A solar energy resources assessment in Mozambique

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Abstract

Just as with other Southern African Development Community (SADC) countries, Mozambique faces severe, interrelated problems of energy and environment linked, with massive consumption of fuel wood biomass. The conventional power grid provides less than 7% of the energy needs for the country's 17 million inhabitants, and about 83% of the energy consumed in the country comes from biomass. Renewable energy resources can play an important role in the process of development of the country. From the vast renewable energy resources available in the country, solar energy represents one of those with the highest potential. Thus, the evaluation of the potential of solar energy systems in small-scale applications suitable for villages is a strategically good starting point for promotion of sustainable rural development. One of the major impediments in carrying out such studies is the fact that the exact behaviour of solar energy resources throughout the country has not been well studied. In this paper a general characterisation of the global, diffuse and direct solar radiation fields in Mozambique is presented. The study is based on experimental data measured by the National Institute of Meteorology (INAM) in the period 1970-2000. For these analyses global, diffuse and direct solar radiation data from three stations along the coast line and three stations in the interior of the country have been used. The six stations were representative of the three main regions of the country, namely south, centre and north. Furthermore, sunshine hours data of one selected station was analysed.

Keywords: solar energy, solar radiation components, resources assessment, southern Africa

1. Introduction

The region, where the member states of the Southern African Development Community (SADC) lie, is located between the latitudes 5° and 40° S, this means inside the 'Sunbelt' 40° north to 40° south. Therefore, one of the energy resources, which can contribute to the enhancement of sustainable development in the SADC region, is solar energy. Both active and passive use of solar energy has a role to play in sunny regions. The advantage of the solar option is that solar energy systems may be installed in isolated villages, without connections to a central electricity grid.

Another important advantage is linked with environmental issues: renewable energy systems do not cause many negative burdens to the environment, as compared with the conventional fossil fuel technologies. Mozambique specifically is situated between 10° and 26° of latitude south and thus has vast solar energy resources. Therefore, evaluation of the potential of solar energy systems in small-scale applications suitable for villages use is a strategically good starting point for promotion of a sustainable rural development.

One of the major impediments in carrying out such studies is that the exact behaviour of the solar energy resources throughout the country has not yet been well studied. This paper reports on a study of the behaviour of components of solar radiation, namely global, direct and diffuse, around the country. Also, the statistical variation of solar radiation is considered in one selected station. The study is based on data recorded by the National Institute of Meteorology (INAM) in stations spread over the country, in the period 1970 – 2000. This study is aimed at creating relevant data from which eventual works on assessment of potential of solar energy technologies can be based. Furthermore, results of this study are of use not only for energy purposes, but also in other applications like climatology and agriculture.

2. Methodology

The source of data for this work was the measurements of solar radiation and also of sunshine hours undertaken by INAM in different stations spread over the country. A 30-year period of data was used for all stations considered in this study, from 1970 to 2000, except for a few where data for shorter periods was available. Details of the methodology are presented in the following sections.

2.1 Global solar radiation

In terms of energy systems, global solar radiation is particularly important for designing flat plate collectors, both for photovoltaics and thermal applications. Global solar radiation can be determined either by direct measurement using pyranometers, or by estimation on the basis of sunshine hours, generally measured using Campbell Stokes equipment. In this study, the global solar radiation was measured by Pyranometer CM6B, from Kipp & Zonen.

2.1.1 Determination of monthly average daily solar radiation on a horizontal surface using daily total solar radiation measured data

For the stations recording daily total solar radiation, the methodology to determine the monthly average daily solar radiation on a horizontal surface consists in (Duffie and Beckman 1991):

(i) Organising the information in the form of a matrix of 30 years by 365 days;
(ii) Calculating the daily averages of total solar radiation for the 30 year period; and
(iii) Computing the averages of total solar radiation for each month.

2.1.2 Determination of monthly average daily solar radiation on a horizontal surface using daily total sunshine hours measured data

Equipment for measuring global solar radiation is much more expensive than that for recording sunshine hours. Therefore most radiation stations perform measurement of sunshine hours only. The estimation of global radiation from recorded sunshine hours consists of the following steps (Duffie and Beckman 1991):

(i) Organizing the information in the form of a matrix of 30 years by 365 days;
(ii) Determining the daily averages of bright sunshine hours for the 30 year period;
(iii) Computing the averages of bright sunshine hours for each month;
(iv) Using the Angstrom equation (modified by Page), to calculate the monthly average solar radiation on a horizontal surface $\bar{H}$ as:

$$\frac{\bar{H}}{\bar{H}_0} = a + b\frac{\bar{n}}{\bar{N}} \quad (1)$$

where $\bar{H}_0$ is the extraterrestrial radiation for the location, averaged over the time period in question. The climatic constants a and b represent parameters depending on location (see Section 3 and Table 1). The ratio between $\bar{H}$ and $\bar{H}_0$ is termed the monthly average clearness index. The symbols $\bar{n}$ and $\bar{N}$ represent the monthly average daily hours of bright sunshine andthe monthly average of the maximum possible daily hours of bright sunshine (i. e., the day length of the average day of the month), respectively.

