Title:
TECHNO-ECONOMIC ASSESSMENT OF HYBRID SOLAR ENERGY FOR RESIDENTIAL APPLICATION IN MOZAMBIQUE

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DECLARATION

I hereby declare that the following dissertation is entirely my own work and has not been submitted, in whole or in part, for any award to any other academic institution.

Signed........................................................................................................................................
Date.............................................................................................................................................
DEDICATION

To my parents Jaime Hacalane Tamele and Regina Filipe Uamusse who I know would be very proud of me today. I wish they were on this world to see this moment. I would like to thank them for all they did for me.

And

To my wife Penina Alfredo Dava, and my daughters Saligência da Regina Victor Tamele, Derma Victor Tamele, Eucilene da Justina Victor Tamele and my son Victor Jaime Tamele Junior for being my source of inspiration and motivation, I will love you forever.
ACKNOWLEDGEMENTS

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The thanks are also to the coordinators of the Distance Sustainable Energy Engineering (DSEE) Master Course at UEM Dr Carlos Lucas and Dr Geraldo Nhumaio for their dedication in coordinating the course. They have spent their time discussing and bringing solutions to our problems.

I extremely appreciate the DSEE students based at UEM, Mozambique Center, for the time we had together, especially Andre Fenias Moiane and Armando Abacar for their invaluable comments and advices to improve this dissertation.

Finally my family is to be thanked for their valuable support, advices and encouragement.
ABSTRACT

In Mozambique many areas are not connected to the national grid because of financial reasons. The renewable energy technology is adequate as a solution for this problem because it would avoid the environmental impact and the increase of air pollution. Hence, the techno-economic assessment of hybrid solar energy was performed for residential application considering a small community of 50 households, each consuming about 1 kWh_{e} and 3 kWh_{th} per day. HOMER, the energy modeling software for hybrid renewable energy system (HRES), was used for reaching this objective.

The techno economic study of a domestic hot water system was performed using RETscreen as HOMER could not be used since it does not model solar collectors.
To model the PV system using HOMER software, the load and the solar resource were assessed, considering the economics, system components, optimization and sensitivity analysis, which enabled the determination of the optimal system configuration and evaluation of how the system is sensitive with different values of primary load, global solar, interest rate and project lifetime.

As the result, the maximum power of the collector was found to be 1.93 kW, hot water storage volume of 138.1 l and 3.05 m² flat plate collectors. The pre-tax IRR – assets is of 14.5%, the simple payback period is of 8.6 years to return the investment and the 7.4 years of equity payback.

The PV system with the optimal system configuration consisting of a 0.3 kW PV array, 4 HI-Fase 200 Ah batteries and a 0.5 kW converter. The initial capital for PV system is of $3.945, operating cost of $82 per year, levelized COE of $1.604/kWh and the total NPC is $4.591.

The sensitivity analysis for PV system has shown that the best estimate scenario with a primary load of 1 kWh/d, global solar of 4.5 kWh/m²/d, interest rate of 11% and 25 years project lifetime is 0.4 kW PV, 4 HI-Fase 200 Ah batteries and 0.5 kW converter.

**Keywords**: Hybrid solar panel, Cogeneration, Residence, HOMER.
# ACRONYMS AND ABBREVIATIONS

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<tr>
<th>AC</th>
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<td>COE</td>
<td>Cost of energy</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed generation</td>
</tr>
<tr>
<td>EMASP</td>
<td>The energy sector management assistance program</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<td>GW</td>
<td>Gigawatt</td>
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<tr>
<td>HTF</td>
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<td>Hot Water Demand</td>
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<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
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<td>Kilowatt Hour</td>
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<td>Royal Institute of Technology</td>
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<td>MW</td>
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<td>NPC</td>
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<tr>
<td>NREL</td>
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<td>PP</td>
<td>Power plant</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<td>RE</td>
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</tr>
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<td>ROI</td>
<td>Return on Investment</td>
</tr>
<tr>
<td>SE</td>
<td>Solar energy</td>
</tr>
<tr>
<td>TPV</td>
<td>Thermal PV</td>
</tr>
<tr>
<td>UEM</td>
<td>Universidade Eduardo Mondlane</td>
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<tr>
<td>UNEP</td>
<td>United Nations Environment Programme</td>
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</table>
SYMBOLS

$A_c$  Collector area

$b_o$  Indicates the dependence of the incidence angle $\theta_b$

$F'$  Collector efficiency factor

$F''$  Collector flow factor

$F_R$  Heat removal factor

$G_{sc}$  Solar constant

$H_o$  Daily extraterrestrial radiation on horizontal surface

$\bar{H}$  Monthly average extraterrestrial daily solar radiation on horizontal surface

$K_T$  Clearness index

$K_{\tau a}$  Incident angle modifier

$N$  Days of the year

$Q_s$  Useful one cycle capacity of a water tank

$Q_u$  Useful energy

$R_F$  Collector's heat removal factor

$S$  Absorbed energy per m$^2$ absorber area

$T_a$  Ambient temperature

$T_i$  Inlet water temperature

$T_p$  Temperature of absorber plate

$T_{pm}$  Absorber surface's average temperature

$U_L$  Heat loss coefficient

$V$  Voltage

$\Delta$  Declination

$H$  Efficiency of solar collector

$\eta_i$  Collector instantaneous efficiency

$\theta_b$  Incident angle

$\psi$  Latitude of the site
<table>
<thead>
<tr>
<th>%</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔT</td>
<td>Temperature range</td>
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</table>
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CHAPTER 1

1. INTRODUCTION

In developing countries like Mozambique many areas are not connected to the national grid because of lack of financial resources. So, it is necessary to find solution for this problem that affects the development of these countries. The use of small scale conventional power generation such as diesel engines would have direct environmental impact and increase air pollution. A logical solution to mitigate greenhouse gas (GHG) emission is the deployment of renewable energy (RE) such as wind and solar power. These are clean indigenous sources of energy.

Solar energy (SE) is a promising technology for power and heat generation suitable to be applied in residence, particularly in remote locations such as islands, oasis and isolated villages in forests in Africa. It is abundant renewable source, widely distributed, with zero greenhouse gas emissions.

Hybrid Thermal PV (TPV) is a promising technology for the cogeneration of power and heat suitable for residential applications. Solar energy can be captured by two types of solar panels. One type is the heating panels, which absorb solar energy and transfer it into heat, while the second type, PV-panels can transform the solar energy directly into electricity. The two types are produced by two totally different technologies and a combination of the two types yields what is normally known as hybrid TPV.
The solar heating systems are the most popular form of solar energy and can provide major part of hot water and heating requirements of residential buildings over the year. Solar panels, however, have efficiency in the range of 10-15% and need to be cost-effective for commercial applications.

Deployment of small-scaled hybrid solar arrays, particularly, in urban areas is getting more attractive, since it can provide a substantial amount of heat and electricity required for residential demands.

The project consist of performing a tecn-o-economic assessment of hybrid solar energy for residential application in Mozambique considering a small community of 50 households, each consuming about 1 kWh\textsubscript{e} and 3 kWh\textsubscript{th} per day.

1.1. Statement of the Problem

Along the coast of Mozambique many tourist settlements are developed, but power is in general a problem and in many remote areas the electricity grid is not available due to the fact that its installation is not feasible because of the limited number of inhabitants and scarce financial resources.

