	13.110	-2646.70
June	34.344	2853.99	10.092	-2450.31
July	34.344	2853.99	11.686	-2386.55
August	41.976	3488.21	17.088	-2804.69
September	57.240	4576.64	22.376	-3681.60
October	68.688	5707.97	27.361	-4613.53
November	57.240	4576.64	29.936	-3379.20
December	57.240	4576.64	34.266	-3206.00

Table 5.6: Financial parameters - A

Panels (€)	Inverters (€)	Cabling (€)	Water Pump (€)	Energy to buy (€)	Energy to be sold (€)
145049.10	14112.26	819.82	18728.17	43895.63	11069.56

This is also the case for the situations studied below.

To finish the study of situation A, the years of return on investment were calculated. In order to do that, the current annual electricity expenditure has to be included as part of the revenue, as it counts as a savings compared to today's value. This value is given by:

$$Rev = \sum_{January}^{December} \text{Estimated Sold Energy} \times 0.04 = 11069.56\text{€} \tag{5.3}$$

Equation 5.3 leads directly to equation 5.1.1.

$$\text{Payback Years} = \frac{\text{Investment}}{\text{Revenue}} = \frac{178709.35}{11069.56} = 16 \text{ years and } 2 \text{ months}$$

Based on the value of the return years obtained, it appears that this approach might be an appealing option.

5.1.2 Scenario B

For this second situation, the number of panels is doubled - 1020. With this, there's only an addition of 510 PV Panels and a new inverter. While testing and simulating groups of the same type, equations and methods are repeated. As expected, it will lead to duplicated values of produced energy, the main investment increases but since the water pump is already considered above, it is expected a reduction on the payback value. Therefore, it is obtained:

$$1020 \text{ panels} \times 284.41€ = 290098.20€$$

Now using only 2 inverters, the price is:

$$2 \text{ inverters} \times 14112.16€ = 28224.32€$$

As elaborated in the previous situation, the necessary cable length was estimated, and the values presented in the table 5.7 were obtained.

Table 5.7: Estimated distances - B

Inter-panel (m)	Panel-Inverters (m)	Grounding (m)
71.9	1	74.02

With these data, it is concluded that the cost of the cabling is in:

$$71.9\text{m} \times 17.69€ + 74.02\text{m} \times 4.49€ = 1604.26€$$

Once again, it's proceeded as in situation A: the energy that can be sold and that which needs to be bought from the grid is estimated. The results obtained are shown in the table 5.8

Table 5.8: Energy balance, respective cost and profit - B

	Energy to buy (MWh)	Cost (€)	Energy to be sold (MWh)	Balance (€)
January	34.344	2853.99	71.046	-12.15
February	30.528	2536.88	62.032	-55.60
March	41.976	3488.21	52.196	-1400.37
April	38.160	3171.10	36.374	-1716.14
May	38.160	3171.10	26.220	-2122.30
June	34.344	2853.99	20.184	-2046.63
July	34.344	2853.99	23.372	-1919.11
August	41.976	3488.21	34.176	-2121.17
September	57.240	4576.64	44.752	-2786.56
October	68.688	5707.97	54.722	-3519.09
November	57.240	4576.64	59.872	-2181.76
December	57.240	4576.64	68.532	-1835.36

In table 5.9, the values associated with the various parameters accounted for in the initial investment and the annual value of the energy balance are observed.

Table 5.9: Financial parameters - B

Panels (€)	Inverters (€)	Cabling (€)	Water Pump (€)	Energy to buy (€)	Energy to be sold (€)
290098.20	28224.32	1604.26	18728.17	43895.63	22139.12

With the help of equation (5.1.1), the return years are then calculated:

$$\text{Payback Years} = \frac{\text{Investment}}{\text{Revenue}} = \frac{338654.95}{22139.12} = 15 \text{ years and } 4 \text{ months}$$

With this, it is concluded that, despite being produced a larger value of energy, the investment tends to reduce in 7%. Seen this relation, a 3rd option does not have a need to be studied since it is expected the same return years as before.

5.1.3 Scenario C

The final experiment has a total of 1530. Adding once again a group of 510 panels and 1 inverter, the investment becomes a bit less than 3 times the main investment, while the sold energy is 3 times the one reached on Situation A. Repeatedly, all calculations are presented below:

$$1530 \text{ panels} \times 284.41€ = 435147.30€$$

$$3 \text{ inverters} \times 14112.16€ = 4236.48€$$

Not forgetting cabling, it's lengths are also reached.

Table 5.10: Estimated distances - C

Inter-panel (m)	Panel-Inverters (m)	Grounding (m)
107.85	1.5	111.03

Consuming a total price of cables around:

$$107.85\text{m} \times 17.69€ + 111.03\text{m} \times 4.49€ = 2406.3912€$$

As referred before, it is expected a sold energy 3 times greater than in Situation A, whilst the bought energy has no change. Table 5.11 relates to these calculations.