Values of $\bar{H}_0$ can be calculated from the following equation, using recommended average days for months and values of n by months, according to (Duffie and Beckman, 1991):

$$H_0 = \frac{24\ X\ 3600\ G_{sc}}{\pi}\left(1 + 0.033\ \cos\frac{360\ n}{365}\right) \times\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (2)$$

Here G_{SC} is the solar constant, whose value is 1367 W/m^2; ϕ is the latitude of the place, δ its declination and n the day of the year; ω_s is the sunset hour angle, in degrees, given by:

$$\cos\omega_s = -\tan\phi\tan\delta \quad (3)$$

δ in its turn, which represents the angular position of the sun at solar noon (i. e. when the sun is on the local meridian) with respect to the plane of the equator, is given by the equation of Cooper:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \quad (4)$$

As the arccos function is not available in all computers languages, the sunset hour angle can be computed using the arctan function as follows:

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \quad (5)$$

where: $X = 1 - (\tan\phi)^2 \bullet (\tan\delta)^2$

2.2 Beam and diffuse components of solar radiation

Models for calculating beam and diffuse components of monthly solar radiation can be given as follows (Duffie and Beckman 1991):

For $\omega_s \leq 81.4°$ and $0.3 \leq \bar{K}_T \leq 0.8$

$$\frac{H_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\left(\bar{K}_T\right)^2 - 2.137\left(\bar{K}_T\right)^3 \quad (6a)$$

and for $\omega_s > 81.4°$ and $0.3 \leq \bar{K}_T \leq 0.8$

$$\frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\left(\bar{K}_T\right)^2 - 1.821\left(\bar{K}_T\right)^3 \quad (6b)$$

In these expressions, ω_s is the sunset hour angle, given by equation (3), $\bar{K}_T$ is the monthly average clearness index, which represents the ratio of monthly average daily radiation on a horizontal surface to the monthly average daily extraterrestrial radiation, or

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0}. \quad (7)$$

The monthly average daily solar radiation on a surface is a result of the sum of the monthly average daily direct or beam component and of the monthly average daily diffuse component:

$$\bar{H} = \bar{H}_b + \bar{H}_d \quad (8)$$

2.3 Determination of the statistical variation of solar radiation using sunshine hours

The statistical variation of sunshine hours must be known to evaluate the optimal thermal storage size and the need for a backup of any solar energy system, be it flat plate or concentrating. Here, it is important to determine the distribution of duration of daily sunshine hours, this means the identification of the number of days with no sun, with 1 hour of sun, with 2 hours of sun and so on. Also, the distribution of duration of periods with no sun is interesting. This exercise should be made for each of the 30 years comprising the period of analysis.

3. Climatic zones of the country

For the purposes of this study, it was important to divide the country into climatic zones. The climate in the region north of the Zambezi River (see Appendix 1) is under the influence of the equatorial low-pressure zone with a NE monsoon in the warm season (Ministry of Construction and Water 1987).

The climate in the region south of the Zambezi River is influenced by the subtropical anti-cyclonic zone. North Sofala and South Zambezia (see Appendix 2) lie in the transitional zone, with high rainfall figures. The rainfall is mainly restricted to the warm season between October/November and April.

According to the classification of Köppen (see Appendix 3), the northern and coastal regions (60%) have a tropical rain savanna climate (A_w). The inland parts of the central and southern sedimentary terrains (28%) have a dry savannah climate (BS_w). A small area around the border crossing of the Limpopo River (2%) has a dry desert climate (BW_w), whereas the upland areas (10%) have a humid temperate climate (C_w). Table 1 gives the climatic constants a and b, in accordance with equation (1), related to the climate zones mentioned here.