1.2. Objectives

1.2.1. Main Objective

The aim of this project is to perform a tecn-o-economic assessment of hybrid solar energy for residential application in Mozambique for a small community of 50 households; each consuming about 1 kWh\textsubscript{e} and 3 kWh\textsubscript{th} per day.
1.2.2. Specific Objectives

Listed above are the project specific objectives:

- to evaluate the solar energy potential in the selected site;
- to estimate the electricity and heat load demand based on a household model;
- to configure the hybrid solar system to meet estimated load demand using different scenarios;
- to optimize the hybrid solar system or the proposed scenarios based on economic grounds;
- to define the parameters to be used in the RETScreen software analysis;
- to determine the characteristic of solar water heating system using RETScreen;
- to perform the financial analysis of solar water heating system using RETScreen;
- to evaluate the total cost and assess the economic feasibility of the conceived hybrid solar system.

1.3. Justification

Hybrid renewable energy systems (HRES) are becoming popular for remote area power generation applications due to advances in renewable energy technologies and subsequent rise in prices of products from petroleum. Economic related issues of these technologies are sufficiently promising to include them in developing power generation capacity for developing countries like Mozambique.
1.4. Scope

Considering the energy demand of about 1 kWh\textsubscript{e} and 3 kWh\textsubscript{th} per day for each of the 50 household of a district in Mozambique, the hybrid solar energy will be techno-economically assessed for residential application in Mozambique considering a small community.

1.5. Applied Method

In order to perform this project and reach the presented results, the following steps were of paramount importance:

a. Literature review of the following topics:
   - basics of solar energy;
   - solar energy resources in Mozambique;
   - solar water heating system; and
   - solar photovoltaics.

b. modeling PV system using HOMER software;

c. techno economic study of solar heating system using RETscreen software.

1.6. Project lay-out

An overview of current state of art within the hybrid system is made in chapter 2 where emphasis is placed on PV system and solar heating system.

After the literature review in chapter 2, the modeling PV system using HOMER software is separately made in chapter 3, prior to the use of
RETscreen software that model the solar water heating system in chapter 4.

In the presentation of the result the parametric studies of the variable such as maximum power of the collector and area, hot water storage volume and demand were analyzed in the solar collector results while for PV system the optimal configuration of the system were discussed.

To summarize chapter 6 presents the important parameters of collector and conclusions based upon sensitivity analysis of PV system showing the optimal system configuration and the best estimate scenario.

1.7. Key words

**Hybrid solar panel** - Combines Photovoltaic with Thermoelectricity.

**Cogeneration** - Cogeneration is a highly efficient means of generating heat and electric power at the same time from the same energy source.

**Residence** - The term residence may refer to house, home, nursing home, etc.

**HOMER** – It is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications.
CHAPTER 2

2. LITERATURE REVIEW

2.1. Basics of solar energy

2.1.1. Energy from the Sun

The solar energy can be used to generate electricity and heat. When the energy from the sun is converted to thermal energy can be used to heat water for using in buildings, swimming pools, or homes and to heat spaces inside greenhouses, buildings and homes.

There are two ways for converting solar energy in electricity namely photovoltaic or solar cells that consist of changing sunlight directly into electricity. PV cells are grouped in panels and arrays of panels that can be used in various applications such as single small cells that charge calculator and watch batteries, systems that power single homes and large power plants covering many acres.

Concentrating Solar Power Plants - generate electricity by using the heat from solar thermal collectors to heat a fluid which produces steam that is used to power the generator.

Two drawbacks of solar energy are:

- The amount of sunlight that arrives at the Earth's surface depends on weather conditions, time of day and year, location. It is not constant.
• To collect the energy at a useful rate is necessary a large surface area, the sun does not deliver that much energy to any one place at any one time.

2.1.2. Declination

According to Duffie and Beckman (1991) declination is the sun angular position at solar noon, related to the plane of the equator. The value of declination in degrees is given by Cooper’s equation:

\[
\delta = 23.45 \sin \left[ 2\pi \frac{284 + n}{365} \right]
\]

Where \( n \) is the day of year (i.e. \( n = 1 \) for January 1, \( n = 32 \) for February 1, etc.). Declination varies between \(-23.45^\circ\) on December 21 and \(+23.45^\circ\) on June 21.

2.1.3. Solar hour angle

For Duffie and Beckman (1991), solar hour angle is the east or west angular displacement of the sun of the local meridian morning negative and afternoon positive. The solar hour angle at solar noon is equal to zero; it varies by 15 degrees per hour from solar noon.

2.1.4. Sunset hour angle

According to Duffie and Beckman (1991) sunset hour angle \( \omega_s \) is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:
\[
\cos \omega_z = -\tan \psi \cdot \tan \delta \quad \text{......................................................... (2. 2)}
\]

Where \(\delta\) is the declination and \(\psi\) is the latitude of the site, specified by the user.

### 2.1.5. Extraterrestrial radiation

Solar radiation outside the earth’s atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, \(H_0\), can be computed for the day of year \(n\) from the following equation:

\[
H_0 = \frac{86400G_{sc}}{\pi} \left[1 + 0.033 \cos \left(2\pi \frac{n}{365}\right)\right] (\cos \psi \cos \delta \sin \omega_z + \omega_z \sin \psi \sin \delta) \quad \text{......................................................... (2. 3)}
\]

Where \(G_{sc}\) is the solar constant equal to 1.367 W/m\(^2\).

### 2.1.6. Clearness index

The clearness index is the ratio of solar radiation at the surface of the earth to extraterrestrial radiation. \(K_T\) is the monthly average clearness index defined by the equation:

\[
\bar{K}_T = \frac{\bar{H}}{H_0} \quad \text{......................................................... (2. 4)}
\]

Where \(\bar{H}\) indicates the monthly average daily solar radiation on a horizontal surface and \(H_0\) is the monthly average extraterrestrial daily solar radiation on a horizontal surface.
KT values depend upon the time of the year considered and location; these values are usually between 0.3 and 0.8 for very overcast climates and very sunny locations, respectively.

2.2. Solar energy resources in Mozambique

2.2.1. 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 (Chenene et al., 2006).
Table 2.2: 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) (Chenene et al., 2006)

<table>
<thead>
<tr>
<th></th>
<th>Maputo</th>
<th>Beira</th>
<th>Pemba</th>
<th>Maniquenique</th>
<th>Chimoio</th>
<th>Lichinga</th>
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<td>19°48'</td>
<td>12°59'</td>
<td>24°44'</td>
<td>19°07'</td>
<td>13°18'</td>
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<tr>
<td>Longitude</td>
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<td>58m</td>
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<td>Global solar radiation (kWh/m²/day)</td>
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<tr>
<td>January</td>
<td>6.9</td>
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<td>5.9</td>
<td>7.4</td>
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<td>February</td>
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<td>6.3</td>
<td>5.3</td>
<td>7.0</td>
<td>6.5</td>
<td>5.1</td>
</tr>
<tr>
<td>March</td>
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<td>5.8</td>
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<td>5.9</td>
<td>5.4</td>
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<td>5.5</td>
<td>4.5</td>
<td>4.9</td>
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<td>5.1</td>
<td>4.1</td>
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<td>5.7</td>
<td>5.9</td>
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<td>6.5</td>
<td>6.2</td>
<td>6.1</td>
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<td>6.8</td>
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<td>6.7</td>
<td>7.5</td>
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<tr>
<td>Partial station averages</td>
<td>5.3</td>
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<td>6.0</td>
<td>5.9</td>
<td>5.8</td>
<td>5.2</td>
</tr>
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</table>

Country’s averages:* 5.7
* Country average means an arithmetic average of the six stations considered

The Table 2.1 summarizes the average global solar radiation data for three stations along the coast line and other three stations in the interior of the country, over the period of 30 years. The location of these stations is shown in Table 2.2.
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 move from south to north. It also decreases as one move from the interior to the coast line, especially in the south. The average of solar radiation in the country is of 5.7 kWh/m²/day (Chenene et al., 2006).

