LUNDS TEKNISKA HÖGSKOLA

AEB820 Degree Project in Energy and Building Design

Testing of solar fruit driers in laboratory and in Mozambique

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Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Acknowledgements

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Abstract

In Mozambique between 25% and 40% of the fruits grown are spoiled every year, while a large part of the population in the country is fighting against malnutrition and starvation. Mozambique has a sufficient solar energy potential to use solar drying as a method to preserve fruit. This is done by combining solar drying with a semipermeable membrane bag, in an attempt to reduce the amount of food wasted and increase the economic wellbeing of the small scale farmers of rural Mozambique. The use of a semipermeable membrane bag allows for the use of drying techniques for fruits with high water content, such as citrus fruits for example, by filling the bags with fruit juice. In order to test this process, two collectors were built and tested in Lund, a passive one and an active one. They were then rebuilt in Mozambique to be tested in real conditions.

The tests in the laboratory in Lund were conducted using a lamp providing an average radiation of $905 W/m^2$ on the solar collectors. The field tests were done outside with an average irradiation of just under 900 W/m^2, this value varies over the course of the day.

This resulted in drying rates varying from 550 to 750 $g/m^2/h$ for the passive dryer and from 800 to 1000 $g/m^2/h$ for the active dryer. These values are compared to drying rates of the control bags of about 400 $g/m^2/h$. The control bags are similar bags, but dried in open air and not in a dryer. For the passive dryer this represents an increase of between 38% and 88%. For the active dryer it represents an increase of between 100% and 150%, even peaking at at 190%.

The dryers achieved a high working temperature despite the wind and clouds, resulting in a drying rate of 440 to 490 $g/m^2/h$ for the passive dryer and between 485 and 508 $g/m^2/h$ for the active dryer compared to a control drying rate of 293 $g/m^2/h$ for the bags with added sugar. The values are lower than in Lund because of the testing conditions in both situations. The bags with no sugar added had a drying rate with the passive dryer ranging from 452 to 462 $g/m^2/h$ and the active going form 592 to 625 $g/m^2/h$ compared to the control bag which had 310 $g/m^2/h$. This was an increase of between 47% for the passive dryer without sugar added and 96% for the active with no sugar added compared to the control bag.

The objective of two or three days of drying time was not reached as four days were needed, although the conditions for drying was not optimal. Nevertheless, it was proven that the dryers increase the drying speed of the bags compared to open air drying. This means the total drying time is decreasing when the bags are placed in the dryer. The dryer designs need further improvements in terms of user friendliness, especially concerning the transparent plastic cover.

Keywords: Solar Direct Dryer, Semipermeable Membrane Bag, Mozambique, Food Waste, Active Solar Dryer, Passive Solar Dryer, Fruit drying.

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1 Introduction

This master thesis is part of a project at Lund University, at LTH, the Architecture and Building Environment Department, Division of Energy and Building Design. Two students took part in the thesis: Peter Samuelsson, master student at LTH and Etienne Deslandes, exchange student from l'Ecole Centrale de Lyon, France. The supervisors were Ricardo Bernardo and Henrik Davidsson, Associate Senior Lecturers at LTH.

1.1 Project background

The ongoing population growth in the world demands a proportional increase in food production, storage and distribution. In many developing countries, lack of nutrients is still a huge problem. In Mozambique 25% to 40% of the harvests are spoiled, not taking into account the wild fruits [1]. This is partly due to poor storing conditions. Large scale food preservation is costly in energy and clean water both of which are in short supply in developing countries such as Mozambique. The purpose of this project is to help find a solution for this problem of so much fruit never getting harvested and spoiling on the fields.

1.2 Context

In many developing countries such as Mozambique the food production would be able to feed the entire population of the country but large quantities are spoiled after it has been harvested. Another problem is that the harvest season is so short that a lot of fruits are spoiled before they can even be harvested.

A possible solution to the storage issue could be drying. The difficulty with the traditional way of drying, open air sun drying, is that the process is slow and that it does not protect the food from rain, dirt, insects, fungus, mold and animals. This research project started with the development of a semi permeable membrane bag made out of a plastic material that will let water vapor out and will also keep contaminants out. This means the amount of water in the bag will decrease while at the same time the juice in the bag will be protected. After the drying process has been completed the remaining fruit can be stored for long periods of time at room temperature. This same technology can be used to dry fruit puree or vegetables.

After the first tests were conducted, it appeared that placing the bag in open air was not enough. The drying was not fast enough to prevent the juice from turning bad. To keep the final product edible, the drying process needed to be faster. To try and tackle this issue, the development of solar dryers started within the project. The bags would then be placed in the dryers to accelerate the drying.

1.3 Research project overview

The multidisciplinary nature of the partners, Lund University, Center for Rural Research (Norway) and University Eduardo Mondlane (Mozambique), is one of the strengths of the project combining four post-doctoral researchers from different nationalities and backgrounds with close support from senior researchers with vast project management experience in such international projects. Furthermore, the different partners have previously participated in projects in Mozambique in collaboration with University Eduardo Mondlane in Maputo.

The expected outcomes of this project are diverse. First of all, developing an efficient process combining the pouches and dryers to increase storage time of fruits, and the quality of the final product to reduce health issues. Another goal is to gather knowledge on social acceptance of this kind of projects in rural areas.

The purpose of this master thesis is to build and test a prototype. Another thesis is conducted at the same time trying to simulate a collector to better understand the heat transfer in the collector, including the heat losses.

1.4 Solar potential in Mozambique

Mozambique has a really good potential for solar power, the mean solar irradiation throughout the year is 5.2 $kWh/m^2/day$ compared to 2.8 $kWh/m^2/day$ in Sweden [2] during the summer. It has two seasons, dry and wet, which means that the solar power potential isn't spread equally throughout the year. The wet season runs from October to March and the dry season from April to September [3].

In 2012, Mozambique's national grid only serves about 18% of the population and is subject to high transmission and distribution losses (25%) [4]. In third world countries where the electricity grid is not developed enough to bring electricity everywhere, off grid solutions are a way of powering these zones rather than waiting for the grid to come.

In conclusion, three factors make Mozambique a country with a high potential for solar power:

- High irradiation
- Low use of solar power for the time being
- Low access to electricity and small development of the electricity grid

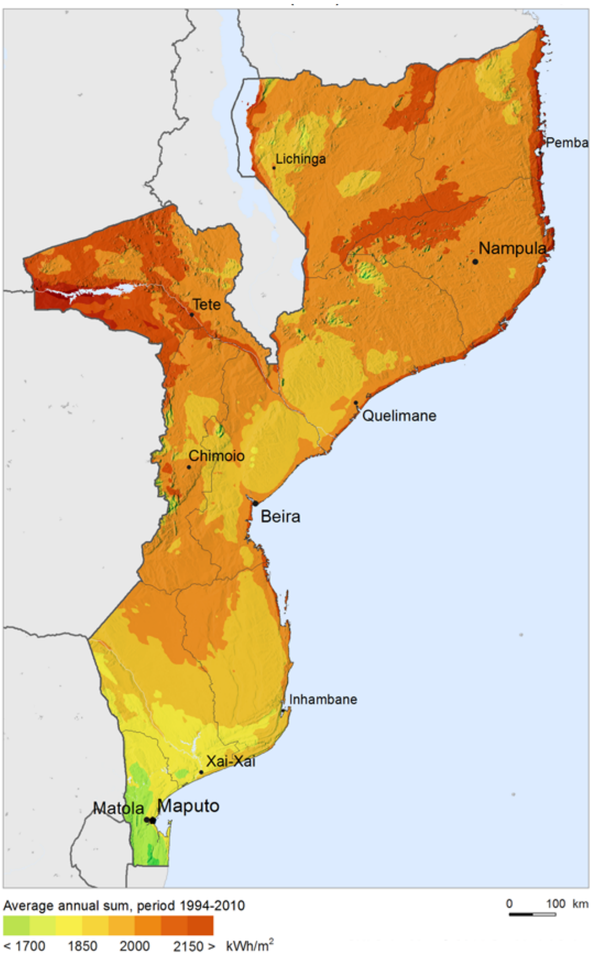

Figure 1: Global horizontal irradiation in Mozambique [GHI Solar Map © 2017 Solargis]

1.5 Objectives

This master thesis is part of a research project that hopes to help with the problem of food conservation by coming up with an affordable way for the local farmers to dry their fruit faster and with less fruit being spoiled. The objectives of this thesis are as follows:

- Construct a simple solar dryer that is easy to use and build both in Sweden and in Mozambique taking into account the limitations such as available tools and materials in Mozambique.
- Make sure that it reaches a desired temperature interval for fruit drying.
- Evaluate the performance of the dryer in the laboratory and in the field.

- Understand the performance of the dryer in relation to drying rate, and identify the crucial drying parameters.

The choice to build and test two different types of dryers was made because of the need to investigate ways of increasing the airflow while still keeping the temperature within the needed interval. The cost of the collector is also a factor that has to be taken into consideration.

1.6 Work Plan

1. Build, in Lund, one active collector and one passive one after choosing the designs. The starting point of the brainstorming was the final design from the previous students (Gustaf Bengtsson and Viktor Döhlen) research [5].

2. Test the dryers in Lund to try and determine which parameters have most influence on the drying rate for both dryers. This helps to understand what changes in the designs could help increase the drying speeds of the dryers.

3. Build and test both dryers on site, in Mozambique. This allowed for testing the dryers in the environment they were intended to be used in. It also helped concluding about how representative the results in Lund are, compared to the normal use of the driers.

4. Compare the performances of both driers, taking into account their prices and complexity.

2 Previous studies and background

This section will give a short review of previous work in the same field and previous thesis conducted in the same project.

2.1 Solar dryers

2.1.1 Direct drying

In a direct solar dryer the fruit receives radiation from the sun. The purpose of the dryer is to directly use the energy from the sun, but this can be done in different ways:

- Open air direct drying: where the fruits are put in the sun (sliced, or prepared in another way) to dry. They will receive energy from the sun and the wind can provide an airflow to help the drying.
- Enclosed direct drying: shown in figure 2, where the fruit are put in a solar collector under a layer of glass. The rise in temperature that is created by the incoming solar irradiation creates a natural airflow resulting in a good environment for drying.

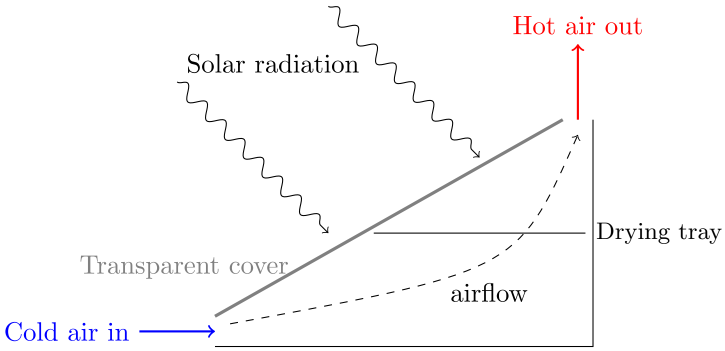

Figure 2: Schematic drawing of an example of a direct solar dryer

2.1.2 Indirect drying

The sun's radiations can damage the fruit, specifically by destroying the vitamins as is the case with direct drying. Indirect solar drying is a method where the fruits are placed in a cabinet to avoid direct sunlight, as shown in figure 3 where the fruit that is inside the dryer is covered and do not receive any direct sunlight. The aim of this method is to protect the fruits from the sun while allowing them to be in an environment with high temperature and low relative humidity. This can be done by using a solar collector to ensure that the air has the best properties for drying the fruits.