Table 1: Climatic constants for use in equation (1)

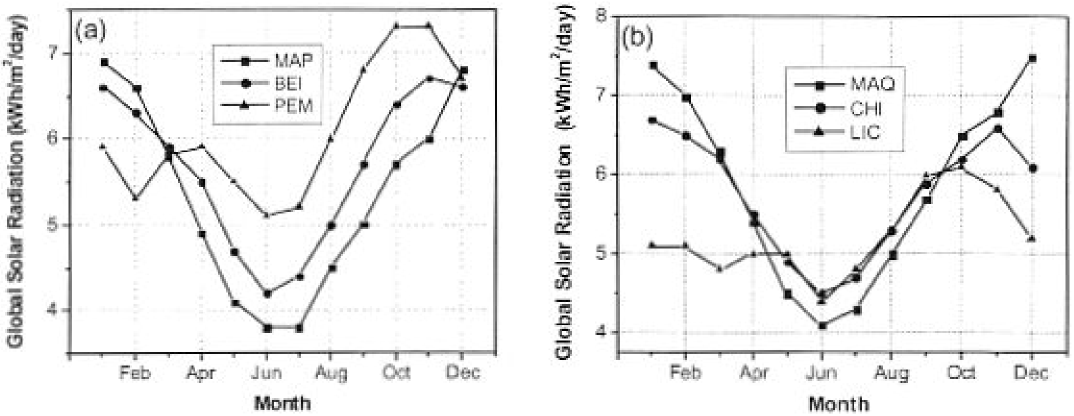
adapted from Duffie and Beckman (1991); Ministry of Construction and Water (1987)

Climate type	*a*	*b*
A_w	0.42	0.22
BS_w	0.41	0.37
BW_w	0.30	0.43
C_w	0.17	0.63

4. The INAM network of climatological stations

The National Institute of Meteorology (INAM) is a body responsible for recording climatological data in the country. The Institute started activities in 1910 and presently has a network of 288 climatological stations spread over the country (see Figure 1).

As far as measurements of solar radiation fields are concerned, INAM counts with 15 stations recording global radiation, from which 6 also record data on diffuse radiation. Additionally, there are 40 stations measuring sunshine hours.



Legend: MAP – Maputo, BEI – Beira, PEM – Pemba, MAQ – Maniquenique, CHI – Chimoio, LIC – Lichinga

Figure 1: Monthly variability of the global solar radiation: a) coastal stations and b) inland stations

5. Results

The aim of this study was to characterise the solar radiation throughout the country taking into account that global solar radiation is particularly important for designing flat plate collectors for both photovoltaic and thermal applications. Sunshine hours are important because they relate both to global and direct radiation, important parameters in designing solar energy systems. Additionally, sunshine hours give relevant information for sizing storage units for solar energy systems.

In the following sections, some important results of this study are presented.

5.1 Global radiation

The average global solar radiation data for three stations along the coast line and other three stations in the interior of the country, over a period of 30

Table 2: Global solar radiation averages taken for a period of 30 years measured in three stations along the coast of Mozambique (Maputo, Beira and Pemba) and another three stations inland of the country (Maniquenique, Chimoio and Lichinga)

	Maputo	*Beira*	*Pemba*	*Maniquenique*	*Chimoio*	*Lichinga*
Latitude	25° 58’	19° 48’	12° 59’	24° 44’	19° 07’	13° 18’
Longitude	32° 36’	34° 54’	40° 32’	33° 32’	32° 28’	35° 14’
Altitude	79m	39m	75m	58m	1,352m	729m
Global solar radiation (kWh/m²/day)						
January	6.9	6.6	5.9	7.4	6.7	5.1
February	6.6	6.3	5.3	7.0	6.5	5.1
March	5.8	5.9	5.8	6.3	6.2	4.8
April	4.9	5.5	5.9	5.4	5.5	5.0
May	4.1	4.7	5.5	4.5	4.9	5.0
June	3.8	4.2	5.1	4.1	4.5	4.4
July	3.8	4.4	5.2	4.3	4.7	4.8
August	4.5	5.0	6.0	5.0	5.3	5.3
September	5.0	5.7	6.8	5.7	5.9	6.0
October	5.7	6.4	7.3	6.5	6.2	6.1
November	6.0	6.7	7.3	6.8	6.6	5.8
December	6.8	6.6	6.7	7.5	6.1	5.2
Partial station averages	**5.3**	**5.7**	**6.0**	**5.9**	**5.8**	**5.2**
Country’s average:* 5.7						

* Country’s average means an arithmetic average of the six stations considered

Table 3: Beam component of solar radiation averages obtained from data of Table 2