### 2.2.2. Beam and diffuse components of solar radiation

The Tables 2.3 and 2.4 illustrate the beam and diffuse components of solar radiation averages obtained from table 2.1 and monthly variability of it.
Table 2.4: Beam component of solar radiation averages obtained from data of Table 2.1

<table>
<thead>
<tr>
<th>Month</th>
<th>Maputo</th>
<th>Beira</th>
<th>Pemba</th>
<th>Maniquenique</th>
<th>Chimoio</th>
<th>Lichinga</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>4.4</td>
<td>4.2</td>
<td>3.5</td>
<td>5.1</td>
<td>4.3</td>
<td>2.7</td>
</tr>
<tr>
<td>February</td>
<td>4.4</td>
<td>4.0</td>
<td>3.0</td>
<td>4.9</td>
<td>4.2</td>
<td>2.8</td>
</tr>
<tr>
<td>March</td>
<td>3.8</td>
<td>3.8</td>
<td>3.6</td>
<td>4.4</td>
<td>4.1</td>
<td>2.5</td>
</tr>
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<td>April</td>
<td>3.2</td>
<td>3.8</td>
<td>4.1</td>
<td>3.8</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>May</td>
<td>2.9</td>
<td>3.3</td>
<td>3.9</td>
<td>3.4</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>June</td>
<td>2.8</td>
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<td>3.6</td>
<td>3.0</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>July</td>
<td>2.7</td>
<td>3.0</td>
<td>3.7</td>
<td>3.1</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>August</td>
<td>3.1</td>
<td>3.4</td>
<td>4.4</td>
<td>3.6</td>
<td>3.7</td>
<td>3.5</td>
</tr>
<tr>
<td>September</td>
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<td>5.0</td>
<td>3.9</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
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<td>3.5</td>
<td>4.2</td>
<td>5.3</td>
<td>4.4</td>
<td>3.9</td>
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<td>4.4</td>
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<td>3.4</td>
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<tr>
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<td>4.4</td>
<td>4.4</td>
<td>3.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Partial station averages:

<table>
<thead>
<tr>
<th></th>
<th>Maputo</th>
<th>Beira</th>
<th>Pemba</th>
<th>Maniquenique</th>
<th>Chimoio</th>
<th>Lichinga</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3</td>
<td>3.8</td>
<td>4.1</td>
<td>4.1</td>
<td>3.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Country’s averages:* 3.8

* Country average means an arithmetic average of the six stations considered.

Table 2.5: Diffuse component of solar radiation averages obtained from data of table 2.1

<table>
<thead>
<tr>
<th>Month</th>
<th>Maputo</th>
<th>Beira</th>
<th>Pemba</th>
<th>Maniquenique</th>
<th>Chimoio</th>
<th>Lichinga</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>2.5</td>
<td>2.4</td>
<td>2.4</td>
<td>2.3</td>
<td>2.4</td>
<td>2.4</td>
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<td>2.3</td>
<td>2.3</td>
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<td>2.1</td>
<td>2.2</td>
<td>1.9</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>April</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
<td>1.6</td>
<td>1.8</td>
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<td>1.4</td>
<td>1.6</td>
<td>1.1</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>June</td>
<td>1.0</td>
<td>1.2</td>
<td>1.5</td>
<td>1.1</td>
<td>1.3</td>
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<td>1.4</td>
<td>1.5</td>
<td>1.2</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>August</td>
<td>1.4</td>
<td>1.6</td>
<td>1.6</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>September</td>
<td>1.9</td>
<td>1.9</td>
<td>1.8</td>
<td>1.8</td>
<td>1.9</td>
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<td>October</td>
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<td>2.2</td>
<td>2.0</td>
<td>2.1</td>
<td>2.3</td>
<td>2.2</td>
</tr>
<tr>
<td>November</td>
<td>2.5</td>
<td>2.3</td>
<td>2.1</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
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<tr>
<td>December</td>
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<td>2.5</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Partial station averages:

<table>
<thead>
<tr>
<th></th>
<th>Maputo</th>
<th>Beira</th>
<th>Pemba</th>
<th>Maniquenique</th>
<th>Chimoio</th>
<th>Lichinga</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>1.9</td>
<td>1.9</td>
<td>4.1</td>
<td>2.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Country’s averages:* 1.9

The graphs of Figures 2.1 and 2.2 show the monthly variability of the beam and diffuse components of solar radiation and 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 (Chenene et al., 2006).

![Figure 2.1](image1.png)

Figure 2.1: Monthly variability of the beam component of solar radiation for (a) coastal and (b) inland stations (Chenene et al., 2006).

![Figure 2.2](image2.png)

Figure 2.2: Monthly variability of the diffuse component of solar radiation for a coastal and (b) inland stations (Chenene et al., 2006).

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 (Chenene et al., 2006).
2.2.3. 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. The Table 2.4 below shows the distribution of duration of daily sunshine hours for selected months observed at Maputo station for the year 1986.

Table 2.6: Distribution of duration of daily sunshine hours for selected months observed at Maputo Station for the year 1986 (Chenee et al., 2006).

<table>
<thead>
<tr>
<th>Hours range</th>
<th>March (days)</th>
<th>June (days)</th>
<th>September (days)</th>
<th>December (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 3</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3 to 6</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6 to 9</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>9 to 12</td>
<td>21</td>
<td>20</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>&gt; 12</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>6</td>
</tr>
</tbody>
</table>

2.3. Solar Water Heating Systems

In order to transfer heat to the load, generally via a storage tank, solar collectors and liquid handling unit are used by solar water heating systems (SWHS). The liquid handling unit includes the pump(s) (used to circulate the working fluid from the collectors to the storage tank) and control and safety equipment (Lane and Olson, 2002). Solar water heaters perform three basic operations:

- **collection** - solar radiation is “captured” by a solar collector;
- **transfer** - circulating fluids transfer this energy to a storage tank; circulation can be natural (thermosiphon systems) or forced, using a circulator (low-head pump); and
• **storage** - hot water is stored until it is needed at a later time in a mechanical room, or on the roof in the case of a thermosiphon system.

![Solar Domestic Hot Water Thermosiphon System](image)

**Figure 2.3: Solar Domestic Hot Water Thermosiphon System (CETC, 2004).**

### 2.3.1. History of Solar Water Heating Systems

It is in Geneva, Switzerland where the story of solar water heating began. A Swiss naturalist, Horace-Bénédict de Saussure, observed that it is always hotter when sun rays pass through a glass covered structure comparing unprotected material with whether in a coach or a building (Perlin, 2005).