Table 5.11: Energy balance, respective cost and profit - C

	Energy to buy (MWh)	Cost (€)	Energy to be sold (MWh)	Balance (€)
January	34.344	2853.99	106.569	1408.77
February	30.528	2536.88	93.048	1185.04
March	41.976	3488.21	78.294	-356.45
April	38.160	3171.10	54.561	-988.66
May	38.160	3171.10	39.33	-1597.90
June	34.344	2853.99	30.276	-1642.95
July	34.344	2853.99	35.058	-1451.67
August	41.976	3488.21	51.264	-1437.65
September	57.240	4576.64	67.128	-1891.52
October	68.688	5707.97	82.083	-2424.65
November	57.240	4576.64	89.808	-984.32
December	57.240	4576.64	102.798	-464.72

In table 5.9, the values associated with the various parameters accounted for in the initial investment and the annual value of the energy balance are observed.

Table 5.12: Financial parameters - C

Panels (€)	Inverters (€)	Cabling (€)	Water Pump (€)	Energy to buy (€)	Energy to be sold (€)
435147.30	4236.48	2406.40	18728.17	43895.63	33208.68

Outreaching a total payback years of:

$$\text{Payback Years} = \frac{\text{Investment}}{\text{Revenue}} = \frac{460518.35}{33208.68} = 13 \text{ years and } 11 \text{ months}$$

Chapter 6

Results

In this chapter, results regarding the three test cases are presented. The problem is described, the steps are presented, the assumptions are stated and their impact on the results is discussed.

6.1 Problem Description

The present work is divided in the following steps:

- the case study is a sugar cane plantation with 187.9 ha in the district of Magude, Mozambique, controlled by a 200 people association;
- irrigation system composed by 3 pump/generator units connected to the national electric grid;
- irrigation is made by aspersion and sprinkler units are manually rotated by workers every 12 hours, with a total demand of 1366 mm/year;
- the costs incurring from irrigation are hardly affordable by farmer's association;
- a new, renewable self-supply system is needed to alleviate energy costs at first, and maybe even profit in the future;
- high values of irradiance through out the year are enticing to the introduction of a photovoltaic park;

6.2 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. Wheather 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 ocupied by Groups of Panels;
- 6. Economic Analysis: Inspection of 3 different types of investments while opting through a microgeneration solution;

6.3 Relevant Results

6.3.1 Water Requirements

Table 6.1 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 estimationswere normalized to the duration of 1 year.

Table 6.1: Water requirements for virgin sugar cane with plantation starting in June

Practice	ET_o[mm]	ET_c[mm]	P_t [mm]	P_e [mm]	I_N [mm]	I_G [mm]
Virgin	1768.2	1960.4	819.6	568.5	1391.8	1701.1
Ratton	1269.9	1449.3	819.6	489.3	960.1	1173.4

From Table 6.1, the average water requirement is 1360 mm/year, which is extremely close to the value presented on Table 3.10 (1366 mm/year), 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. The way it was designed in Tables 3.19 and 3.20, there is a considered slack of cycles for the process to be completed by the end of each month.

6.3.2 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 in Table 3.13 it is verified these 2 smaller pumps are 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 3.23.

6.4 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.

To sum up everything that has been stated so far, 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.

Chapter 7

Conclusions

7.1 Achievements

Following the Steps on Chapter 6.2, a variety of situations had to be overwhelmed.

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 Chapter 5. 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 straight forward 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 looked 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;

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Appendix A

Evapotranspiration

A.1 Reference Evapotranspiration (ET_o)

Evapotranspiration is a combination of two processes occurring simultaneously: evaporation and transpiration. In the former, water is lost from the soil surface through solar radiation, air temperature, air humidity and wind speed, whereas in the latter, water is predominantly lost through plant stomata [13]. These two processes occur simultaneously, however, since evaporation strongly depends on the fraction of radiation that reaches the soil, this process becomes less predominant in relation to transpiration, as the growing of the crop and the development of a larger canopy casts a broader shadow on the soil and the more canopy in a crop the more important transpiration will be.

The evapotranspiration rate is computed in relation to a reference surface, and is then called the reference evapotranspiration, ET_o, where the reference surface is a hypothetical grass reference crop with specific characteristics [13]. As mentioned before, E_o is only influenced by climatic parameters, thus it can be computed solely from weather data. Where this data is unavailable the guide provides procedures for estimating it.

A.1.1 Penman-Monteith combination Equation

The combination method, introduced by Penman in 1948, combined the energy balance with mass transfer to compute the evaporation from an open water surface from climatic records of sunshine, temperature, humidity and wind speed. Later this method was further extended by others by use of resistance factors that incorporate aerodynamic resistance, r_a manifested as friction from upward flowing air through vegetation, and surface resistance, r_s that accounts for the resistance to the flow of vapour through vegetation stomata openings, total leaf area and soil surface [13].