	Beam component of solar radiation (kWh/m²/day)					
	Maputo	*Beira*	*Pemba*	*Maniquenique*	*Chimoio*	*Lichinga*
January	4.4	4.2	3.5	5.1	4.3	2.7
February	4.4	4.0	3.0	4.9	4.2	2.8
March	3.8	3.8	3.6	4.4	4.1	2.5
April	3.2	3.8	4.1	3.8	3.7	3.0
May	2.9	3.3	3.9	3.4	3.4	3.3
June	2.8	3.0	3.6	3.0	3.2	2.8
July	2.7	3.0	3.7	3.1	3.4	3.2
August	3.1	3.4	4.4	3.6	3.7	3.5
September	3.1	3.8	5.0	3.9	4.0	4.0
October	3.5	4.2	5.3	4.4	3.9	3.9
November	3.5	4.4	5.2	4.4	4.2	3.4
December	4.3	4.1	4.4	5.2	3.6	2.8
Partial station averages	**3.5**	**3.8**	**4.1**	**4.1**	**3.8**	**3.2**
Country's average	**3.8**					

Table 4: Diffuse component of solar radiation averages obtained from data of Table 2

	Diffuse component of solar radiation (kWh/m²/day)					
Months	*Maputo*	*Beira*	*Pemba*	*Maniquenique*	*Chimoio*	*Lichinga*
January	2.5	2.4	2.4	2.3	2.4	2.4
February	2.2	2.3	2.3	2.1	2.3	2.3
March	2.0	2.1	2.2	1.9	2.1	2.3
April	1.7	1.7	1.8	1.6	1.8	2.0
May	1.2	1.4	1.6	1.1	1.5	1.7
June	1.0	1.2	1.5	1.1	1.3	1.6
July	1.1	1.4	1.5	1.2	1.3	1.6
August	1.4	1.6	1.6	1.4	1.6	1.8
September	1.9	1.9	1.8	1.8	1.9	2.0
October	2.2	2.2	2.0	2.1	2.3	2.2
November	2.5	2.3	2.1	2.4	2.4	2.4
December	2.5	2.5	2.3	2.3	2.5	2.4
Partial station averages	**1.9**	**1.9**	**1.9**	**1.8**	**2.0**	**2.1**
Country's average: 1.9						

years, are summarized in Table 2. The location of these stations is shown in Appendix 1. Figure 1 illustrates the seasonal variation of the global solar radiation. The figure considers two situations, namely along the coast line and in the interior of the country. In each situation three cases are considered, namely the southern part of the country, between Save and Maputo Rivers, the central part, between Zambezi and Save Rivers, and last the northern part, between Rovuma and Zambezi Rivers.

Important conclusions can be drawn from the analysis of the data. In all stations, the global solar radiation values increase from winter to summer. The regularity of the distribution of the solar radiation resources decreases as one moves from south to north. It also decreases as one moves from the interior to the coast line, especially in the south. This is in accordance with the climate zones distribution referred to earlier.

The data also revealed that there is an increase of the value of the global solar radiation from south to north along the coast line. This was expected, as the radiation should increase as one moves to the equatorial line. Nevertheless, in the interior, there is a decrease of the value of global solar radiation as one moves from south to north.

The rainfall regime, which increases from south to north, is the one affecting the availability of solar radiation distribution in the interior. The highest val-

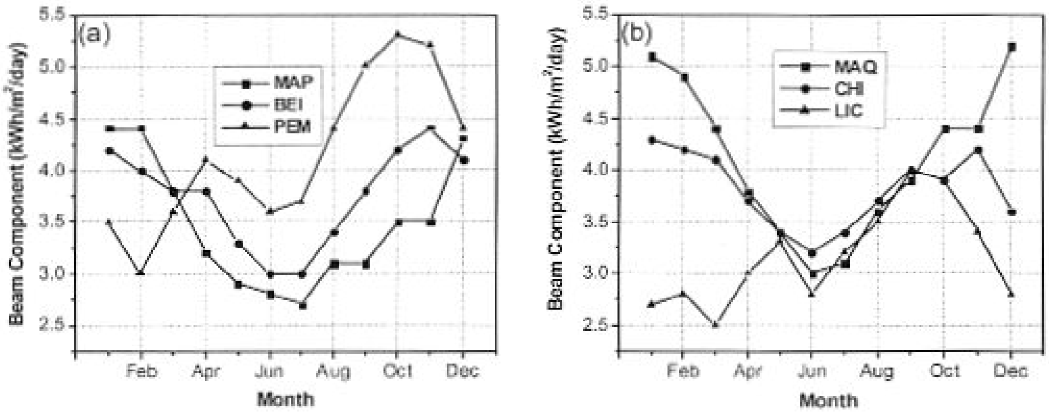


Figure 2: Monthly variability of the beam component of solar radiation for (a) coastal and (b) inland stations