In 1767 he built an insulated box in order to put his hypothesis to scientific scrutiny, to absorb as much sun energy as possible its bottom was painted black, with two panes of glass covering the top. De Saussure found that the inside heated to temperatures far above the boiling point of water when the box was exposed perpendicular to the sun (Perlin, 2005).
In the 1890 Clarence Kemp invented the first commercial solar water heater, it was simple solar water heater system combining collection and storage in one box (Perlin, 2005).

William J. Baily, in 1909, separated the solar heating of the water from its storage. He attached the water pipes to a black-painted metal plate inside a glass-covered box and connected to an insulated remote storage tank located above the collector (Lane and Olson, 2002).

2.3.2. Solar Collectors

Solar collectors transform solar radiation into heat and transfer that heat to a medium (water, solar fluid, or air). Then solar heat can be used for heating water, space heating, heat for industrial process, to back up heating systems or for heating swimming pools (Kim et al, 2007).

The heart of a solar collector is the absorber, which is usually composed of several narrow metal strips. The carrier fluid for heat transfer flows through a heat-carrying pipe, which is connected to the absorber strip. In plate-type absorbers, two sheets are sandwiched together allowing the medium to flow between the two sheets (Crawford et al, 2003).

The absorber is a heart of solar collector; it is usually composed of several narrow metal strips. The heat carrying pipe in which the carrier fluid for heat transfer flows through is connected to the absorber strip. Two sheets are sandwiched together in plate-type absorber allowing the medium to flow between the two sheets (Crawford et al, 2003).
The sketch of a solar thermal collector system is presented in Figure 2.4.

![Solar Thermal Collector System Sketch](image)

**Figure 2.4: Sketch of a solar thermal collector system (KTH, 2005)**

For heating liquids there are several kind of solar collectors, the type of solar collector to be selected depend upon the temperature of the application being considered and the climate or season of use. We can find as the most common solar collector types such as: evacuated tube solar collectors, glazed liquid flat-plate collectors, and unglazed liquid flat plate collectors (Crawford et al, 2003).

### 2.3.2.1. Unglazed liquid flat-plate collectors

These solar collectors are usually made of black polymer. They do not include a frame, insulation at the black and selective coating. They are low cost collectors and good at capturing the energy from the sun, particularly in windy locations, thermal losses to the environment increase rapidly with water temperature. Unglazed collectors, as a result, are commonly used for applications requiring energy delivery at
low temperatures such as pool heating, process heating applications, make-up water in fish farms, etc; due to high thermal losses of collector, in colder climates are typically only operated in the summer season (Kim et al, 2007).

### 2.3.2.2. Glazed liquid flat-plate Collectors

A glazed flat-plate collector consists of a transparent cover, a frame, an absorber, and insulation. As a transparent cover usually an iron-poor solar safety glass is used, as it transmits a great amount of the short-wave light spectrum. A schematic of flat-plate solar thermal collector is presented in Figure 2.5.

![Figure 2.5: Schematic of a flat plate solar thermal collector (KTH, 2005)](image)

Only very little of the heat emitted by the absorber escapes the cover (greenhouse effect).

The carrying of the collected heat away by wind and breezes is prevented by the transparent cover (convection). The cover, together with the frame, protects the absorber from adverse weather
conditions. The frame material include galvanized steel, aluminum, sometimes fiberglass reinforced plastic is used.

The heat loss through conduction is prevented by the insulation on the side walls lessens and on the back of the absorber. Insulation is usually of mineral wool, polyurethane foam, though sometimes mineral fiber insulating materials like rock wool, glass wool, glass fiber are used.

Flat collectors demonstrate a broad range of mounting (unattached, in the roof itself, or the roof), as well as a good price performance ratio.

2.3.2.3. Evacuated tube collectors

In order to heat domestic hot water, or for hydronic space heating, evacuated tube collectors, as shown in Figure 2.6, have multiple evacuated borosilicate glass tubes that heat up solar absorbers and solar working fluid. The convection and conduction heat loss is reduced by the vacuum within the evacuated tubes, allowing them to reach higher temperature compared with most flat-plate collectors. We can distinguish two types of tube collectors by their heat transfer methods: in older type a heat transfer fluid (antifreeze or water) is pumped through a U-shaped copper tube in each of the glass tube collectors. A sealed heat pipe containing a liquid that vapourises as it is heated (KTH, 2005).
The advantage over the flat plate collectors is that the collector is always perpendicular to the sun’s rays because of the constant profile of the round evacuated tubes and therefore the energy absorbed is approximately constant over the course of a day.

2.3.3. Energy provided by a solar collector

By definition, the efficiency of a solar collector is the quotient of usable thermal energy versus received solar energy. There is optical loss as well, besides thermal loss. The percentage of the solar rays penetrating the transparent cover of the collector (transmission) and the percentage being absorbed are indicated by the conversion factor or optical efficiency $h_0$.

K-value or thermal loss factor indicate the heat loss, this is given in the particular temperature difference (in °C) between the absorber and its surroundings and in watt per m² collector surface. The more heat is lost when the temperature difference is higher. The amount of heat
loss equals the energy yield of the collector, above a specific temperature difference, so that no energy at all is delivered to the solar circulation system. For good collector we will have a low k-value and high conversion factor.

### 2.3.4. How to choose the suitable collector

The most important factor in choosing the correct type of collector is the desired temperature range of the material. For producing a process heat an uncovered absorber is certainly not suitable. When planning a solar array the amount of space must all be carefully considered, the exposure to storms, and the amount of radiation on the spot.

Another important factor is the specific cost of collectors. Evacuated tube collectors are substantially more expensive compared with flat-plate or even plastic absorbers. A good collector does not guarantee a good solar system; all components should be of similar capacity, strength and high quality.

### 2.3.5. Basic Flat-Plate Energy Balance Equation

In principle a solar collector is a heat exchanger radiation that is characterized by low and variable energy flow, and the important part of the heat balance is that radiation (Duffie and Beckman, 2007).

The useful energy $Q_u$ from a solar collector is given by

$$ Q_u = A_c \left[ S - U_L \left( T_{pm} - T_a \right) \right] $$

Where:

- $A_c$ - collector area,
- $S$ - absorbed energy per m$^2$ absorber area,
U<sub>L</sub> - heat loss coefficient,
T<sub>pm</sub> - the average temperature of absorber temperature,
Ta - ambient temperature (subscripts <i>p</i> for plate and <i>m</i> for mean value).

Instead of Equation 2.5 it is therefore instead used the above expression, as it is difficult both to measure and calculate T<sub>pm</sub> (Duffie and Beckman, 2007):

\[
Q_a = A_t F_R \left[ S - U_L \left( T_i - T_a \right) \right]
\]  \hspace{1cm} (2.6)

Where:
F<sub>R</sub> - the collector's heat removal factor; and
T<sub>i</sub> - the inlet water temperature.