The Penman-Monteith combination equation is then:

$$\lambda \mathrm{ET} = \frac{\Delta(\mathrm{R_n} - \mathrm{G}) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{A.1}$$

where

$\mathrm{R_n}$: net radiation $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$

G : soil heat flux $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$

$e_s - e_a$: vapour pressure deficit of the air [kPa]

ρ_a : mean air density at constant pressure $[\mathrm{Kg}/\mathrm{m}^3]$

c_p : specific heat of the air [KJ/Kg]

Δ : slope of the saturation vapour pressure temperature relationship [kPa/° C]

γ : psychrometric constant [kPa/° C]

r_s : bulk (surface) resistance [s/m]

r_a : aerodynamic resistance [s/m]

For a grass reference surface, the aerodynamic and surface resistances are just

$$r_a = \frac{208}{u_2} \tag{A.2}$$

$$r_s = 70 \tag{A.3}$$

Substituting (A.2) and (A.3) in (A.1), it follows the FAO Penman-Monteith method to estimate $\mathrm{ET_o}$:

$$\mathrm{ET_o} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{A.4}$$

where

$\mathrm{ET_o}$: reference evapotranspiration [mm/day]

$\mathrm{R_n}$: net radiation at the crop surface $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$

G : soil heat flux density $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$

T : mean daily air temperature at 2 m height [° C]

u_2 : wind speed at 2 m height [m/s]

e_s : saturation vapour pressure [kPa]

e_a : actual vapour pressure [kPa]

$e_s - e_a$: vapour pressure deficit [kPa]

Δ : slope of the saturation vapour pressure temperature relationship [kPa/° C]

γ : psychrometric constant [kPa/° C]

The FAO Penman-Monteith Equation then requires data concerning air temperature, humidity, radiation and wind speed for the desired time-step calculations. Usually these are daily, weekly, ten-day or monthly calculations, but since the only directly available data is temperature - hourly monthly averages, as discussed before, the missing data will be estimated in accordance with the guide's instructions.

Location:

Table A.1: Location of the case study.

Latitude	Longitude	Altitude
25º01'S	32º41'E	26 m

Note: Data taken from google earth/google maps.

Temperature: The (average) daily maximum and minimum air temperatures are required:

Table A.2: Average daily maximum and minimum air temperatures by month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
T_{min} [° C]	23.02	23.20	22.14	19.91	17.31	15.43	14.70	15.96	18.47	19.93	21.19	22.46
T_{max} [° C]	30.46	31.69	30.44	28.29	27.54	25.89	25.14	26.86	29.14	29.55	30.01	30.79

Humidity: As for humidity, the (average) daily actual vapour pressure, e_a, in kilopascals (kPa) is required, but since this is not available, the guide says it can be derived from the dewpoint temperature (ºC). However, the dewpoint is also not available but, when missing, it can be assumed to be equal to the (average) daily minimum air temperature.

Radiation: In regard to the radiation factor, the (average) daily net radiation ($MJ.m^{-2}.day^{-1}$ is required, but when missing it can be derived from the daily (average) hours of sunshine.

Wind speed: The (average) daily wind speed ($m.s^{-1}$ measured at a height of 2 m is required, but when missing it can be assumed to be 2 meters per second.

Atmospheric Pressure (P)

The atmospheric pressure, P, is given by:

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \tag{A.5}$$

where z is the elevation above sea level [m].

For the location in question, z = 26 m results in P = 100.993 kPa.

Latent Heat of Vaporization (λ)

Over normal temperature ranges, λ remains fairly constant, and a value of 2.45 MJ/kg corresponding to an air temperature of approximately 20ºC is assumed.

$$\lambda = 2.45 \tag{A.6}$$

Pychrometric Constant (γ)

The psychrometric constant, γ, is given by:

$$\gamma = \frac{c_p P}{\epsilon \lambda} \tag{A.7}$$

where

- γ : pychrometric constant [kPa/° C]
- P : atmospheric pressure [kPa]
- λ : latent heat of vaporization [MJ/Kg]
- c_p : specific heat at constant pressure, $1.013\,10^{-3}$ [MJ/(Kg.° C)]
- ϵ : ratio molecular weight of water vapour/dry air $= 0.622$

For the previously determined value of P = 100.993 kPa, the psychrometric constant is $\gamma = 0.0671$ kPa/° C

Mean Air Temperature (T_{mean})

The FAO Penman-Monteith equation requires the mean daily air temperature (T_{mean}) to calculate the slope of the saturation vapour pressure curves (Δ) and to quote the guide, "for standardization, T_{mean} for 24-hour periods is defined as the mean of the daily maximum (T_{max}) and minimum temperatures (T_{min}) rather than as the average of hourly temperature measurements".

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \tag{A.8}$$

From Table A.2, the monthly average mean temperature is immediately obtained:

Table A.3: Daily average mean temperature by month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
T_{mean} [° C]	26.7400	27.4450	26.2900	24.1000	22.4250	20.6600	19.9200	21.4100	23.8050	24.7400	25.6000	26.6250

Mean Saturation Vapour Pressure (e_s)

Saturation vapour pressure can be calculated from air temperature with the relationship expressed by:

$$e^o(\mathsf{T}) = 0.6108\, e^{\left[\frac{17.27\,\mathsf{T}}{\mathsf{T}+237.3}\right]} \tag{A.9}$$

where

$e^o(\mathsf{T})$: saturation vapour pressure at air temperature T [kPa]
T : air temperature [° C]

The guide advises that "due to the non-linearity of the above equation, the mean saturation vapour pressure for (...) a month should be computed as the mean between the saturation vapour pressure at the mean daily maximum and minimum air temperatures for that period":

$$\mathsf{e_s} = \frac{e^o(\mathsf{T_{max}}) + e^o(\mathsf{T_{min}})}{2} \tag{A.10}$$