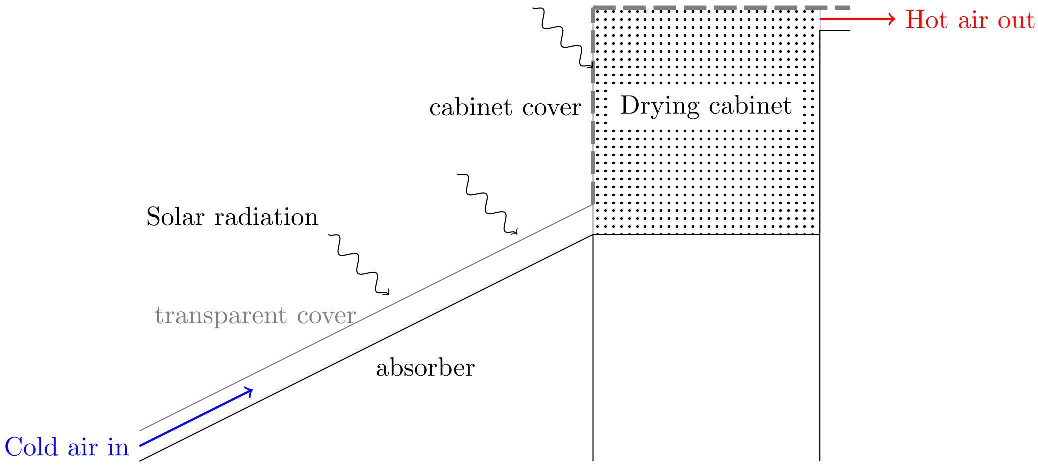

Figure 3: Schematic drawing of an example of indirect solar dryer

2.1.3 Active/Passive drying

An active dryer requires an extra source of energy. It can be solar power if used through a PV panel to produce electricity. Powering a fan to create an airflow is an example of active drying, as is the use of an auxiliary electrical heater. On the one hand, active drying is used to accelerate the drying, but on the other requires a larger investment for collectors of similar sizes. A passive dryer doesn't need any external power source because it uses natural convection driven by the sun.

2.1.4 Mixed

A mixed solar collector combines the direct and an indirect techniques. The product would be directly exposed to solar radiation and at the same time an auxiliary collector would provide a hot airflow. For example in figure 3, the drying cabinet cover could be made out of glass or plastic to allow the sun into the cabinet, while the air would get heated up in the leaning part. To use this technique the sun's radiation cannot be harmful to the drying product. The product would then receive extra radiation from the sun, and still receive a hot airflow that will help reduce the local relative humidity around the bag increasing the drying speed. [6] [7]

In general the type of dryer to be used depends on the requirements to meet for the conditions of drying (temperature interval, maximum drying time), the quality of the final product, the possibility to expose the product to direct sunlight, etc.

2.2 The semi permeable membrane pouches

The bags are made from a semi permeable layer of polyurethane that will let water vapor through but not liquids, as shown in figure 4. The bags can be used for drying without the use of any sort of equipment in direct sunlight. [8]

The bags are used to protect the fruit from the environment while still letting water vapor out but not letting bacteria into the drying fruit. The bags will simplify drying of fruit purée, juices and fruits with a high water content. The possibility to dry fruits with higher water content, such as citrus fruits, is what makes this technology special.

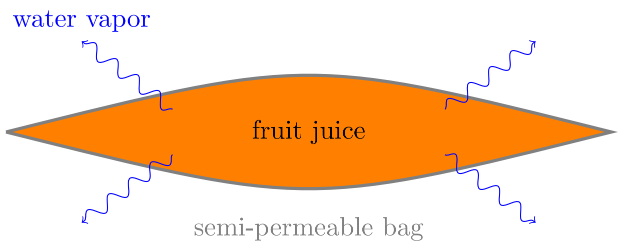

Figure 4: Cross section of the membrane bag

2.3 Solar drying of fruit

There are several considerations to take into account when it comes to drying fruit in semi-permeable bags. The most important variables will be described in the topics below. The output variables in a dryer are the airflow velocity, temperature and relative humidity.

2.3.1 Airflow

The purpose of the airflow is to remove the air saturated in water that surrounds the bags to lower the relative humidity in order to prevent the bag from being covered with water. If the bag becomes covered with water the drying process slows considerably.

Two types of airflow can be found in dryers. The first one is natural circulation where the airflow is driven by the temperature difference. The second one is forced convection where the airflow is driven by a fan which can be powered by a PV panel for example.

2.3.2 Temperature

The temperature of the product should be within a certain interval ($50°C - 65°C$) during the drying, high enough to insure a fast drying but low enough to not to destroy the nutrients. High temperatures reduces or even completely stops the growth of mold and bacteria. The increased drying speed slows down the contamination and delays the time when the product becomes inedible.

Keeping the temperature within this interval limits the maximum airflow velocity which can be reached with a forced airflow. If a forced airflow is too high, the air will not have enough time to heat in the collector before reaching the bags. The amount of energy transferred to the air over a certain amount of time will be limited because the solar energy that is incoming to the collector will be limited by its area as is the amount of energy that will reach the absorber from the sun.

The relation between humidity and temperature is not obvious, but it is crucial to know how many bags could be placed in a collector at the same time. Placing bags in certain types of collectors will reduce the area of the absorber (if it's a direct dryer). This will reduce the temperature inside the collector. Furthermore, adding more bags can also increase the relative humidity in the collector (more bags releasing water in the same volume of air).

2.3.3 Relative humidity

The lower the relative humidity is, the faster the drying will be. The environment where the drying takes place is then be very important. The relative humidity is very different in Lund compared to Maputo for example, especially when it is the wet season in Mozambique. This will influence the amount of water inside the air entering the collector. An easy way to lower the relative humidity is to increase the temperature without adding any water vapor.

2.4 Previous reports and studies

This master thesis is continuation of another thesis. Two students, Gustaf Bengtsson and Viktor Döhlen, worked on a prototype of solar collector. They built a collector that they tested in Mozambique and got a lot of valuable information back: the collector should not be built with wood because of the termites, the temperature is not the only influencing parameter as the airflow around the bag has a large influence. They then came back and designed a second collector based on these conclusions. [9]

2.4.1 First collector

The first collector built by the previous students is presented in figure 5. It is an indirect solar collector made of wood. It has two separable parts: the collector and the drying cabinet. The absorber is made of black paint spread on the wood. A layer of glass is put over the absorber. The cold air flows into the collector at the bottom and gets heated up by the absorber. Then, it enters the drying cabinet where it gets moist by removing the humidity surrounding the drying bag. Finally it exits the drying cabinet at the top of this one. The heat storage is meant to get warm during the day in order to extend the drying time during the night when the sun is not heating the absorber any more. Its function is also to avoid having too high temperature at the sun's radiation peak by storing heat.

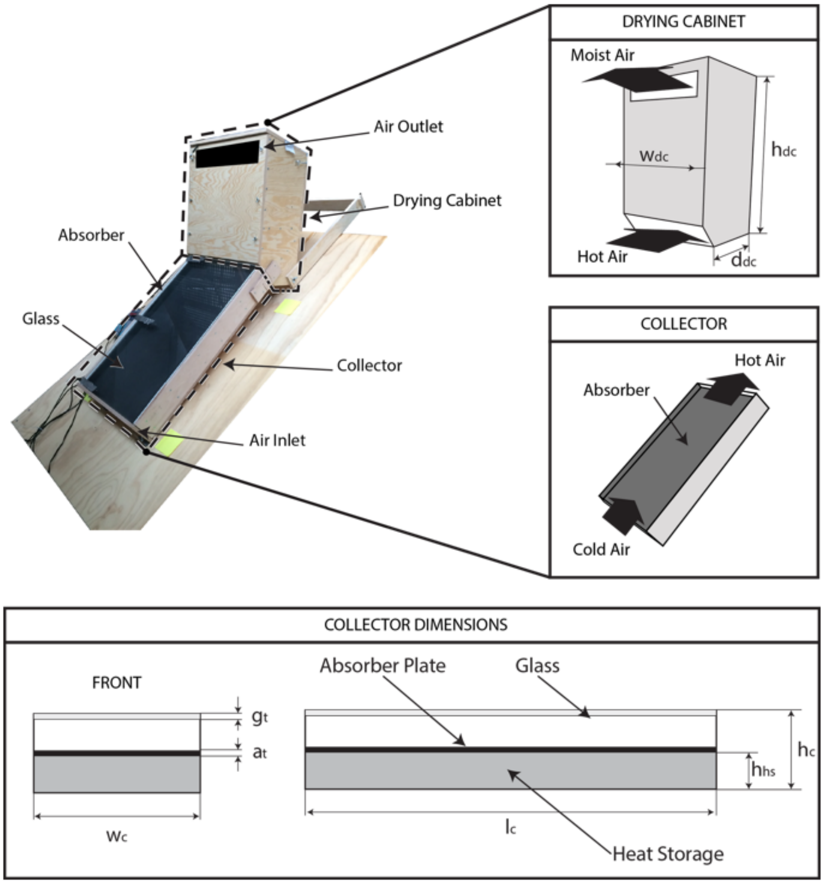

Figure 5: First collector constructed by Gustaf Bengtsson and Viktor Döhlen [9]

This dryer was taken to Mozambique to be tested. The first problem discovered on site was that the collector should not be built in wood because it would get eaten by termites. The students also realized that the concept of the prototype had to be simplified to be reproducible on site. The materials and building techniques had to be thought of for production in Mozambique. The heat storage wasn't tested, because of its complexity to be implemented. The main focus was to have a working simple dryer, and only when this was achieved to improve it.

At the time that the first collector was built, the main focus was on temperature. This design allows to achieve a high temperature in the drying cabinet.

But on site, the air surrounding the bag got saturated with water, this lead to droplets forming on the bags. The problem was that the airflow in the drying cabinet was too low to carry he water away from the bags.

2.4.2 Second collector

The food technology department at LTH then decided to test what would happen if the bags were exposed to direct sunlight. They concluded the bags could be exposed without compromising the quality of the final product. This allowed the construction of a direct solar dryer, presented in figure 6.