Insertion of \( S \) from Equation \( S = (\alpha x)_{av} G_T \) changes this equation into:

\[
Q_a = A_t \left[ F_R (\alpha x) G_T - F_R U_L \left( T_i - T_a \right) \right]
\]  \hspace{1cm} (2.7)

The \( \eta \) gives the efficiency of solar collector:

\[
\eta = \frac{\int Q_a \, dt}{A_t \int G_T \, dt}
\]  \hspace{1cm} (2.8)

2.3.6. Temperature Distributions in Flat-Plate Collectors

The temperature \( T_p \) of an absorber plate varies both in parallel and perpendicular to the water (or fluid) channels, that is not constant over the surface.
The inlet temperature is lower than the outlet temperature, under operation, so absorber temperature increases in parallel with the water flow.

Under operation, the outlet temperature is higher than the inlet temperature, so absorber temperature increases in parallel with the water flow. Heat is conducted through the absorber towards the water channels, so the absorber temperature perpendicular to the channels is lowest at the channels and highest in the middle between them (Duffie and Beckman, 2007).

Finally, there is a temperature difference between the channel (tube) and the water. The absorber temperature is therefore on the average higher than the water inlet temperature; hence the factor $F_R$ in Equation 2.7 (Duffie and Beckman, 2007).

2.3.7. Collector Overall Heat Loss Coefficient

The sum of the top, bottom and edge loss coefficients is called heat loss coefficient $U_L$ [W/m$^2$K]:

$$ U_L = U_t + U_b + U_e \tag{2.9} $$

The bottom and edge coefficients are due to heat conduction and the top to convection and radiation. All three are kept as low as economical for an efficient collector. Adequate insulation is necessary to minimize bottom and edge loss (Duffie and Beckman, 2007).
Without decreasing S is more difficult to make the top coefficient low. The convection losses are decreased by an extra plastic or glass film between the glass and absorber, but also S gets lower.

According to Duffie and Beckman (2007), keeping the average temperature of the absorber as low as possible is one more way to minimize losses, as there is relationship of proportionality between the difference between average and ambient temperature and heat losses from an absorber.

UL is between 2 and 8 W/m²K. UL can be calculated from thermal, optical and geometrical properties of the collector, also manufacturers can measure it (Duffie and Beckman, 2007).

2.3.8. Collector Heat Removal Factor $F_R$

For Duffie and Beckman (2007), the product of the collector efficiency factor $F'$ and the collector flow factor $F''$ is the heat removal factor. The fact that the temperature of absorber cross section perpendicular to the water flow is higher than the temperature of water ($F'_{av} \approx F$) is compensated by $F'$; and the fact that the average temperature along the water flow $T_{av}$ is higher than inlet temperature $T_i$ is compensated by $F''$

2.3.9. Collector Characterization

The equation 2.10 gives the collector's instantaneous efficiency $\eta_i$:

$$\eta_i = \frac{Q_u}{A_i \cdot G_T} = F_R \left( \tau \alpha \right) - \frac{F_R U_L (T_i - T_a)}{G_T} \quad \text{..........................................................(2. 10)}$$
The incidence angle modifier is given by:

\[ K_{\tau a} = \left( \frac{\alpha}{\alpha} \right)_a = f(\theta_b) \] .................................(2.11)

Below the three basic solar collector parameters:

- \( F_{R}(\tau a)_n \) indicates how energy is absorbed;
- \( F_{R}U_L \) indicates how energy is lost; and
- \( b_0 \) indicates the dependence of the incidence angle \( \theta_b \).

2.3.10. Energy Storage: Water Tanks

There are many forms of storing the energy (heat), usually as sensible heat (without phase change) in water.

The equation 2.12 gives the useful one-cycle of a water tank:

\[ Q_s = (mC_p)_s \Delta T_s \] \[ J \] .................................(2.12)

Where \( \Delta T_s \) indicates the temperature range. For a non-stratified or fully mixed tank, yields the power balance below:

\[ (mC_p)_s \frac{dT_s}{dt} = Q_a - L_s - (UA)_s \left( T_s - T_a^+ \right) \] ................................. (2.13)

For numerical integration of the Equation 2.13 is calculated a new temperature:

\[ T_s^+ = T_s + \frac{\Delta t}{(mC_p)_s} \left[ Q_a - L_s - (UA)_s \left( T_s - T_a^- \right) \right] \] \[ J \] .................................(2.14)
Stratified water storage tank is frequently included in modern solar heating system. The cold water is taken from the bottom of the tank to the collector loop via a heat exchanger, and at the top or, even at the position in the tank where there is the same temperature as the water from the collector the hot water from the collector loop is added (Duffie and Beckman, 2007).

2.4. Solar Photovoltaic

A photovoltaic cell or solar cell is a nonmechanical device usually made from silicon alloys used to convert solar energy directly into electrical power (UNEP, 2008). The Figure 2.7 shows the flat plates PV technology.

![Figure 2.7: PV technology, flat plates (Surek, 2006)](image)

For Green (2007), the photovoltaic cells systems are widely and increasingly applied in telecommunication, navigational aids, battery charging, satellites, residential power where there is no grid available, solar power vehicles, etc.
The PV cells have the advantage of being modular (mW to many MW), reliable, abundant, indigenous resource, noise and pollution free, having no or few moving parts. The figure 2.8 shows the PV system in a health center at Chibabava in Mozambique.

![PV system in Chibabava health center in Mozambique](image)

**2.4.1. History of the Photovoltaic Cell**

Bell, telephone researchers, developed the first practical photovoltaic in 1954.

PV cells were used to power U.S. space satellites in the late 1950s. After that PV cells were used to provide electricity in remote location and small consumer’s electronics like watches and calculators. In the mid-1990s the PV use has expanded greatly due to government financial incentives and technology advances (UNEP, 2008).
2.4.2. How Photovoltaic Systems Operate

The power of about 1 or 2 watts produced by one cell is not enough for most applications; the size of individual cells can vary from about 0.5 inches to about 4 inches across. So, cells are electrically connected into module to increase power output, in turn, to form array modules can be further connected. The amount of power output needed defines the number of modules connected together in an array.

2.4.3. Photovoltaic system components

A PV system is made up of:

- **Photovoltaic generator** - Photovoltaic modules which are interconnected to form a DC power producing unit, usually called an array.

- **Power conditioning and control** - Electronic devices used for accommodating the variable nature of power output from the PV generator; e.g. The power conditioning and control equipment makes it possible to convert the DC power generated to AC, protect the battery against the discharge or overcharge and optimize the energy transfer between the PV generator and the load.

- **Storage system** - Stand-alone PV systems, which make provision for energy storage.

2.4.4. Stand-Alone Photovoltaic Systems

Stand-alone systems, as presented in Figure 2.9 need back-up storage, usually lead-acid batteries. As usual for a stand-alone system,
an inverter is needed, as PV arrays generate DC power. Mainly two types of inverters can be used to achieve AC power at the voltage used in the main grid (Green, 2007):

- **line commutated**, where the grid signal is used to synchronize the inverter with the grid; and
- **self commutated**, where the inverter's intrinsic electronics lock the inverter signal with that of the grid.

![Figure 2.9: Simplified stand-alone PV power system (Green, 2007)](image)

According to Martin Green (2007) issues to be considered when selecting an inverter include efficiency, safety, power quality, compatibility (with the array), and presentation (compliance with relevant electric codes, size, weight, construction and materials, protection against weather conditions, terminals and instrumentation).