Again, considering Table A.2, this yields

Table A.4: Daily average mean saturation vapour pressure.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
e_s [kPa]	3.5846	3.7579	3.5090	3.0848	2.8280	2.5464	2.4335	2.6749	3.0820	3.2315	3.3808	3.5791

Slope of Saturation Vapour Pressure Curve (Δ)

At a given temperature, the slope of the curve is

$$\Delta = \frac{4098\left[0.6108\, e^{\left(\frac{17.27\,\mathsf{T}}{\mathsf{T}+237.3}\right)}\right]}{(\mathsf{T}+237.3)^2} \tag{A.11}$$

where

Δ : slope of the saturation curve at air temperature T [kPa/° C]
T : air temperature [° C]

In the FAO Penman-Monteith equation, the slope of the vapour pressure curve is computed using mean air temperature. Thus, from Table A.2 it follows that

Table A.5: Daily average slope of the saturation vapour pressure curve.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Δ [kPa/° C]	0.2064	0.2140	0.2017	0.1800	0.1648	0.1500	0.1441	0.1562	0.1773	0.1861	0.1946	0.2052

Actual Vapour Pressure (e_a) derived from dewpoint temperature

The actual vapour pressure (e_a) is the saturation vapour pressure at the dewpoint temperature (T_{dew}):

$$e_a = 0.6108\, e^{\left[\frac{17.27\, T_{dew}}{T_{dew}+237.3}\right]} \tag{A.12}$$

The dewpoint temperature is unknown, but it can be assumed to be equal to the (average) daily minimum temperature (T_{min}),

$$T_{dew} = T_{min} \tag{A.13}$$

Then, from Table A.2, it follows that

Table A.6: Monthly actual vapour pressure.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
e_a [kPa]	2.8128	2.8436	2.6666	2.3253	1.9761	1.7531	1.6727	1.8136	2.1258	2.3282	2.5162	2.7190

Vapour Pressure Deficit ($e_s - e_a$)

The difference between the saturation vapour pressure (e_s) and the actual vapour pressure (e_a) for a given time period is called the vapour pressure deficit. For periods such as a month e_s is computed from Equation A.10 using the T_{max} and T_{min} averaged over that time period. Similarly the e_a is computed with equation A.12, using average dewpoint temperatures over that period. Thus, from Tables A.4 and A.6, it follows that:

Table A.7: Daily average actual vapour pressure.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
$(e_s - e_a)$ [kPa]	0.7717	0.9143	0.8424	0.7595	0.8519	0.7933	0.7608	0.8613	0.9562	0.9033	0.8647	0.8601

Extraterrestrial Radiation for daily periods (R_a)

According to the guide, 'the extraterrestrial radiation, R_a, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year" by:

$$R_a = \frac{24\,(60)}{\pi}\, G_{sc}\, d_r\, [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \tag{A.14}$$

where

R_a : extraterrestrial radiation $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$
G_{sc} : solar constant $= 0.0820\, \mathrm{MJ}/(\mathrm{m}^2.\mathrm{min})$

d_r : inverse relative distance Earth-Sun

ω_s : sunset hour angle [rad]

φ : latitude [rad]

δ : solar declination [rad]

and with the inverse relative distance Earth-Sun, d_r, and the solar declination, δ, given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\,\pi}{365}J\right) \tag{A.15}$$

$$\delta = 0.409\sin\left(\frac{2\,\pi}{365}J - 1.39\right) \tag{A.16}$$

where J denotes the number of the day of the year and assumes values between 1 (1 January) and 365 or 366 (31 December).

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \tag{A.17}$$

Since the computation of ω_s, d_r and δ is performed on a daily basis, the extraterrestrial radiation R_a is also given on a daily basis, i.e., R_a is an array with 365 values.

Now, the previous discussed parameters that are required for the estimation of ET_o were computed on a monthly basis (because that is the imposed time step with the available data), and so, monthly averages for R_a were performed:

Table A.8: Monthly average extraterrestrial radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_a [MJ/(m^2.day)]	41.5469	38.1371	32.4134	26.4658	22.1987	21.4039	24.2853	29.8252	35.6907	40.3072	42.6700	43.1112

Daylight Hours (N)

The number of hours of daylight, N, is given by:

$$N = \frac{24}{\pi}\omega_s \tag{A.18}$$

where ω_s is given by equation A.17.

As before, this results in a array with 365 elements, so once more, monthly averages were performed:

Table A.9: Daily average daylight hours.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
N [h]	13.1415	12.5373	11.7685	11.0659	10.5579	10.4662	10.8314	11.4987	12.2439	12.9654	13.4473	13.5262

Solar Radiation (R_s) derived from air temperature differences

In the absence of solar radiation data, the Hargreaves' radiation formula, adjusted and validated at several weather stations in a variety of climate conditions, becomes:

$$R_s = k_{R_s} \sqrt{T_{max} - T_{min}}\, R_a \tag{A.19}$$

where

R_s : solar radiation $[MJ/(m^2.day)]$
T_{max} : maximum air temperature $[^\circ C]$
T_{min} : minimum air temperature $[^\circ C]$
k_{R_s} : adjustment coefficient $(0.16 .. 0.19)$ $[^\circ C^{-0.5}]$

The guide says that 'for interior locations, where land mass dominates and air masses are not strongly influenced by a large water body, $k_{R_s} \simeq 0.16$ and for coastal locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, $k_{R_s} \simeq 0.19$.' Given the location of Magude, it is reasonable to assume an intermediate value of $k_{R_s} = 0.175\,^\circ C^{-0.5}$.