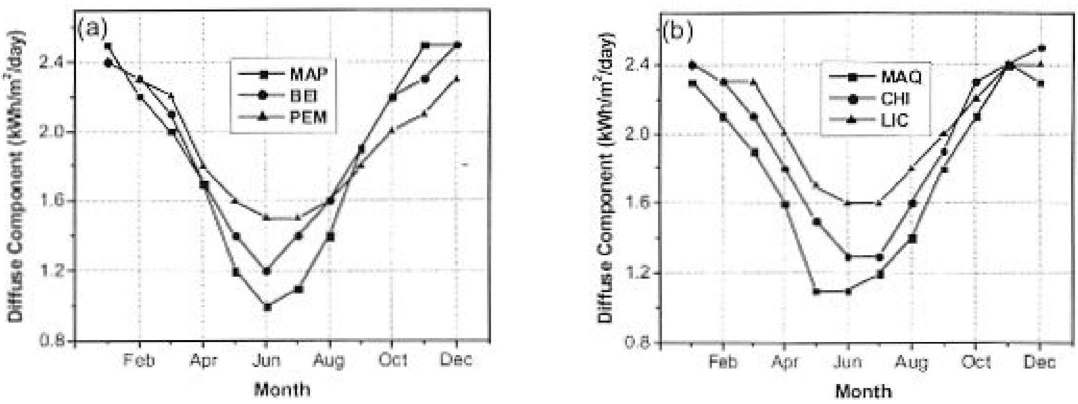


Figure 3: Monthly variability of the diffuse component of solar radiation for (a) coastal and (b) inland stations

ues of global solar radiation were observed in Maniquenique (24° 44'S) during December with a magnitude of 7.5 kWh/m^2/day, and the lowest in Maputo (25° 58'S) during June and July with a value of 3.8 kWh/m^2/day. The average of solar radiation in the country is of 5.7 kWh/m^2/day, with a minimum average of 5.2 kWh/m^2/day, registered in Lichinga, and the maximum average of 6.0 kWh/m^2/day, registered in Pemba. Maniqueninque has an average value of 5.9 kWh/m^2/day.

5.2 Beam and diffuse components of solar radiation

In this study, the beam and diffuse components of solar radiation were obtained by calculations applying formulas (6a), (6b) and (8) (see Appendix 4). As in the case of global radiation here the results in the graphs are displayed in groups of stations representing coastal line and inland stations, as well as the set of three stations in each group showing the three major regions of the country (south, centre and north regions). The general trend of the beam solar radiation is that its behaviour is more regular in the dry areas and its value is also higher in such regions.

Maniquenique station, for instance, displays the highest value of beam radiation of 4.1 kWh/m^2/day and the lowest value of diffuse radiation, of 1.8 kWh/m^2/day, while at Lichinga station, the same components measure 3.2 kWh/m^2/day and 2.1 kWh/m^2/day (see Figures 2 and 3 and Tables 3 and 4). This means in coastal areas and also in the central and northern parts of the country, the beam component is much influenced by the prevailing climatic conditions, like rainfall. Therefore, the scattering of the radiation is much more pronounced and thus, the corresponding diffuse component for these stations is higher.

5.3 Statistical variation of solar radiation

The Maputo station will be used for this analysis as an example, as it has detailed data of sunshine hours if compared with the others. The year of 1986 has been chosen for this analysis.

Table 5 shows the distribution of duration of daily sunshine hours for selected months. It considers 5 ranges of sunshine hours, namely the range from 0 to 3 hours, from 3 to 6 hours, from 6 to 9 hours, from 9 to 12 hours and the range of more than 12 hours, including the corresponding number of days falling in such ranges in each month. From the table, it is clear that the range 9 -12 hours registered the highest number of days, namely 21 days in March, 20 in June, 13 in September and December.