### 2.4.5. Grid Connected Photovoltaic Systems in buildings

The number of PV panels on grid-connected houses in the world is increasing, but requires for the time being governmental support.
Photovoltaics can be used in grid connected mode in two ways: as arrays installed at the end site, e.g. on roof tops or as utility scale generating stations.

In a building, PV systems can provide power for a number of functions:

- **architectural** - dual purpose: electricity generation and roofing, walls, or windows.
- **demand-side management** - to offset peak time loads; and
- **hybrid energy systems** - supplementing other sources for lighting, heat pumps, air conditioners, etc.

![Figure 2.10: Block diagram of a grid-connected photovoltaic generator (Surek, 2006)](image)

As the block diagram shows in Figure 2.10, on-site storage is not essential for grid-connected systems but can greatly increase their value. Storage can be provided at grid level, or via batteries on site.
CHAPTER 3

3. MODELLING PV SYSTEM USING HOMER SOFTWARE

One of the powerful tool used for designing and analyzing hybrid power systems is HOMER, it is an energy modelling software for Hybrid Renewable Energy System, containing a mix of renewable energy sources, cogeneration, conventional generators, etc (Lambert et al, 2006).

With HOMER it is possible to run simulations of different energy systems, determining the economic feasibility of hybrid energy system and optimizes the system design (Lambert et al, 2006).

According to Gilman (2002), there are four processes occurring inside HOMER:

a) Hourly energy balance
   - in the single hour compares the electric demand and the energy supply; and
   - decide how to discharge and charge batteries or run generator for system with fuel powered generators or batteries.

b) Simulation
   - for each system design calculates hourly the energy balance;
   - determines the feasibility of the design; and
   - for each design makes the cost estimation.
c) Optimization
- for identifying least cost design, repeated simulations are carried out;
- sorted by cost effectiveness, a ranked list of feasible designs is made.

d) Analysis of sensitivity
- For analyzing the way variable factors affect the system design, repeated optimization is carried out.

3.1. Load assessment

In this project a small community of 50 households was considered assuming that each household consumes about 1 kWh. To define the load profile was based on a hypothetical single home with appliances presented in the Table 3.1.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Common Power demand (W)</th>
<th>QTY</th>
<th>Duration</th>
<th>kWh/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flourescent lamp</td>
<td>18</td>
<td>3</td>
<td>5h/day</td>
<td>0.27</td>
</tr>
<tr>
<td>TV color</td>
<td>150</td>
<td>1</td>
<td>2h/day</td>
<td>0.3</td>
</tr>
<tr>
<td>Radio</td>
<td>40</td>
<td>1</td>
<td>9h/day</td>
<td>0.36</td>
</tr>
<tr>
<td>Video</td>
<td>45</td>
<td>1</td>
<td>1h/day</td>
<td>0.045</td>
</tr>
<tr>
<td>Razor</td>
<td>20</td>
<td>1</td>
<td>10min/day</td>
<td>0.003</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1573</td>
<td></td>
<td></td>
<td>0.978</td>
</tr>
</tbody>
</table>

For selecting the electrical appliances in the Table 3.1 was based on important usage in the house. The lamps are used for 5 hours from 5 am to 6 am and from 6 pm to 10 pm whilst the radio is used from 10 am to 6:00 pm.
The TV colour is functioning for 2 hours during day time while the video 1 hour. It may be seen from the table that the radio consumes much of the energy, with 0.36 kWh, which is 20% higher than its predecessor TV.

The daily load is shown in Figure 3.1, where the peak power occurs around 7:00 pm when all the appliances are on as all the family members are back home and awake by this time.

![Figure 3.1: Hourly load profile](image)

The annual average load based on uniform daily load throughout the year is presented in Figure 3.2; observable here is fluctuation around 0.2 kW because the maximum daily profile load is 0.21 kW.

![Figure 3.2: Annual average load](image)
3.2. Solar resource assessment

Maputo is the modelled region, it is located at 25°58’ latitude, 32°36’ longitude and 79 m altitude with a good solar resource. The annual average solar radiation is 5.3 kWh/m²/day for this area. The solar radiation data was obtained from the report of solar energy resource assessment in Mozambique (Chene et al., 2006).

As this project focus on solar PV it is included the regional solar irradiance, the clearness index and the temperature data, as depicted in the Figure 3.3 below.

![Figure 3.3: Solar radiation profile for Maputo](image)
3.3. Economics

For the project was assumed a real annual interest rate of 12%. The value of interest rate is dependent upon the financial strength of the entity implementing the project, current macroeconomic conditions, and concessional financing or other policy incentives. (Givler and Lilienthal, 2005)

The variable of real annual interest rate is equal to the difference between the nominal interest and the inflation rate. (Givler and Lilienthal, 2005)

3.4. System components

Component can be defined as any part of a micropower system which the function is to generate, convert, deliver or store energy (Lambert at al., 2006). In the figure 3.4 is shown the schematic system component with primary load that is electrical demand that the power system must meet; in a process called inversion electric power is converted from DC to AC by converter; the battery bank to store a certain amount of DC electricity; PV array is the device for producing DC electricity in direct proportion to the global solar radiation incident on it.
3.4.1. Photovoltaic panels cost

The PV panels’ capital and replacement cost account for all costs related with the PV subsystem, such as PV panels, tracking system, wiring, mounting hardware and installation. The capital and replacement cost of PV panels is $9500/kW, the cost for PV module was estimated based on quotes from local market.

It is highly recommended that the PV panels must be oriented to the equator line in order to maximize the solar radiation during the entire year. As Maputo in Mozambique is located in the south hemisphere, the panels must be oriented to the north.

The energy generation varies within the year, for its optimization the inclination of the PV panels must be approximately equal to latitude of the site.

The output of the PV array can be deviated from that expected under ideal conditions because of effects of wire losses, elevated temperature, dust on the panel, etc. to account for that the derating factor is assumed 90%.
3.4.2. Converter

To convert electric power from DC to AC is used a converter in a process called inversion, and in the process called rectification the electric power is converted from AC to DC.

According to Lambert et al (2006), the maximum amount of AC power that can be produced by the device inverting DC power is the converter size, refers to the inverter capacity and it is a decision variable.

For all sizes considered, the inverter and rectifier efficiency were assumed to be 90% and 85% respectively.

3.4.3. Batteries

Battery used during this design process is a Dynamic HI-FASE type which is 12 V and a capacity of 200 Ah. They were chosen because are the one available in the local market. Homer considered up to 13 of these batteries. The life expectancy is from 5 to 10 years, assuming 300 cycles at 80% depth of discharge.

The cost of the components depicted in the Table 4.2 below was estimated based on the quotes from local markets.
Table 3.2: Detail cost of the solar PV system

<table>
<thead>
<tr>
<th>Component</th>
<th>Size</th>
<th>Capital cost ($)</th>
<th>Replacement cost ($)</th>
<th>O&amp;M cost ($)/year</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>0.05-4 kW</td>
<td>$9500/kW</td>
<td>$9500/kW</td>
<td>0</td>
<td>20 years</td>
</tr>
<tr>
<td>Batteries Hi-Fase</td>
<td>200 Ah/12V</td>
<td>$130/battery</td>
<td>$130/battery</td>
<td>$4/year</td>
<td>917 kWh of throughput per battery</td>
</tr>
<tr>
<td>Converter</td>
<td>0-4 kW</td>
<td>$250/kW</td>
<td>$250/kW</td>
<td>$25/year</td>
<td>10 years</td>
</tr>
</tbody>
</table>

The optimization variables used for simulation for the PV system components shown in HOMES search space are depicted in the Table 3.3.