It should also be noted that instead of using the determined daily extraterrestrial radiation values in the above formula, the average monthly values were used, yielding:

Table A.10: Daily average solar radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_s $[MJ/(m^2.day)]$	19.8318	19.4464	16.3419	13.4074	12.4252	12.1143	13.7319	17.2319	20.4021	21.8780	22.1766	21.7746

Clear-Sky Solar Radiation (R_{so})

"When calibrated values for a_s and b_s are not available", the equation to be used is:

$$R_{so} = (0.75 + 2\,10^{-5}\, z) R_a \tag{A.20}$$

where z is the elevation above sea level [m].

For monthly averages of the extraterrestrial solar radiation, R_a, it follows that

Table A.11: Daily average clear-sky solar radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_{so} [MJ/(m^2.day)]	31.1818	28.6227	24.3269	19.8631	16.6606	16.0641	18.2266	22.3844	26.7866	30.2514	32.0247	32.3559

Net Solar or Net Shortwave Radiation (R_{ns})

"The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:"

$$R_{ns} = (1 - \alpha R)_s \tag{A.21}$$

where α is the albedo or canopy reflexion coeeficient, which is 0.23 for the grass crop reference.

Table A.12: Daily average net solar radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_{ns} [MJ/(m^2.day)]	15.2705	14.9737	12.5833	10.3237	9.5674	9.3280	10.5736	13.2686	15.7096	16.8461	17.0760	16.7665

Net Longwave Radiation (R_{nl})

The net longwave radiation is given by:

$$R_{nl} = \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \tag{A.22}$$

where

σ : Stefan-Boltzmann constant $[4.903\, 10^{-9}$ MJ/(K^4.m^2.day)$]$
$T_{max,K}$: maximum absolute temperature during the 24-hour period [K]
$T_{min,K}$: minimum absolute temperature during the 24-hour period [K]
e_a : actual vapour pressure [kPa]
R_s : calculated solar radiation [MJ/(m^2.day)]
R_{so} : calculated clear-sky radiation [MJ/(m^2.day)]

From Tables A.2, A.6, A.10 and A.11, it follows that

Table A.13: Daily average net longwave radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_{nl} [MJ/(m^2.day)]	2.1240	2.3626	2.4482	2.7215	3.5265	3.7821	3.8427	3.8618	3.5209	3.0614	2.6976	2.4169

Net Radiation (R_n)

The difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation R_{nl}) is called the net radiation (R_n):

$$R_n = R_{ns} - R_{nl} \tag{A.23}$$

Table A.14: Daily average net radiation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
R_n [MJ/(m^2.day)]	13.1465	12.6111	10.1351	7.6022	6.0409	5.5459	6.7309	9.4068	12.1887	13.7847	14.3784	14.3496

Soil Heat Flux (G)

For monthly periods, the soil heat flux for a given month i is given by:

$$G_{month,i} = 0.07(T_{month,i+1} - T_{month,i-1}) \tag{A.24}$$

where it is assumed that the monthly average temperature for the month i = 0 is that of i = 12 (December) and in the same manner, the monthly average temperature for month i = 13 is that of month i = 1 (January), from which:

Table A.15: Daily average soil heat flux.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G [MJ/(m^2.day)]	0.0574	-0.0315	-0.2341	-0.2706	-0.2408	-0.1753	0.0525	0.2719	0.2331	0.1257	0.1319	0.0798

Wind Speed (u_2)

"Where no wind data is available within the region, a value of 2 m/s can be used as a temporary estimate."

$$u_2 = 2\,\text{m/s} \tag{A.25}$$

Estimated Reference Evapotranspiration (ET_o)

Plugging all previous information in equation A.4, it follows that

Table A.16: Estimated daily reference evapotranspiration from the Penman-Monteith equation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
ET_o [mm/day]	4.4281	4.5031	3.7949	3.0298	2.7769	2.5746	2.7503	3.4785	4.3234	4.6967	4.8183	4.8479

A.1.2 An Alternative Equation for ET_o when weather data is missing

In the absence of data on solar radiation, relative humidity and/or wind speed, the estimation of these parameters is performed using the procedures presented in the previous section in order to compute the ET_o from the Penman-Monteith equation.

Now, the ET_o is estimated using the Hargreaves ET_o equation:

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max - T_{min}})^{0.5} R_a \tag{A.26}$$

where all parameters have been previously defined.

So, taking the monthly average values of extraterrestrial solar radiation from Table A.8, it follows that

Table A.17: Estimated daily reference evapotranspiration from the alternative equation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
ET_o [mm/day]	4.7366	4.7180	3.8636	3.0124	2.6801	2.4984	2.7775	3.6231	4.5517	4.9906	5.1610	5.1871

A.2 Crop Evapotranspiration (ET_c)

The guide indicates a general procedure for calculating ET_c:

1) Compute ET_o
2) Select stage lengths (verified and supplemented locally)
3) Single crop coefficient, K_c
4) Select values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$
5) Adjust $K_{c\ ini}$ to reflect wetting frequency of soil surface
6) Adjust $K_{c\ mid}$ and $K_{c\ end}$ to local climatic conditions
7) Construct K_c curve
8) Determine $ET_c = K_c ET_o$

1) Computed ET_o

The reference evapotranspiration, ET_o was estimated by the Penman-Monteith equation and by the alternative Hargreaves equation:

Table A.18: Estimated daily reference evapotranspiration by two different methods.