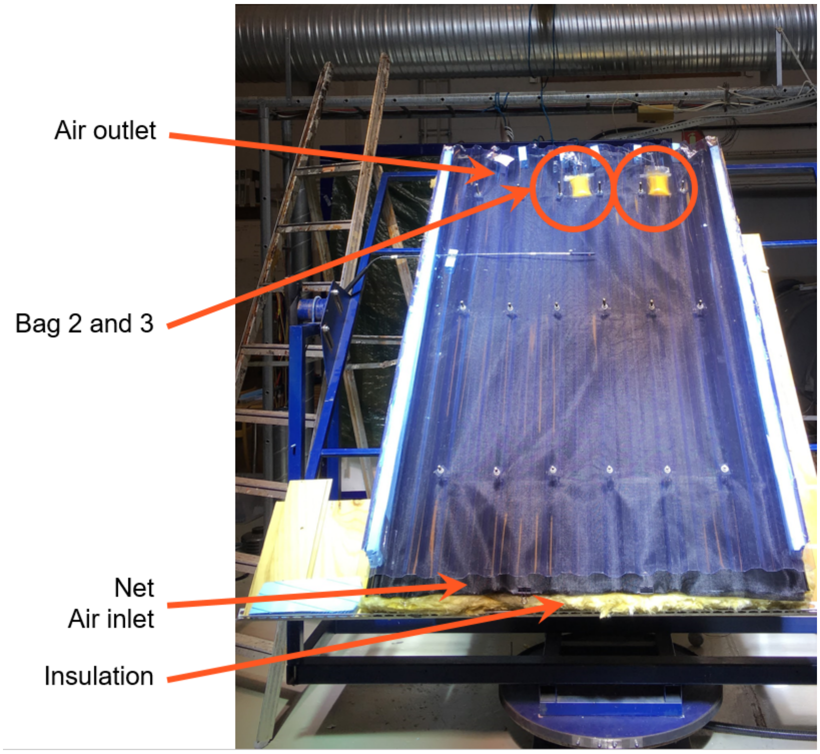

Figure 6: Second collector constructed by Gustaf Bengtsson and Viktor Döhlen [5]

The dryer in 6 absorber is made of a corrugated metal sheet. The insulation under it is made of about 10cm of rock wool. The glazing is a transparent layer of PVC. Screws are keeping the layers together and allow to control the distance between the plastic sheet and the metal sheet.

The results from this design were very promising, a significant increase in drying rate compared to control bags was obtained. This design offered the possibility to add a chimney and fan to increase the airflow. Attempts to do so were unsuccessful because the pressure losses in the funnel didn't allow for a sufficient increase in the airflow to obtain a higher velocity than with natural convection. [5]

3 Theory

Drying is one of the oldest methods of preserving food. The most common techniques to dry food are air drying, sun drying, smoking and wind drying. [9] The focus will be on sun drying and air drying because they are the easiest to implement in Mozambique.

This section will describe the theoretical background of the thesis, necessary to understand how the dryers work.

3.1 Energy balance in the dryer and heat exchange

Figure 7 displays the heat exchanges in the collector [10]. The solar radiation hitting the collector is split in three after the glass: one part transmitted, one part absorbed and one part reflected. Only part of the sun's radiation will be useful after the sun's radiation has gone through the glass. The transmitted radiation will hit the collector.

The absorbing surface will absorb the transmitted radiation, transforming part of it into heat. It will then radiate some of this heat to the glass, ($h_{rad,in}$) in figure 7, exchange heat with the air inside the collector ($h_{con,in}$) and radiate under it ($h_{rad,out}$). The collector will exchange heat with the outer air by convection ($h_{con,out}$) and radiation ($h_{rad,out}$) through all its surfaces. The role of the insulation is to make sure that the loss under the absorber is as low as possible. This is done by having λ, the heat transfer coefficient, as low as possible.

The air inside the collector will exchange heat with the collector and inner sidewalls by convection. ($h_{con,in}$)

The reflectance ,R , absorptance, α, transmittance, τ and emissivity, ϵ are crucial when looking at how the dryer will perform both with regards to how the transparent cover and the absorber will perform. For instance the transparent cover you want to have as high transmittance as possible and low reflectance and absorptance while for the absorber you want high absorptance and low emissivity and reflectance.

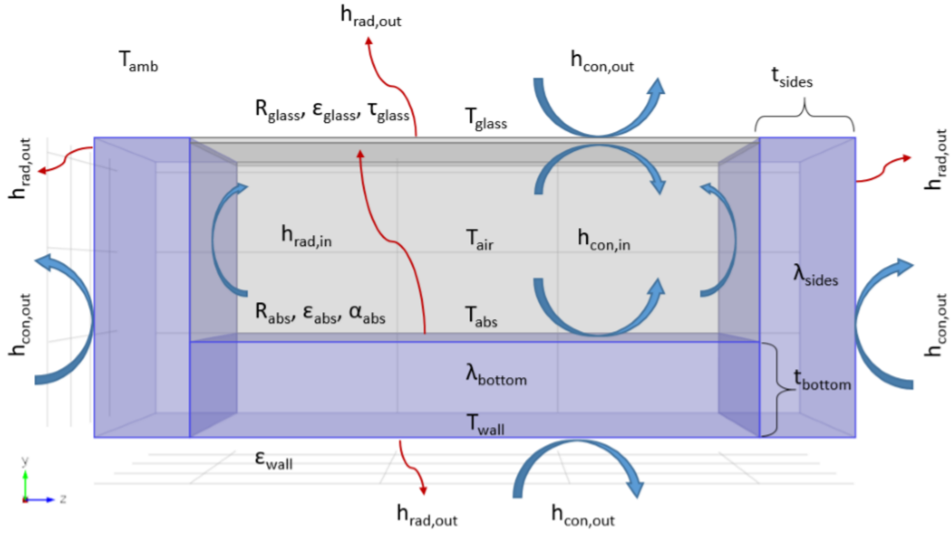

Figure 7: Schematic model figure for all energy flows, coefficient and temperatures in a solar collector, courtesy of Joakim Olsson [10]

Table 1 divides these exchanges into useful exchanges and losses. Please note that $h_{rad,in}$ is in both columns because part of this energy will be absorbed by the glassing and sent back in the collector.

Table 1: Summary of the collector's heat transfer

Losses	Useful heat transfer
$h_{rad,out}$, $h_{rad,in}$, $h_{con,out}$	$h_{con,in}$, $h_{rad,in}$

3.2 Water activity

When trying to preserve fruit by drying, the water content is of high interest. Water activity is not the same as water content because fruit can contain water in many ways such as chemically bound, physical barriers and physically bound[8] [11]. Without difficulty, it is only possible to remove the free water by drying, i.e. decrease the water activity. Below is a list of properties that illustrates a few ways bound water differs from free water in the way it behaves [12]. Bound water:

- Can't act as a solvent for salts and sugars
- Significantly lower freezing temperature
- Has close to no vapor pressure
- Higher density than free water

The goal when drying fruit is to get the water activity below 0.7, at that point bacterial growth along with fungus and mold growth has almost halted and the product can usually be stored for extended periods of time without spoiling [11].

$$a_w = \frac{\text{Equilibrium Relative Humidity}}{100} = \frac{p}{p_0} \tag{1}$$

$$p = \text{vapor pressure of water in material}$$

$$p_0 = \text{vapor pressure of water at same temperature}$$

In equation 1 the way to calculate the water activity in a sample can be seen. This takes into account the bound water in the sample. As can be seen in the item list above, the vapor pressure from the bound water is negligible. That means that equation 1 will only show the contribution of the free water to the total vapor pressure. [11] [13]

3.3 Tilt angle

In Mozambique, the season for harvesting most of the citruses is March to June (Valencia oranges ripen later). As Mozambique is in the southern hemisphere it is the time of the year where the days are the shortest, which is not the optimal for drying. But it is also the dry season, which is very important. One of the first point to discuss for our design is the tilt angle of the collector. Figure 8 shows what the tilt, β, represents. It is the angle between the ground (if flat) and the collector. It directly influences the angle of incidence, β, which also varies along the day.

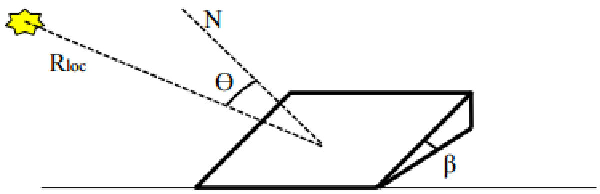

Figure 8: Drawing presenting θ and β, the angle of incidence on a surface and the tilt. (Courtesy of Ricardo Bernardo)

The choice of the β for the collector is to maximize the amount of energy received by the collector from the sun. The purpose of choosing β is minimizing θ, $\theta = 0$ corresponding to the sun normal to the surface. The problem is that along the day, as the sun moves in the sky, θ changes. It is then needed to do a detailed study considering the day of the year and the tilt to maximize the amount of energy received throughout the day.

For example, the comparison between a tilt of 45° and 55° on the 21st of June is presented in figure 9.

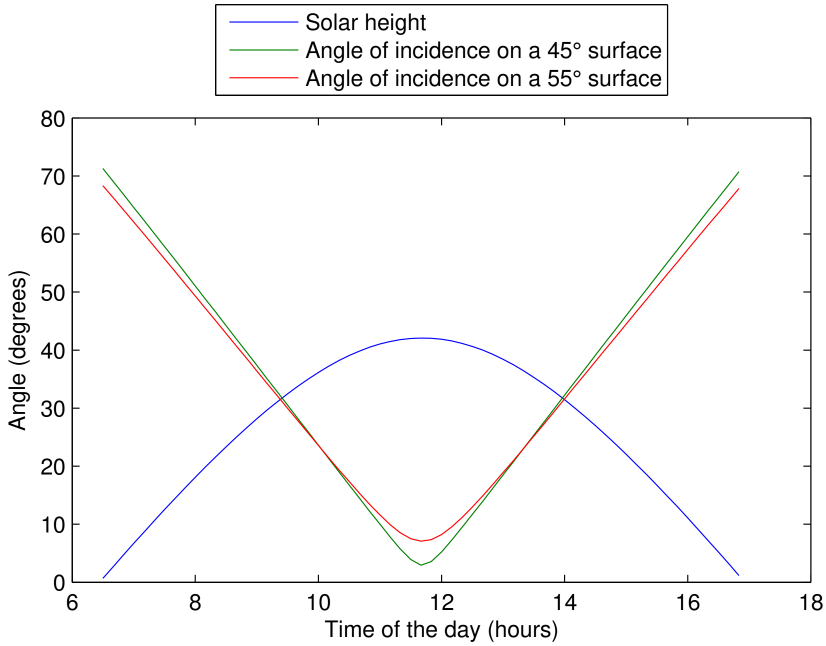

Figure 9: Incidence angle along the day, on the 21st of June in Inharrime, for two different tilts

In figure 9, we see that the losses due to the increase of the tilt from 45 to 55 degrees at noon (when the solar height is at its peak) are compensated in the morning and evening (when the sun is lower). It is interesting to compare the total energy received during the day. It is $cos(\theta)$ dependent. Calculating this over the day we realized that using a 55° tilt has three main advantages:

- The total energy received throughout the day rises by 1.8% (this was calculated by integration of the curves in figure 9). Note that no reflection effect has been taken into account. This effect would create less losses in the morning and evening for a 55° inclination as the incidence is lower than for 45°, but more at noon.
- The energy received during the morning and evening, when it is at its lowest, rises.
- The energy received at noon, when it is at its highest, decreases. This can prevent some of the materials from melting (plastic sheet).