Table 3.3: Optimization variables

<table>
<thead>
<tr>
<th>PV Array (kW)</th>
<th>Battery HI-FASE (Quantity)</th>
<th>Converter (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>0.050</td>
<td>2</td>
<td>0.10</td>
</tr>
<tr>
<td>0.100</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>0.200</td>
<td>4</td>
<td>0.20</td>
</tr>
<tr>
<td>0.250</td>
<td>5</td>
<td>0.40</td>
</tr>
<tr>
<td>0.300</td>
<td>6</td>
<td>0.50</td>
</tr>
<tr>
<td>0.400</td>
<td>7</td>
<td>0.75</td>
</tr>
<tr>
<td>0.800</td>
<td>8</td>
<td>1.00</td>
</tr>
<tr>
<td>0.900</td>
<td>9</td>
<td>1.25</td>
</tr>
<tr>
<td>1.000</td>
<td>10</td>
<td>1.50</td>
</tr>
<tr>
<td>1.100</td>
<td>11</td>
<td>2.50</td>
</tr>
<tr>
<td>1.200</td>
<td>12</td>
<td>3.00</td>
</tr>
<tr>
<td>1.300</td>
<td>13</td>
<td>4.00</td>
</tr>
</tbody>
</table>
In the Figure 3.4 depicted below are presented the values of sensitivity variables used for simulation for PV system components.

![Sensitivity Inputs Table]

**Figure 3.4: Sensitivity variables**
CHAPTER 4

4. TECHNO ECONOMIC STUDY OF SOLAR HEATING SYSTEM USING RETSCREEN

To determine the feasibility of clean energy projects can be used project analysis software called RETScreen. It provides a lot of options for assessing suitability in terms of technical, financial and environment for an investment in clean energy project, including energy efficiency, renewable energy, and cogeneration (Graham, 2004).

There are six worksheets available in the Solar Water Project workbook such as solar resource and heating load calculation, cost analysis, energy model, financial summary and sensitivity and risky analysis, greenhouse gas emission reduction analysis (Clarke, 2009).

4.1. Input data for RETScreen simulation

In this chapter the techno economic study of solar heating system in tropical countries using RETScreen is performed considering the heat demand of 3 kWh\textsubscript{th} per day for each of the 50 household with 3 members per family of a district in Mozambique.

For performing all RETScreen analysis for solar water heating system is used RETScreen version 4 with the following parameters:
4.1.1. Start screen

For entering the climate conditions reference, general information about the project and the standard settings necessary to perform the analysis is used the Start worksheet. Figures 4.1 and 4.2 show the start screen and climate data location of Maputo in Mozambique respectively, obtained from the RETScreen.

![Figure 4. 4: Start screen](image)

Figures 4.2 and 4.3 present the data set used in the simulation such as relative humidity, project location, climate data, daily solar radiation - horizontal, monthly air temperature, etc.
Figure 4.5: Climate data and project location

Table 4.1 presents the start screen input data used for modeling the project.
Table 4.6: start screen input data

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modeling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility type</td>
<td>Residential</td>
</tr>
<tr>
<td>Project type</td>
<td>Heating</td>
</tr>
<tr>
<td>Technology</td>
<td>Solar water heater</td>
</tr>
<tr>
<td>Analysis type</td>
<td>Method 1</td>
</tr>
<tr>
<td>Heating value reference</td>
<td>High</td>
</tr>
<tr>
<td>Climate data location</td>
<td>Maputo</td>
</tr>
</tbody>
</table>

4.1.2. Energy model screen

As depicted in Table 4.2, for low hot water demand (HWD) of 30 liters per person, the daily demand (DD) for three person household is 90 liters (AAE, 2009).

The minimum and maximum water supply temperatures were taken from the climate data location of Maputo embodied in RETScreen software. According to Figure 4.2, the minimum temperature is in July while the maximum temperature is in February.

Table 4.7: load characteristics

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modeling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Hot water</td>
</tr>
<tr>
<td>Load type</td>
<td>House</td>
</tr>
<tr>
<td>Daily hot water use</td>
<td>90 (3 persons)</td>
</tr>
<tr>
<td>Temperature</td>
<td>50°C</td>
</tr>
<tr>
<td>Supply temperature method</td>
<td>User-defined</td>
</tr>
<tr>
<td>Operating days per week</td>
<td>7</td>
</tr>
<tr>
<td>Water supply temperature – minimum</td>
<td>18,2°C</td>
</tr>
<tr>
<td>Water supply temperature – maximum</td>
<td>25,5°C</td>
</tr>
</tbody>
</table>
The collector must be oriented to the sun in order to obtain the largest yield as its output depends strongly on the effects of its characteristics and the inclination angle of the collector to the sun. The optimum angle of tilt is equal to the degree of latitude of the site, as a general rule. But the minimum angle of the collector should be 15 degree to assist the thermosyphon effect (AEE, 2009). Table 4.3 illustrates the slope and the azimuth angles.

Table 4. 8: Resource assessment

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modeling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar tracking mode</td>
<td>Fixed</td>
</tr>
<tr>
<td>Slope</td>
<td>25°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>0°</td>
</tr>
</tbody>
</table>

The characteristics of solar water heater presented in the Table 4.4 were obtained from the RETScreen product database integrated to the software.

Table 4. 9: solar water heater

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modelling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Glazed</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Hassier Alternative Energie</td>
</tr>
<tr>
<td>Model</td>
<td>Omegasol S</td>
</tr>
<tr>
<td>Gross area per solar collector</td>
<td>3.05 m²</td>
</tr>
<tr>
<td>Aperture area per solar collector</td>
<td>2.76 m²</td>
</tr>
<tr>
<td>Fr (tau alpha) coefficient</td>
<td>0.69</td>
</tr>
<tr>
<td>Fr UL coefficient</td>
<td>4.07 (W/m²)/°C</td>
</tr>
<tr>
<td>Temperature coefficient for Fr UL</td>
<td>0</td>
</tr>
<tr>
<td>Number of collectors</td>
<td>1</td>
</tr>
<tr>
<td>Miscellaneous losses</td>
<td>3% (assumed)</td>
</tr>
</tbody>
</table>

This system will have a storage tank, but will not use a heat exchanger. The typical values of ratio of storage capacity to collector area range from 37.5 to 100 L/m² (MNRCan, 2005).
For this project was assumed 50 L/m² as ratio of storage capacity and
6% for miscellaneous losses as shown in Table 4.5.

Table 4. 10: balance of system and miscellaneous

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modelling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>storage</td>
<td>Yes</td>
</tr>
<tr>
<td>Storage capacity/solar collector area (L/m²)</td>
<td>50</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>100% for integrated collector – storage or thermosyphon</td>
</tr>
<tr>
<td>Miscellaneous losses</td>
<td>6% (assumed)</td>
</tr>
<tr>
<td>Pump power / solar collector area</td>
<td>0</td>
</tr>
<tr>
<td>Electricity rate</td>
<td>0.144 USD/kWh</td>
</tr>
</tbody>
</table>

According to the literature (CETC, 2004), for residential water heating
system with storage tank and for electricity as fuel type, the seasonal
efficiency is of 88% as depicted in the Table 4.6. The fuel rate was
taken from the price of electricity in Mozambique.