ET_o [mm/day]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penman-Monteith	4.4281	4.5031	3.7949	3.0298	2.7769	2.5746	2.7503	3.4785	4.3234	4.6967	4.8183	4.8479
Hargreaves	4.7366	4.7180	3.8636	3.0124	2.6801	2.4984	2.7775	3.6231	4.5517	4.9906	5.1610	5.1871

It should be noted that the results from the Penman-Monteith equation, where the missing data was estimated, are more accurate than the alternative equation when missing data is not accounted for and instead only the extraterrestrial solar radiation is weighted in. In light of this, from now on, only the values obtained from the Penman-Monteith equation will be considered.

Although there are alternatives to the Penman-Monteith Equation, the later is reported as the most accurate and therefore widely used. So, while the FAO guide gives an alternative equation, for when weather data is missing - only uses temperature data -, the Penman-Monteith FAO method allowing for the use of approximate parameters is still more accurate in predicting the real water requirements of crops.

2) Stage Lengths

The guide provides a table with the lengths (in days) of crop development stages for various planting periods and climatic regions. As seen before, Magude is located at a latitude of 25ºS which puts it in the immediate vicinity of the south hemisphere tropic, and so, the following lengths were considered:

Table A.19: Assumed lengths (days) of crop development stages of sugar cane for Magude.

Practice	L_{inic}	L_{dev}	L_{mid}	L_{late}	L_{tot}
Virgin	50	70	220	140	480
Ratoon	30	50	180	60	320

3) Single Crop Coefficient (K_c)

The guide provides a table as a means of choosing the type of the coefficient approach. Since the time step assumed thus far is on a monthly basis and the purpose is to determine the average water requirements for irrigation, the choice must then fall for the single crop coefficient.

4) Selection of values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$

Similarly, the guide provides a table with the single (time-averaged) crop coefficients, Kc for use with the FAO Penman-Monteith ETo.

Table A.20: Sugar cane crop coefficients $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$.

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Sugar Cane	0.40	1.25	0.75

5) Adjustment of $K_{c\ ini}$ to wetting frequency

With an initial estimate for $K_{c\ ini}$ taken from the previous table, now the interval between wetting events must be estimated to properly adjust the value of $K_{c\ ini}$.

Wetting events can either refer to rainfall or irrigation. With regard to rainfall, which was discussed in previous sections, the only data available is the monthly averages. The frequency of rainy days or the interval between rains is unknown.

As for the irrigation events, from the infield specification data, we know the irrigation is made by sprinkler with the relevant data on the irrigation management taken from Table 3.10. Assuming the smallholders association follows the irrigation scheme as laid out by the project, then there are 35 cycles of irrigation per year, where each cycle lasts for 6 days with 12 hours a day as stated in the infield specifications.

Assuming the type of sugar cane planted has a lifecyle of exactly one year, then, for each crop planted, there are $35 \times 6 = 210$ days of irrigation and $365 - 210 = 155$ days with no irrigation occurs. And supposing that the cycles are equally apart, then, the interval between irrigation cycles is just

$$\frac{155}{34} \simeq 4.56 \text{ days}$$

Note: The species of sugar cane planted or even the agriculture practice (virgin/ratoon) is unknown, and so, one can only guess how long the duration of the crop actually is. However, from Table A.19, the total length of the culture is either 480 days $\simeq 1.3$ years for virgin cane or 320 days $\simeq 0.9$ years for ratoon cane). Direct conversation with the association could eliminate this uncertainty by allowing to better calibrate the lengths of crop development stages. Nevertheless, the values will be assumed as they are in the computations ahead.

Another important issue is the date of plantation of the crop, specifically the month, which varies greatly according to the type of cane or the mode of plantation (whole year cane, year and a half cane, winter cane, etc). The reason why this is so important is due to the frequency of raining and the type of the wetting event in question. The guide differentiates between 'Light wetting events (infiltration depths of 10 mm or less): rainfall and high frequency irrigation systems' and 'Heavy wetting events (infiltration depths of 40 mm or more): surface and sprinkler irrigation'. An inadequate choice between these may be detrimental to the correct calibration of $K_{c\ inic}$.

In this analysis it will be assumed that the plantation occurs before August. The latest satellite images from google earth, indicate that a new crop was planted and already irrigated (dark circles) before the beginning of August 2020 and no discernible culture was yet evident at this time. Again, for a better understanding of the crop management practices there should be a local correction of these parameters, namely through communication with the association, as the guide suggests, but one is limited to the available information.

From this discussion, and correlating with the monthly average precipitation for the months preceeding August, specifically May, June and July, which have the lowest (average) daily values of precipitation ($<$1 mm), one would have to assume light wetting events. On the other hand there is obviously irrigation by sprinkler, and with such low values of daily precipitation and naturally expected long periods between rains (for these months), it stands to reason the wetting is almost entirely assured by sprinkler irrigation, which would classify as a heavy wetting event. Again, without further information from the field, this is impossible to determine. For the time being, we will assume light wetting events during the initial stage of the sugar cane development.