Table 5: Distribution of duration of daily sunshine hours for selected months observed at Maputo Station for the year 1986

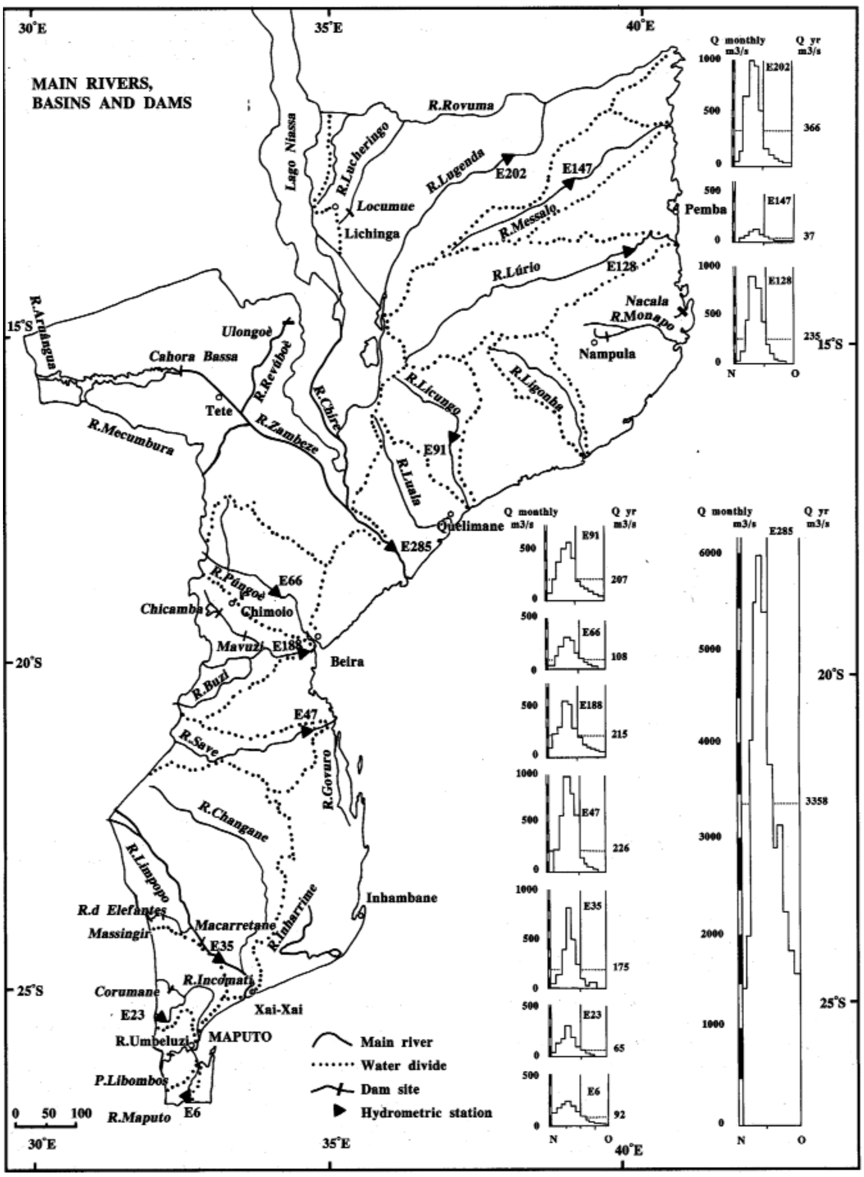
Hours range	*March (days)*	*June (days)*	*September (days)*	*December (days)*
0-3	3	1	4	4
3-6	3	2	5	4
6-9	4	7	8	4
9-12	21	20	13	13
>12	-	-	-	6

6. Conclusion

Although the work was based on data of limited accuracy and on a limited number of stations, but representative of the three main regions (namely Southern, Central and Northern) of the country, some important conclusions can nevertheless be drawn. The country has substantial solar energy resources. The global average is of 5.7 kWh/m^2/day, being the minimum average of 5.2 kWh/m^2/day, registered in Lichinga and the maximum 6.0 kWh/m^2/day, registered in Pemba. Maniquenique station, in the dry areas of the interior, registered an average of 5.9 kWh/m^2/day.

The data reveal that there is an evident increase of the value of the global solar radiation from south to north along the coast line. This was expected, as the radiation should increase as one moves to the equatorial line. Nevertheless, in the interior there is

Appendix 1: A map of Mozambique showing the main rivers



a decrease of the value of global solar radiation from south to north.

The rainfall regime, which increases from south to north, is the one affecting the availability of solar radiation distribution in the interior. The highest availability of beam solar radiation is found in the dry areas of the interior, being Maniquenique station as an example, with an average beam solar radiation of 4.1 kWh/m^2/day. The statistical discussion of the sunshine hours was restricted to Maputo station for the year 1986, and it has shown that in the majority of the days, the number of sunshine hours is above 6. This information is of importance in sizing solar energy systems.

Acknowledgements
The authors would like to acknowledge the financial support of the Swedish Agency SIDA/SAREC, the Norwegian Agency NUFU, and the UK Agency, British Council.