Table 4. 11: heating system

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modelling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel type</td>
<td>Electricity</td>
</tr>
<tr>
<td>Seasonal efficiency</td>
<td>88%</td>
</tr>
<tr>
<td>Fuel rate</td>
<td>0.144 USD/kWh</td>
</tr>
</tbody>
</table>

The heating system initial cost and the O&M cost in Table 4.7 were
estimated based upon the data from the internet.
**Table 4.7: financial analysis**

<table>
<thead>
<tr>
<th>RETScreen input line</th>
<th>Selected modelling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation rate</td>
<td>3.5%</td>
</tr>
<tr>
<td>Project life</td>
<td>25 years</td>
</tr>
<tr>
<td>Dept ratio</td>
<td>0%</td>
</tr>
<tr>
<td>Heating system initial cost</td>
<td>2525 USD</td>
</tr>
<tr>
<td>Incentives and grants</td>
<td>0</td>
</tr>
<tr>
<td>O&amp;M cost</td>
<td>50 USD/year</td>
</tr>
</tbody>
</table>
CHAPTER 5

5. RESULTS AND DISCUSSION

5.1. Photovoltaic system

5.1.1. Optimization results

HOMER version 2.68 beta, released by National Renewable Energy Laboratory (NREL) of the U.S. is the simulation tool for this work.

The optimal system configuration for this scenario consists of: a 0.3 kW PV array, 4 HI-Fase 200 Ah batteries and a 0.5 kW converter. The initial capital is of $3.945, operating cost of $82 per year, levelized COE of $1.604/kWh and the total NPC is $4.591 as shown in Figures 5.1 and 5.2.

Figure 5.1: Categorized optimization results
Figure 5.2: Cost Summary

According to the diagram in the Figure 5.3, November has the least electric production while June is the month with the maximum electric production.

Figure 5.3: Monthly average electric production

The Figure 5.4 shows that the PV array production is 542 kWh/yr and the AC primary load consumption is 365 kWh/yr, 12.4% of the total electric energy produced by the system is excess electricity, and energy that is not used by the system goes to waste.
5.1.2. Sensitivity results

For sensitivity analysis, the primary load, global solar, interest rate and project lifetime were used as sensitivity variables to analyze how they influence in the result of the system.

The Figure 5.5 highlights the best estimate scenario with a primary load of 1 kWh/d, global solar radiation of 4.5 kWh/m2/d, interest rate of 11% and 25 years project lifetime. The optimal system configuration for this scenario is 0.4 kW PV, 4 batteries and 0.5 kW converter.

![Figure 5.5: Tabular sensitivity results showing optimal system configuration](image)
The graph in Figure 5.6 shows that the PV-battery system is optimal for the global solar below 4.5 kWh/m²/d for the load less than 0.5 kWh/d as per the assumption used in this analysis. For the global solar above 4.5 kWh/m²/d the system is optimal for the load up to 1 kWh/d.

![Figure 5.6: Optimal system type graph](image)

**5.2. Solar Water Heating Systems**

This section presents the results of the techno economic study of solar heating system for residential application in Maputo performed with RETScreen. The summarized results are presented in Tables 5.1.
Table 5.2: Solar heating system results

<table>
<thead>
<tr>
<th>Location</th>
<th>Output data for Maputo, Mozambique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy demand (Heating)</td>
<td>1.1 MWh</td>
</tr>
<tr>
<td>Solar collector area</td>
<td>3.05 m² flat plate collector</td>
</tr>
<tr>
<td>Collector capacity</td>
<td>1.93 kW</td>
</tr>
<tr>
<td>Storage capacity</td>
<td>138.1 l</td>
</tr>
<tr>
<td>Renewable energy delivered</td>
<td>0.8 MWh</td>
</tr>
<tr>
<td>Solar fraction</td>
<td>78%</td>
</tr>
<tr>
<td>Hot water demand (HWD)</td>
<td>30 l per person and day</td>
</tr>
</tbody>
</table>

Shown in the results (Figures 5.7 and 5.8) is that, the maximum power of the collector is in the range of 1.93 kW while the hot water storage volume and the flat plate collector area are of 138.1 l and 3.05 m² respectively.

![Solar water heater characteristic](image)

The calculated annual energy demand for water heating is 1.1 MWh, which corresponds approximately to the heat demand of 3 kWh th per day for each of the 50 households with 3 members per family.
Figure 5.8: Balance of system and miscellaneous

Also shown in Figure 5.8 is that, the amount of annual energy delivered by the solar water heating system is 0.8 MWh, which indicates the renewable energy delivered. This energy is expected to replace the heating energy that would have otherwise to be met by a conventional or base case system.

The solar fraction is 78%, which represents the fraction (%) of the water heating load for the months analyzed met by the solar water heating system.

5.2.1. Financial analysis

Table 5.2 and Figure 5.9 depict the financial viability of the project.

<table>
<thead>
<tr>
<th>Pre-tax IRR – assets</th>
<th>14.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple payback</td>
<td>8.6 years</td>
</tr>
<tr>
<td>Equity payback</td>
<td>7.4 years</td>
</tr>
</tbody>
</table>
Figure 5.9: Financial viability

The cumulative cash flow shown in Figure 5.10 indicates a payback period of 7.4 years when the cumulative cash flow balance is equal to zero. The payback has the disadvantage because does no account for risk, time-value of money, financing or other important consideration like opportunity cost for analyzing the financial viability (Williams, 2012).

Figure 5.10: Cumulative cash flows graph
CHAPTER 6

6. CONCLUSIONS AND RECOMMENDATIONS

The project consisted of performing techno-economic assessment of hybrid solar energy for residential application in Mozambique for small community of 50 households; each consumes about 1 kWh$_e$ and 3 kWh$_{th}$ per day.

The aims and objectives of this study, as stated in the Introduction, have been achieved.

For the project modelling was used HOMER software version 2.68 beta. This software was used to model the PV panels for electricity generation. The solar heating system was not modeled using HOMER because this software does not model solar collectors. So, the RETScreen software was proposed to perform a techno economic study of solar heating system for residential application in Maputo.

After performing the sensitivity analysis with the HOMER software, the conclusion is that the PV-battery system is optimal for the global solar below 4.5 kWh/m$^2$/d for the load less than 0.5 kWh/d. For the global solar above 4.5 kWh/m$^2$/d the system is optimal for the load up to 1 kWh/d as per the assumption used in this analysis.

The maximum power of the collector obtained with the RETScreen software was found to be 1.93 kW, hot water storage volume of 138.1 l and 3.05 m$^2$ flat plate collector area.
The pre-tax IRR – assets is of 14.5%, the simple payback period is of 8.6 years to return the investment and the 7.4 years of equity payback.

As recommendation, the collectors must be installed in the roof area or on a frame near the house just in case of difficult installation on the roof. The pipes to and from the tank must be as short as possible.

As Maputo is in the southern hemisphere, it is strongly recommended the collector faces North and not shaded at any time of the year, either by trees, building or other collectors.
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