In this case, increasing the tilt will redistribute energy in a favorable way, allowing the drying to be slightly more balanced during the day.

This shows the importance of wisely choosing the tilt considering the period of the year during which the dryer is used. It will be discussed later in the project.

The purpose of this study is to compare the amount the radiation hitting a collector depending on its tilt. On the graphs the x-axis is the day number during the year and the y-axis is a percentage. This percentage represents the fraction of energy received by the collector from the sun along the day divided by the amount of energy received during 24 hours of normal incidence. So 0.5 represents 12 hours of light at normal incidence and 0.25 represents 6 hours.

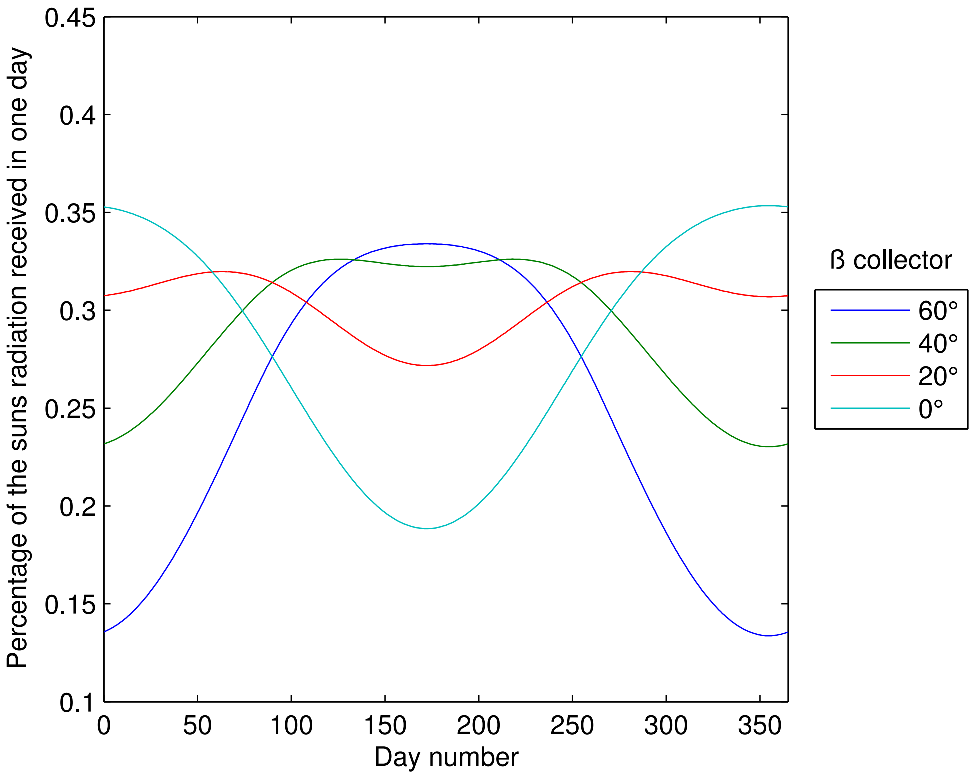

Figure 10: Results over the year in Inharrime

Figure 10 represents the results of the study over the year for 0, 20, 40 and 60 degree tilts. First, this shows that the most efficient tilt for a collector in terms of received energy is highly dependent on the time of the year. A 20 degree tilt gives the most stable results of the tested tilts, over the year. A higher tilt gives better results in the middle of the year, and a lower gives better result at the beginning and the end of the year.

For the purpose of drying tangerines in Mozambique, the harvesting season is between March and July. We then need to focus the study on that time of the year to determine which tilt is the most interesting. Figure 11 is a focus of figure 10 on the period going from the 1st of April to the 1st of July. This figure shows that a flat collector, with a tilt of 0 degree, is the worst case in terms of received energy through the day during the harvest season.

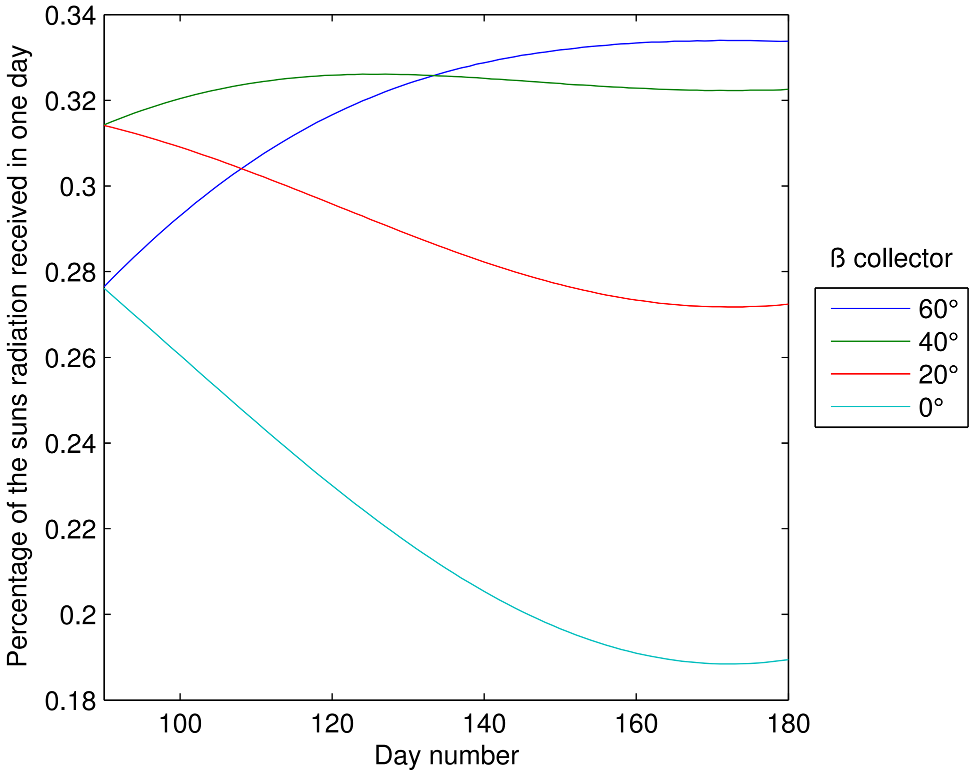

Figure 11: Results over the harvest season

Table 2 presents the ratio of received energy during harvest season compared to a tilt of 50 degree. The ratio is a mean on that period. It shows that choosing a tilt of 0 rather than 50 leads to an average 33% loss of received energy per day of the harvest season. But the interest of using a lower tilt is to make the collector longer while still keeping the height below 1.80 meters. This is shown using green and red colors in table 2.

Table 2: Summary of the collector's received energy (the mean at 50 deg length 2.5m is taken as reference) and height of the collectors depending on the tilt

Angle	Length 2.5m 01/04 - 01/07	Length 5 m 01/04 - 01/07	Max height for 2.5m length, in meters	Max height for 5m length, in meters
0	0.67	1.34	0	0
10	0.79	1.58	0.43	0.87
20	0.88	1.77	0.86	1.71
30	0.95	1.90	1.25	2.5
40	0.99	1.98	1.61	3.21
50	1 (Reference)	2	1.92	3.83
60	0.98	1.96	2.17	4.33

Making the collector larger can potentially increase the incoming radiation, then if the collector is too long the tilt is limited because of the height of the collector. For example, among the values tested and for the period that was used in the calculations, an angle of 40° gives the highest incoming radiation for a 2.5 meters length and a length of 5 meters limits the tilt to 20°. With the help of table 2 the conclusion of the influence of the tilt compared to the size of the collector can be reached. The time of the year when the collector will be used is crucial in the choice of the design. Note the relation between an increase in size and the temperature inside the collector is unclear as the losses are not taken into account in this study. It is then impossible to compare performances of 2.5m dryers and 5m dryers. Moreover, the effect of the inclination on natural convection is not considered either.

4 Prototype development

This section presents how the development of the dryers was undertaken, from the initials parameters to the changes made along the process and with the goals to meet with the dryers. During the building of the prototypes in both Lund and Mozambique a power drill was used. This was done to reduce the time required before testing could begin.

4.1 Design criteria

Table 3: Summary of the new collector's parameters, as of 16th of January, 2017

Design Parameters	Requirement
Direct/Indirect/Mixed Dryer	Direct or Mixed
Passive/Active Dryer	Both
Airflow (Speed, characteristics, direction)	Velocity: **As high as possible, except if slowing the process** Characteristics: better turbulent (higher heat transfer) Direction: Parallel to the biggest dimension of the bag
Temperature Interval	$50°C - 65°C$
Drying time	Two to three sunny days
Material	No wood, has to be available in Mozambique
User friendliness	As high as possible

Table 3 presents the first decisions made about the collector that was built, as of 16th of January 2017.

4.2 Designs

The designs are further explained in the following section. The two different designs that were chosen to be built and tested will be more closely described.

4.2.1 Insulation

The decision to change the insulation thickness from 9 cm in the collector from the previous students to about 4.5 cm according to simulations made by Joakim Olsson [14] regarding the diminishing returns of increasing the thickness of the insulation. This can be seen in figure 12. Doubling the insulation thickness from 5cm to 10cm only increases the absorber temperature of around 5°C when it is already at 90°C, which results in an air temperature increase of 0.5°C.

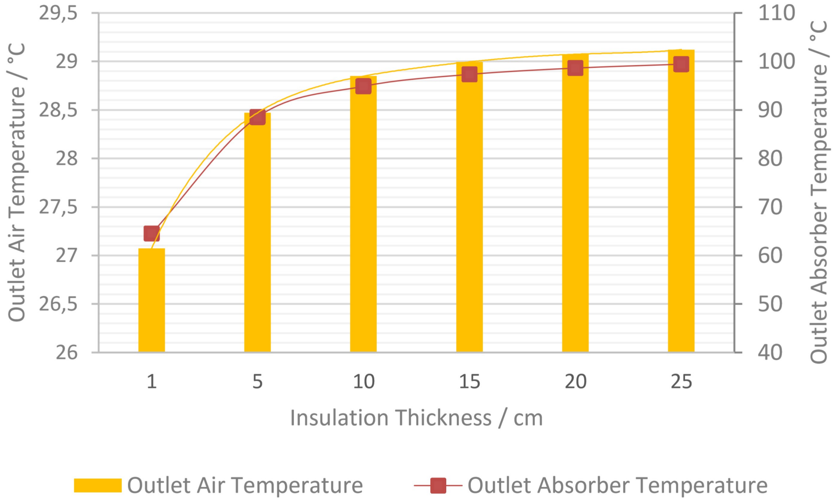

Figure 12: Graph of the diminishing returns of increasing the insulation thickness, courtesy of Joakim Olsson [14]

4.2.2 Passive collector

Following the design needs and using a passive collector, the decision was made to keep a tilted part to maximize the incoming radiation and to have the natural flow of air. Having the collector tilted could pose a problem for the drying of the bags especially later in the drying process. As more water evaporates from the bags, if they are leaning the exchange surface will decrease as the remaining juice will flow to the bottom to form the bag into a teardrop shape. This problem was solved using an extension at the end of the dryer in the form of a horizontal ending so that the bags could lay flat during the entire drying process.