Thus, for light wetting events, those between 3 and 10 mm per event, the adjustment of $K_{c\ inic}$ is performed graphically, in accordance with Figure A.1 adapted from the guide.

For the months in question, the ones where it is assumed that the plantation of a new crop might have occurred, May, June or July, the determined ET_o is within the interval $[2.57 - 2.78]$ mm/day. The interval between wetting events was determined to be around 4.56 days (if the infield specifications from the original design are followed).

Graphically, it will look something like this (roughly)

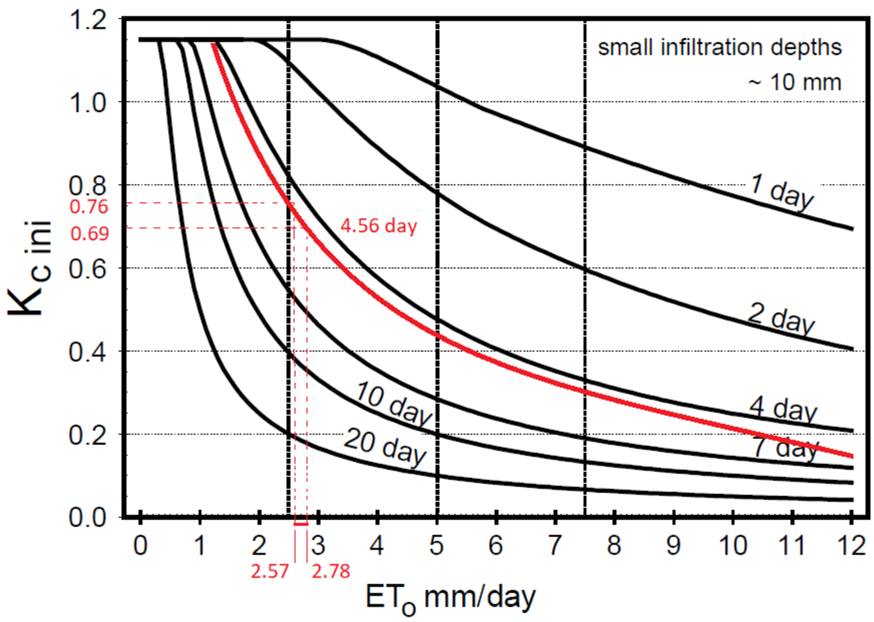

Figure A.1: Correction for $K_{c\ ini}$ under light wetting events and assumed irrigation time intervals.

Then, $K_{c\ ini}$ is between 0.69 and 0.76. The mean of these values is assumed: $K_{c\ ini} = 0.725$

In addition, wetting by sprinkler, as is the case at the Magude plantation, has a fraction f_w of soil surface wetted equal to 1, so no additional correction is necessary for $K_{c\ ini}$.

6) Adjustment of $K_{c\ mid}$ and $K_{c\ end}$ to local climatic conditions With no wind and humidity data available and without local information, is impossible to correct $K_{c\ mid}$ and $K_{c\ end}$.

7) Crop Coefficient Curve

In order to construct the crop coefficient curve, an annual crop will be assumed. The construction on the curve needs only three points, $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ and follows the steps described in the guide:

1) Divide the growing period into four growth stages that describe crop development (initial, crop development, mid-season, and late season), determine the lengths of the growth stages, and identify the three Kc values that correspond to $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$.

2) Adjust the Kc values to the frequency of wetting and/or climatic conditions of the growth stages.

3) Construct a curve by connecting straight line segments through each of the four growth stages. Horizontal lines are drawn through $K_{c\ ini}$ in the initial stage and through $K_{c\ mid}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\ inic}$ to $K_{c\ mid}$ within the course of the crop development stage and from $K_{c\ mid}$ to $K_{c\ end}$ within the course of the late season stage.

For virgin sugar cane, the curve obtained is

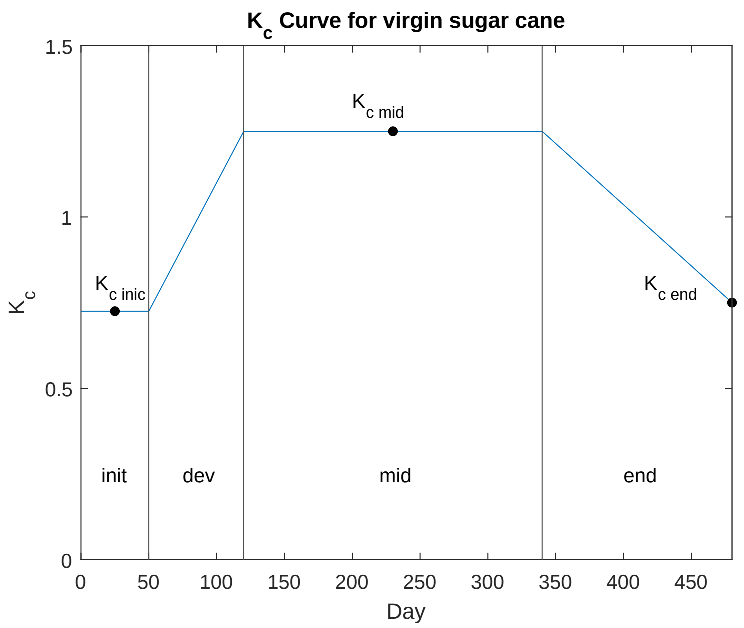

Figure A.2: K_c curve for virgin cane, assuming 480 days of crop cycle.