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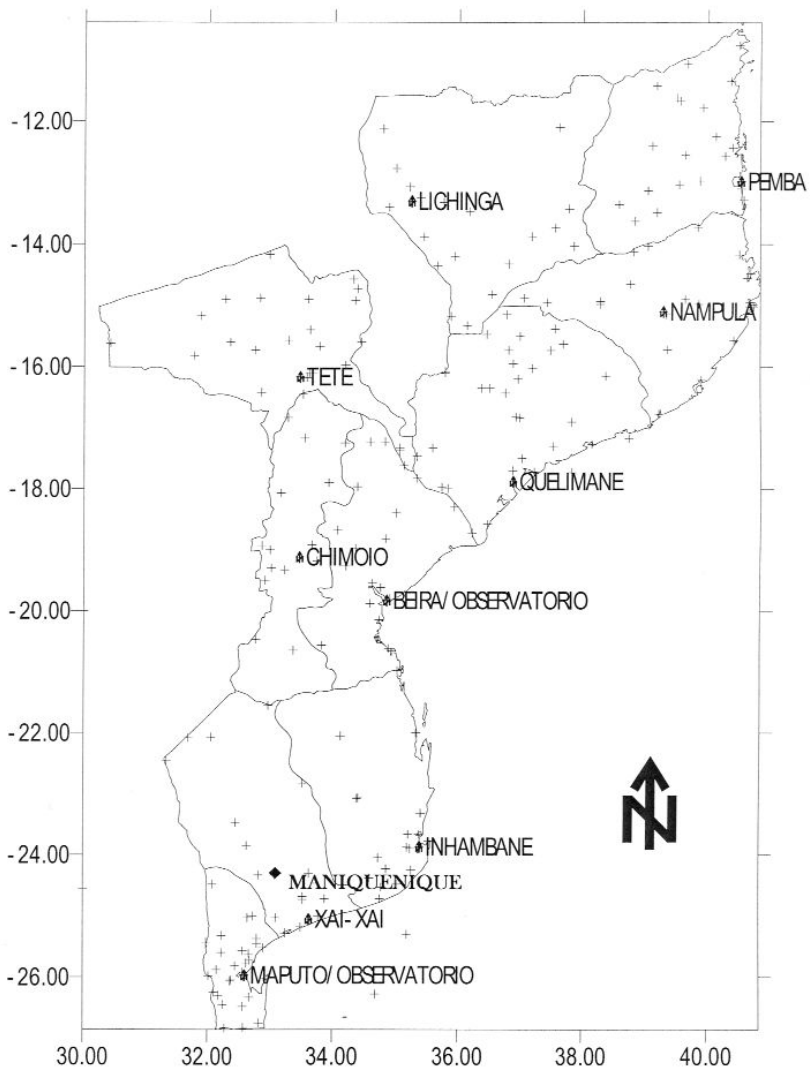
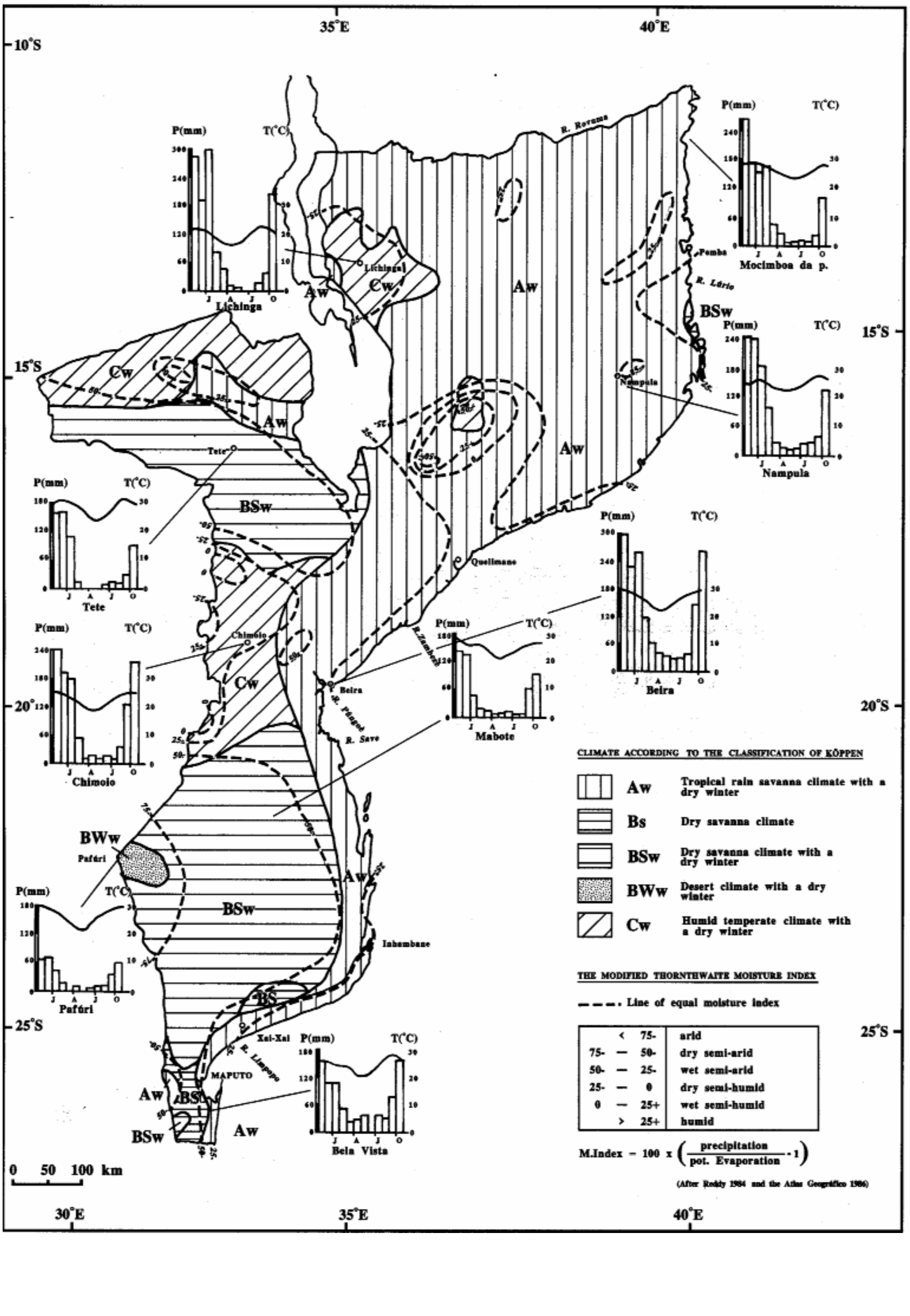
Received 1 February 2006 ; revised 16 June 2006