A schematic picture of the passive collector can be seen below in figure 13. The picture below shows how the horizontal part is mounted in relation to the inclined part. The bags are placed in the flat part only.

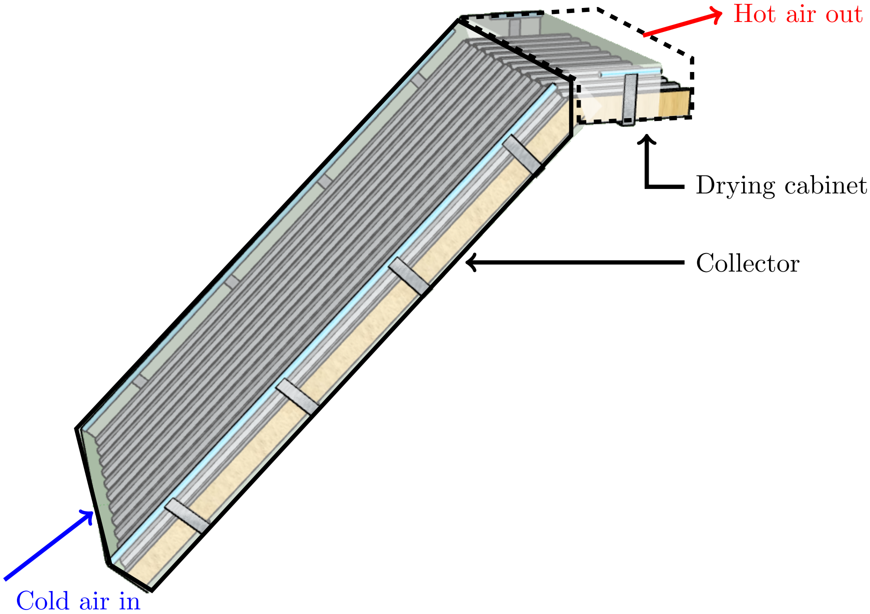

Figure 13: The leaning collector design with horizontal part

The passive collector, presented in an exploded view in figure 14, is composed from top to bottom by:

- A transparent plastic sheet: this was chosen because it was safer to handle than glass and also cheaper and easier to find in Mozambique.
- Plastic side supports: these were made to ensure that there was a distance between the plastic sheet and the absorber. They are fastened on the tip of the metal angles.
- Top corrugated metal sheet and plastic net: They form together the absorber of the collector. They are cheap and easy to find, and the net is used to increase the heat transfer area from the absorber to the air.
- Rock wool: this was added to decrease the heat losses through the back of the collector. It was replaced in Mozambique by styro foam and expanding foam due to the lack of rock wool in Maputo.
- Bottom sheet of corrugated metal: this was used to ensure the structure was stable and make the dryer easier to handle.
- Metal angles for fastening the side supports for the plastic.

- Screws were used along with the metal angles to keep the corrugated metal sheets and rock wool together.

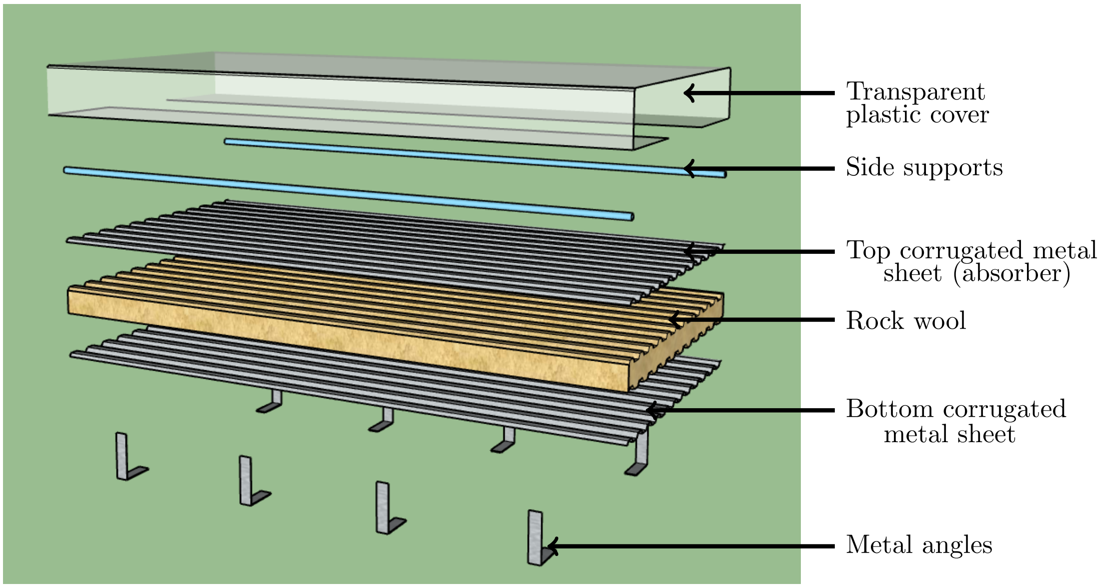

Figure 14: Exploded concept view of the collectors

The passive dryer is opened at both ends to ensure that an air-flow is generated through natural convection. The flow through the collector could possibly be utilized more than it currently was, as the air contained just slightly more vapor at the output than it was then. This means that the airflow is not taking away a lot of water before exiting the collector. This gave the idea for the active collector that is described below.

4.2.3 Active collector

Following the needs, a closed collector with fans was built for the active collector. This collector has fans blowing straight on the bags to dry them with high air speed and high temperature environment. In this case, the airflow from the fans are assumed to be the same for a given voltage.

The air-flow in the active dryer is forced. It means the dryer can almost be entirely closed while still having an airflow inside. This gives the possibility of increasing the operating temperature. An opening can be used to regulate the relative humidity inside the dryer and exchange the air.

The active collector design that was chosen could be closed to only allowed leakage to keep the relative humidity inside the dryer low to insure a high drying rate. This was done through controllable side openings. The collector was built in the same way as the passive one. In Lund, the leaning part of the passive dryer was converted into the base of the active dryer as shown in figure 15 is a concept image of the active collector. A PV-cell powers fans that are placed inside the dryer for high airflow around the bags. The bags are then placed on a grate that supports them and makes sure that the airflow is able to flow both over and under the bags. The plastic on the shorter sides can be opened to regulate the relative humidity and temperature inside the collector while the longer sides will be closed when the collector is in use.

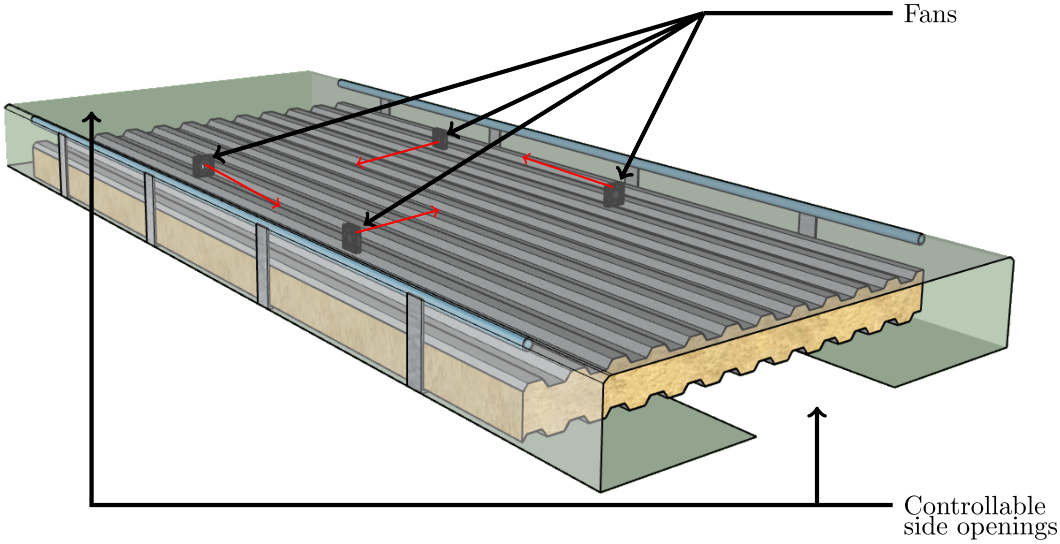

Figure 15: Concept image of the active collector, with the fans inside

4.3 Support structure

In Lund a metal frame with a controllable angle compared to the floor was used. In Mozambique, wooden structure was built. The problems linked to using wood have been described in section 2.4. Due to a tight schedule, this temporary solution was chosen to allow the best testing conditions.

4.4 Prices for components used in the dryer

The price for the components bought in Mozambique for the collectors can be seen in table 4. It can be seen that, as expected, the fans and PV panel are the most expensive component. Choosing the active collector raises the prices from 143% compared to the passive collector.

Table 4: The price of all the components used in the collectors, the last three items are only applicable for the active dryer (for 1 MZN = 0,133572 SEK, as of 2017-08-08 07:21 UTC)

Product	Size	Unit price	Qt. active	Price active	Qt. passive	Price passive col.
Metal sheet	800*3600*0.4mm	1039 Mts	1	1039 Mts	1	1039 Mts
Net	3*1m	549 Mts	1	549 Mts	1	549 Mts
Styrofoam	100*200*2cm	896 Mts	1	896 Mts	1	896 Mts
Fillinf foam	750ml	383 Mts	2.5	957.5 Mts	2.5	957.5 Mts
Plastic sheet	4*5m	149 SEK	0.5	74.5 SEK	0.5	74.5 SEK
Metal angles	8 pcs 10*10cm	1	1	294 Mts	1	294 Mts
Plastic support	10mm*2.5m	49 Mts	2	98 Mts	2	98 Mts
Nuts and bolts	50 pcs, 6*75mm	468 Mts	1	468 Mts	1	468Mts
Wood for frame	38*38*5400mm	243 Mts	3	729 Mts	4	1230 Mts
Wood screws	50 pcs, 4*45mm	100 Mts	1	100 Mts	1	100Mts
Fans	120*120mm	177 SEK	4	708 SEK	0	0
PV-panel	20W	460 SEK	1	460 SEK	0	0
Cables	N/A	N/A	N/A	0	0	0
Total				1927.7 SEK		792.2 SEK

5 Method

This section describes how the work in this thesis was conducted while also presenting the measuring equipment and also where the experiments were conducted.