Whereas for ratoon sugar cane, the curve obtained is

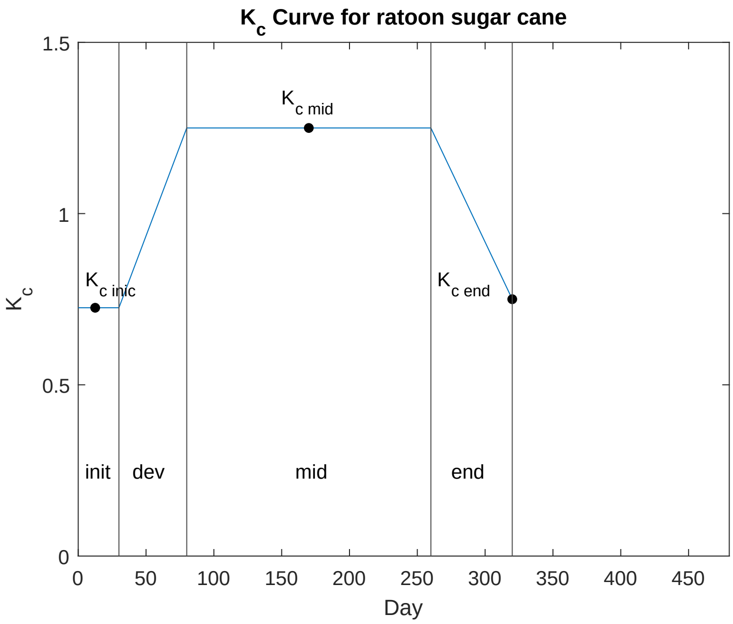

Figure A.3: K_c curve for ratoon cane, assuming 320 days of crop cycle.

8) Determination of ET_c

Given that the reference ETo was computed in a monthy time step, monthly values for Kc are necessary to compute ET_c. A general procedure is to construct the K_c curve, overlay the curve with the lengths of the months in question, and to derive graphically from the curve the K_c value for the period under consideration.

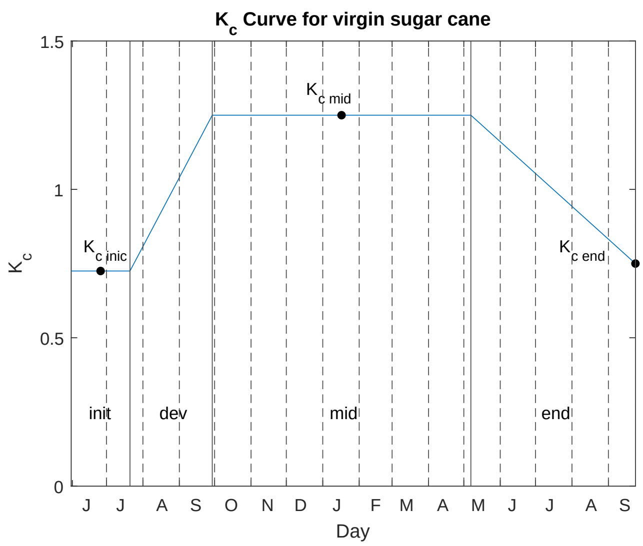

Figure A.4: K_c curve for virgin cane, assuming June as the commencement of crop cycle.

Previously it was assumed the plantation of the crop began somewhere between May and July. For the purpose of these computations let us assume the crop is usually planted in the beginning of June. This being the case, then the graph becomes that of Figure A.4.

Taking the values determined for the reference evapotranspiration, ET_o, and extracting the correspondent K_c for each month, results in

Table A.21: Estimated daily crop evapotranspiration by the crop coefficient method - virgin cane, plantation initiated in June.

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
ET_o [mm/day]	2.5746	2.7503	3.4785	4.3234	4.6967	4.8183	4.8479	4.4281	4.5031	3.7949	3.0298	2.7769	2.5746	2.7503	3.4785	4.3234
K_c	0.7250	0.7500	0.9375	1.1500	1.2500	1.2500	1.2500	1.2500	1.2500	1.2500	1.2500	1.2033	1.0917	1.0000	0.9000	0.8000
ET_c [mm/day]	1.8666	2.0627	3.2611	4.9719	5.8709	6.0229	6.0598	5.5351	5.6289	4.7436	3.7873	3.3414	2.8107	2.7503	3.1306	3.4587

Computing the monthly averages yields:

Table A.22: Estimated monthly crop evapotranspiration by the crop coefficient method - virgin cane, plantation initiated in June.

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
ET_c [mm/month]	55.9977	63.9436	101.0929	149.1562	181.9970	180.6875	187.8553	171.5871	157.6087	147.0514	113.6178	103.5837	84.3210	85.2581	97.0492	79.5500

This results in a total of 1960.4 mm/cycle.

The procedure for the ratoon cane is the same and the result is 1449.3 mm/cycle.