Appendix 2: A map of Mozambique showing the province capitals and the INAM climatological stations



Appendix 3: The climate of Mozambique after Köppen



Appendix 4: Tables of monthly average sunset hour angle and monthly average Clearness index calculated for coastal and inland stations

			Maputo		*Beira*		*Pemba*		*Maniquenique*		*Chimoio*		*Lichinga*	
	δ (°)	*n (dia)*	ω_s (°)	K_T	ω_s (°)	K_T	ω_s (°)	K_T	ω_s (°)	K_T	ω_s (°)	K_T	ω_s (°)	K_T
Jan	20.9	17	100.7	0.58	97.9	0.57	95.1	0.53	100.1	0.63	97.6	0.58	95.2	0.46
Feb	13.0	47	96.5	0.60	94.8	0.57	93.1	0.49	96.1	0.64	94.6	0.59	93.1	0.47
Mar	2.4	75	91.2	0.59	90.9	0.58	90.6	0.56	91.1	0.64	90.8	0.60	90.6	0.46
Apr	-9.4	105	85.4	0.60	86.6	0.63	87.8	0.63	85.6	0.65	86.7	0.62	87.8	0.53
May	-18.8	135	80.5	0.62	83	0.64	85.5	0.66	81.0	0.66	83.2	0.64	85.4	0.60
June	-23.1	162	78.0	0.64	81.2	0.62	84.4	0.66	78.7	0.68	81.5	0.65	84.2	0.57
July	-21.2	198	79.1	0.62	82	0.63	84.9	0.66	79.7	0.68	82.3	0.66	84.7	0.61
Aug	-13.5	228	83.3	0.62	85.0	0.62	86.8	0.68	83.7	0.67	85.2	0.65	86.8	0.60
Sept	-2.2	258	88.9	0.56	89.2	0.60	89.5	0.69	89.0	0.62	89.2	0.61	89.5	0.61
Oct	9.6	288	94.7	0.55	93.5	0.60	92.2	0.68	94.5	0.61	93.4	0.57	92.3	0.57
Nov	18.9	318	99.6	0.52	97.1	0.59	94.5	0.66	99.1	0.59	96.8	0.57	94.6	0.52
Dec	23.0	344	101.9	0.57	98.8	0.56	95.6	0.60	101.3	0.63	98.5	0.52	95.8	0.46