Below follows a short description of the relevant parts of the experiment setup. This will be divided into a part describing the tests in Sweden and the tests in Mozambique and also between the two different dryer designs that were tested. The equipment used for both tests will be described, including their respective accuracy and range.

5.1 Lund laboratory setup

Below in figure 16 a mapping of the incoming radiation on the leaning part of the passive dryer from the lamp used in Lund can be seen. The average incoming radiation is 905 W/m^2 but as can be seen in figure 16 the variation of the incoming radiation is not something that can be ignored. For instance the incoming irradiation at the top is only just over 400 W/m^2 while at the highest point in 45x80cm it is close to 1400 W/m^2.

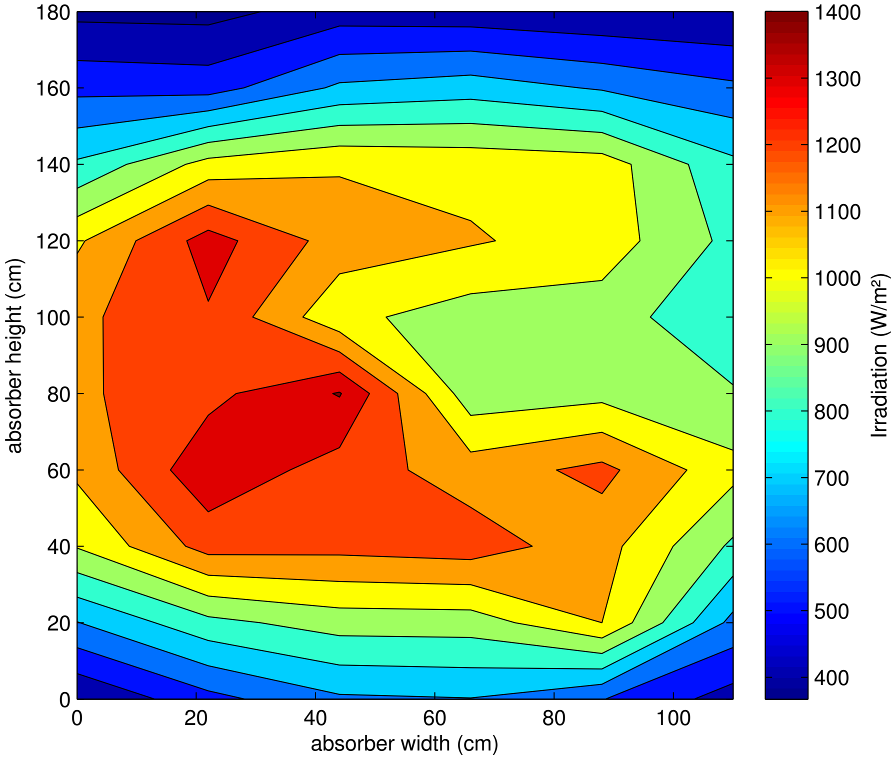

Figure 16: Irradiation on the leaning collector in the Lund laboratory

5.2 Measuring equipment

In table 5, a list of the measuring equipment can be seen along with their accuracy and range and location while the experiment is running.

Table 5: Measuring equipment used along with accuracy and range of each device

Device	Measures	Unit	Accuracy	Range	Location
Testo 435-2	Airspeed	m/s	± (0.3m/s + 4% of mv)	0 to 20m/s	Bag
	Temperature	C°	± 0.3C°	-20 to 70C°	Bag
	RH	%	± 2%	0 to 100%	Bag
Vernier LabQuest	Temperature	C°	± 0.5C°	-40 to 135 C°	Ambient
	RH	%	± 2%	0 to 85 C°	Ambient
	Irradiation	W/m^2	± 5%	0 to 1100 W/m^2	Ambient
	Temperature	C°	± 0.5C°	-25 to 125 C°	Absorber
Scale	Weight	g	± 1g	0 to 3000g	Bag
Pyranometer	Irradiation	W/m^2	± 1.29%	0 to ? W/m^2	Collector

5.3 Shading study

The shading study in Lund was conducted by using a piece of cardboard to shade one bag in the passive collector and then comparing the drying rate of the shaded bag to an unshaded bag. The purpose of this study is to investigate the influence of direct sunlight on the bags.

5.4 Laboratory testing in Sweden

The lab in Lund was used to simulate stable sun conditions while keeping the test in the ambient conditions such as temperature and relative humidity as constant as possible.

5.4.1 Measurement setup

A schematic drawing of the measurement setup for the inclined dryer can be seen in figure 17.

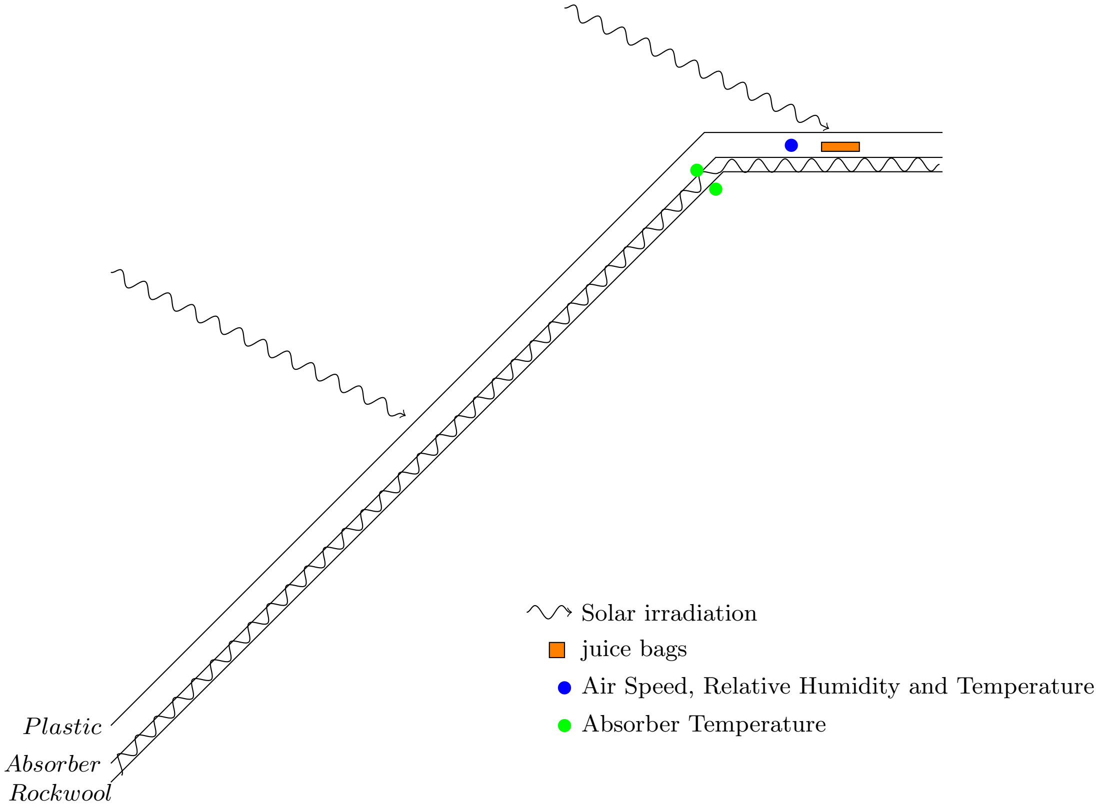

Figure 17: Position of probes on the passive collector in the lab

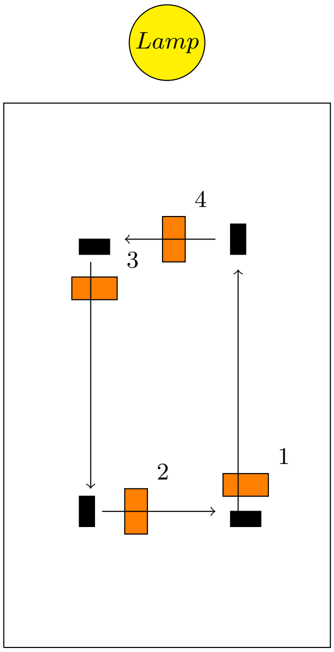

Figure 18: Position of the fans and airflow in the active collector in the lab seen from above

A schematic drawing of the setup for the horizontal dryer is pictured in figure 18 including the placement of fans and bags used for drying.

5.4.2 Laboratory setup

Below in figure 19 a photo of the inclined collector is presented, with the horizontal ending. This shows the setup used for testing.

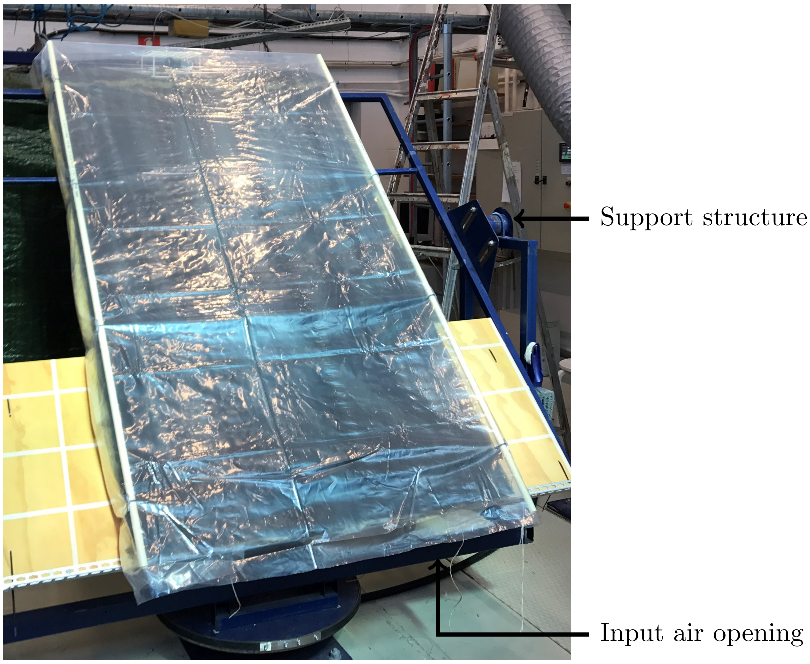

Figure 19: A picture of the inclined collector in Lund

The active collector was made using the leaning part of the passive collector. The metal structure was turned flat and the fans were added inside. In Lund they were controlled by a voltage source to ensure similar conditions for each test.

5.4.3 Sensitivity study

The sensitivity study was conducted to investigate any correlation between the position in the dryer and the air-flow and temperature. In order to do so four positions were measured in the flat part of the collector, as shown in figure 20. They allowed to test the effect of an increase on the y-axis (getting closer to the exit) and on the x-axis (getting closer to the side) on the temperature and airflow velocity.

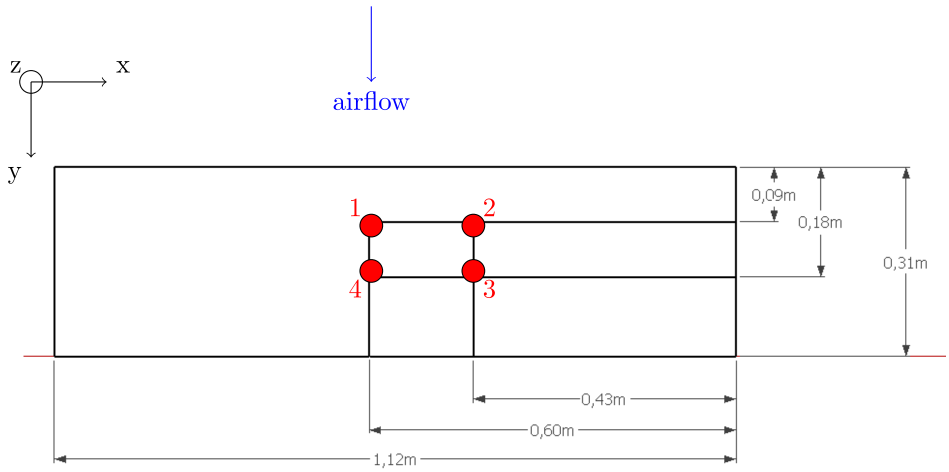

Figure 20: Drawing of the flat part of the passive collector, view from above, with the 4 positions chosen for the sensitivity study

5.5 Testing in Mozambique

Ambient conditions were logged every day with the Vernier equipment that can be seen in table 5. Temperature, relative humidity, wind speed and irradiation were logged with the Vernier data logger. The loggers were not compatible with the pyranometer so the output voltage of it was logged instead and then converted to W/m^2 in accordance with the data sheet provided by Vernier (1V = 250 W/m^2).

Due to the fact that the insulation used in Lund could not be found in Maputo we measured the temperature on the top and bottom sheet of corrugated metal. Also the incoming irradiation on the dryer was assumed to not vary depending on the position inside the dryer. This means that the measured irradiation that was taken with the Vernier pyrometer was used for the entire dryer, which wasn't the case in Lund.

5.5.1 Juice preparation

The juice was made from oranges bought in Mozambique. They were then juiced, and pasteurized (except for the first tests in Maputo). The bags with sugar were prepared so 10% of the final weight was added sugar and 90% juice.

5.5.2 Maputo setup

The placement of sensors on the collectors themselves was comparable to what it was in Lund, as far as it was possible due to the differing dimensions of the dryers.. The following figures 21 and 22 are pictures taken in Maputo of the two dryers that were built there with the local materials. The dryers were placed outside, in an open area at the University Eduardo Mondlane in Maputo. In figure 21 the chair is used to put the logging equipments. It is not part of the collector.

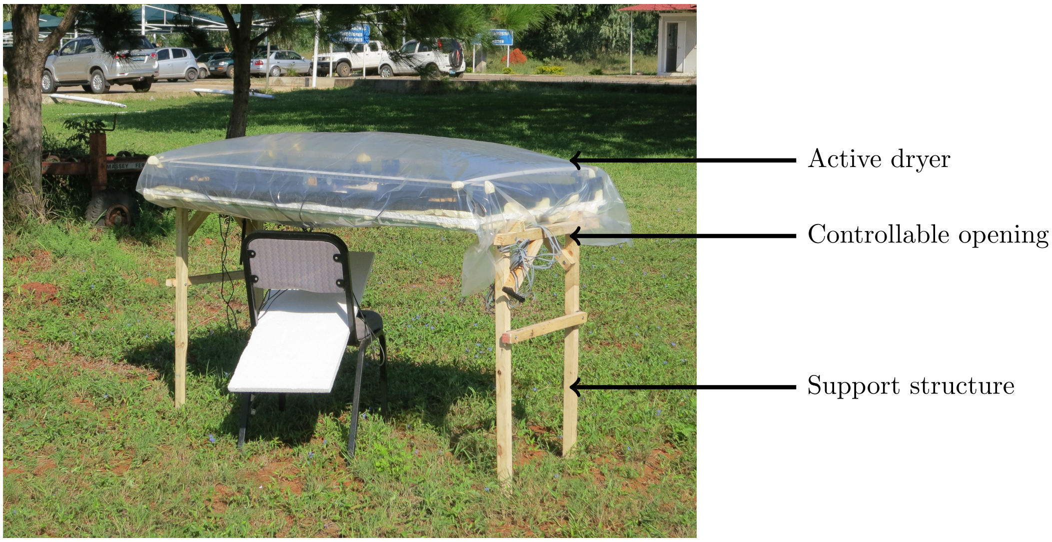

Figure 21: A picture of the horizontal collector in Maputo

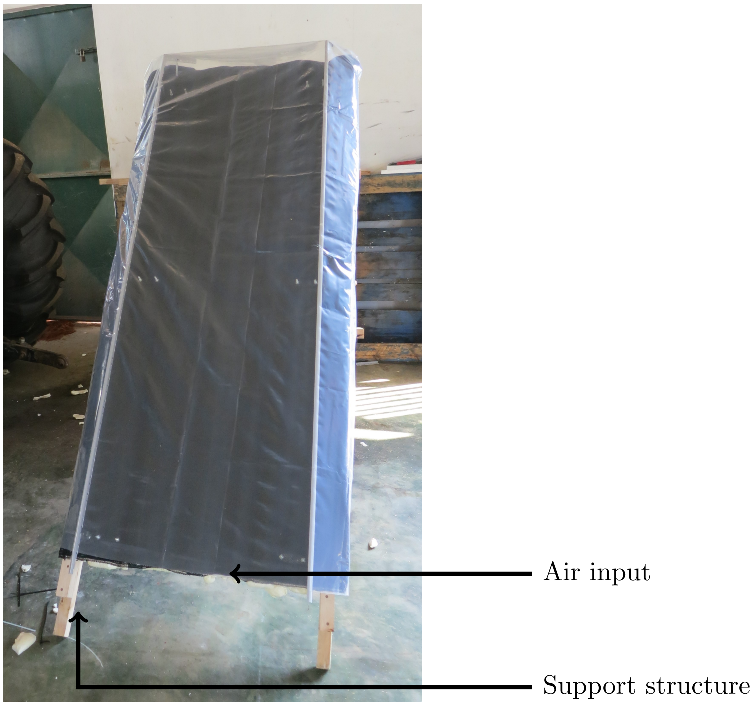

Figure 22: A picture of the passive dryer in Maputo

5.5.3 Inharrime setup

The dryers were just moved from Maputo to Inharrime and setup in a similar way. This can be seen in figure 23. The way the control bags were set up can also be seen.

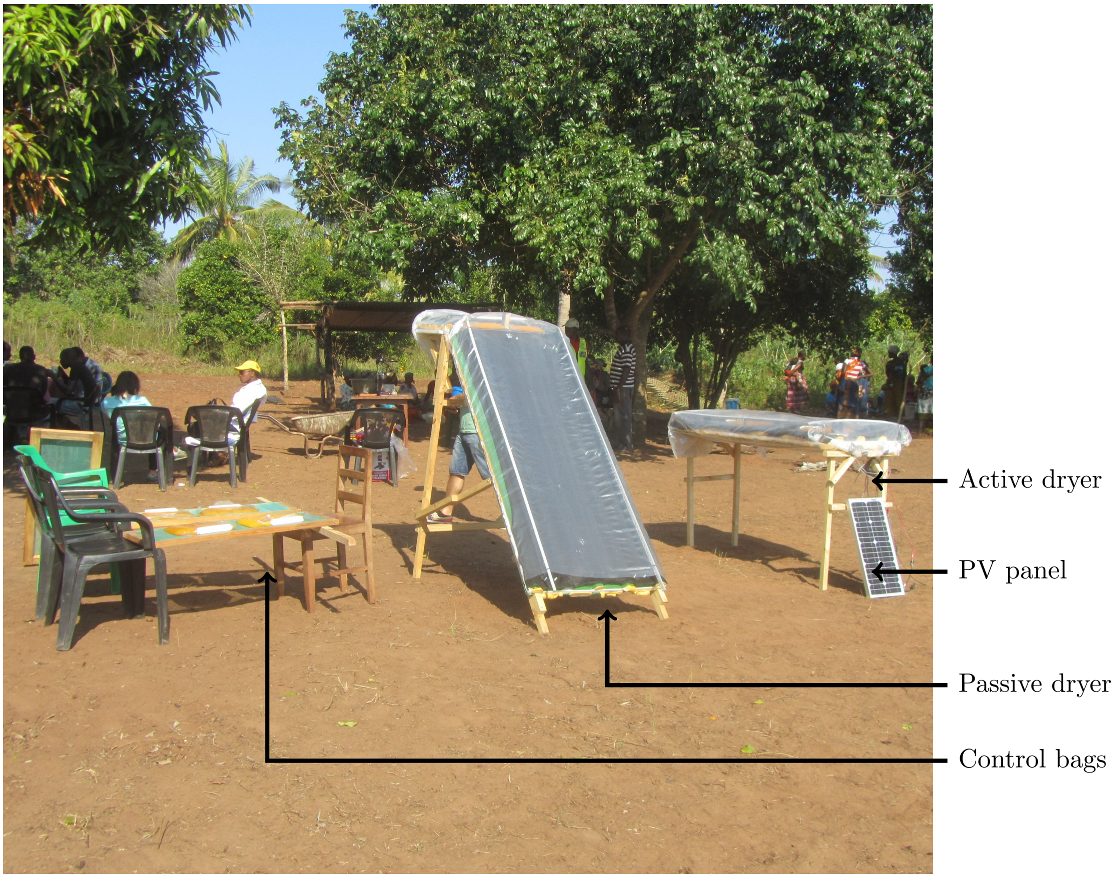

Figure 23: A picture of the collectors and control bags in Inharrime

5.5.4 Field testing at University Eduardo Mondlane, Maputo

The setup for testing in Maputo was similar to the one in Lund. The only difference being the size of the collectors themselves. This was to limitations placed by the available materials, the corrugated metal sheet was 80 cm wide instead of 100 cm in Lund. The weave of the net used in Mozambique was a lot thicker and the color of the corrugated metal sheet was green instead of black. There was no rock wool insulation available at the local hardware store so the insulation was instead made with styrofoam and an expanding foam spray that is usually used for sealing holes.

5.5.5 Field Testing in the Inharrime Region

The tests in Inharrime with the farmers were focused on seeing how user friendly the dryers are to use and put together. Their performances in real conditions were also tested. This was also done to give us more data when comparing the two different dryer designs.

5.6 Collector comparisons

The performance of the dryer will be evaluated on the basis of the drying rates compared the control bags placed in ambient conditions. Price and user-friendliness of the dryer will also be taken into account.

6 Results

The result chapter is divided into three sections. The first one deals with preliminary studies such as a sensitivity study for the passive dryer done in Lund, a shading study. Then the second part presents the drying results from Lund for both the passive and active dryers. Finally, the last part is the tests done in Mozambique.

6.1 Preliminary studies

6.1.1 Sensitivity study of the output parameters of the passive collector

Figure 24 presents the results of the sensitivity that was conducted to investigate the airflow through the horizontal part of the passive collector. Positions 1, 2, 3 and 4 are detailed in figure 20. The measurements were made using the Testo 435-2 probe (see table 5)

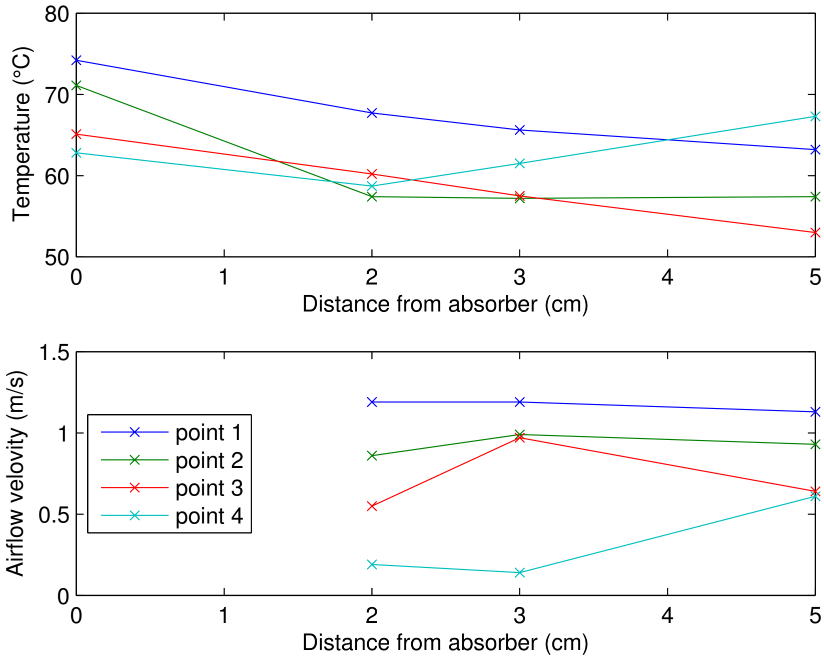

Figure 24: Temperature and airflow depending of distance to the absorber in the four locations

In figure 24, it is important to note that there is a difference in the absorber temperature of over 10°C with only four different measurements (shown on the temperature graph, at 0cm distance from absorber). Different trends are visible for the temperature when increasing the distance from the absorber (this means closer to the plastic cover): constant for position 2, decreasing for positions 1 and 3 and increasing for position 4.

There is no clear pattern either for airflow velocity. Interestingly in figure 24, the airflow velocity at position 4 increases as the distance from the absorber is increased.

6.1.2 Shading study in Lund

Table 6 shows the results of the shading study, comparing the drying rate of a bag when it is either shaded or exposed to direct light from the lamp. All other conditions such as room temperature and relative humidity being kept as constant as possible. The difference in drying rate between the two cases tested is not significant.

Table 6: Shading study conducted in Lund

Bag	Drying rate $g/m^2/h$
Shaded	650
Unshaded	632

Table 7 shows the conditions around the bag in the passive dryer while the bag was shaded and unshaded. The temperature, airflow velocity and relative humidity were measured right before the bag in the flow direction with the Testo 435-2 and anemometer probe. Note that the shaded bag is drying faster than the unshaded. In fact, there is no significant difference in the measures, so it is considered that the shading in the laboratory has no influence on the drying rate.

Table 7: Conditions for the shaded and unshaded bag

	Shaded bag	Unshaded bag
Air temperature $°C$	65.2	67.4
Air velocity m/s	1.22	1.47
Relative humidity %	3.93	3.74

6.1.3 Opening of the active collector

A test was run in Lund with bags containing orange juice to see the influence of closing the collector on the temperature and relative humidity of the air inside. This is shown in figure 25. After 4 hours, when the parameters were stable, it could be seen that the temperature of the closed collector was slightly higher ($69.3°C$ compared to $66.4°C$). This increase in temperature was paired with a much higher relative humidity (34.5% compared to 9.5%). Condensation was seen in the corners of the collector. This is sign that the absence of opening does not allow the relative humidity to stay low enough everywhere in the collector to avoid saturation and condensation.

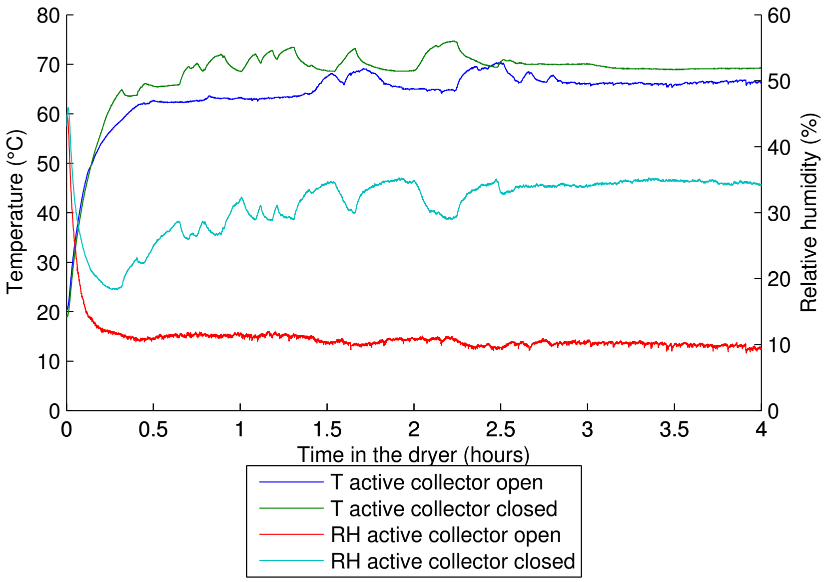

Figure 25: A graph comparing the relative humidity and temperature in the active collector when opened and closed

The same test was conducted in Mozambique to test the possibility of pasteurizing orange juice inside the active collector. The same creation of condensation was observed, and the orange juice was not heated enough to achieve pasteurization. This means the juice has to be pasteurized outside before being put in the collector to insure safety. The resulting condensation on the plastic around the dryer can be seen in figure 26.

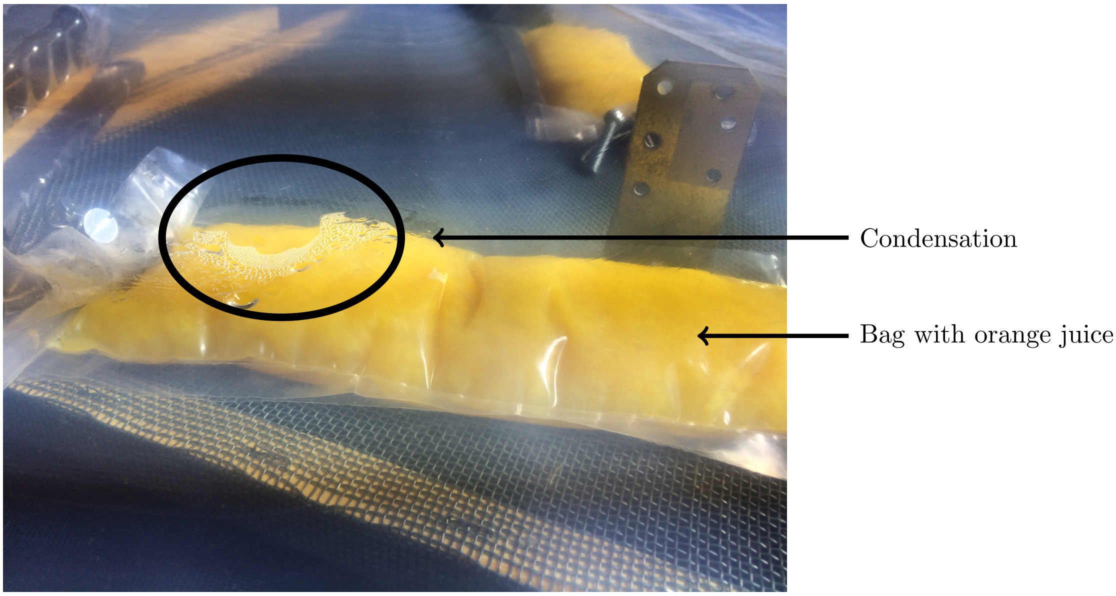

Figure 26: A picture showing the condensation on the plastic as a result of no air exchange

6.1.4 Influence of the weather

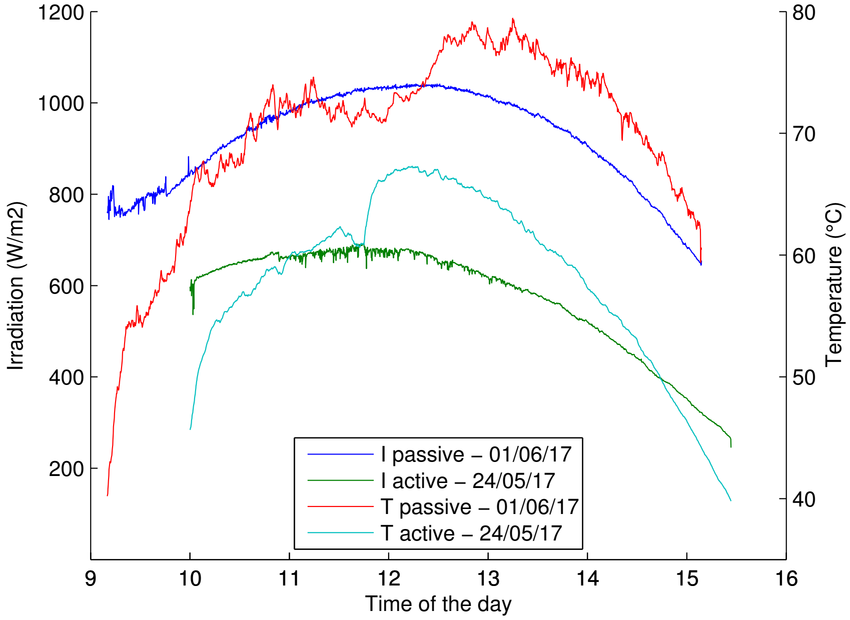

Figure 27: A graph showing good days of drying for both collectors in Maputo

The graph in figure 27 shows what is assumed to be two typical days of drying with the resulting temperatures in the dryers for both the active and passive dryer. The incoming radiation on the passive collector was much higher than on the active collector. This was due to the inclination difference, and was expected as a results of the inclination study in section 3.3. It can be seen that the temperature curve for the active collector is much more stable. This is due to a higher sensitivity to the wind with regards to the temperature in the passive collector. The exception being around 12, where a sharp decline and increase can be seen in the temperature of the active collector. This is explained by the plastic cover that was moving during the first part of the measurement before it was properly fixed in place.

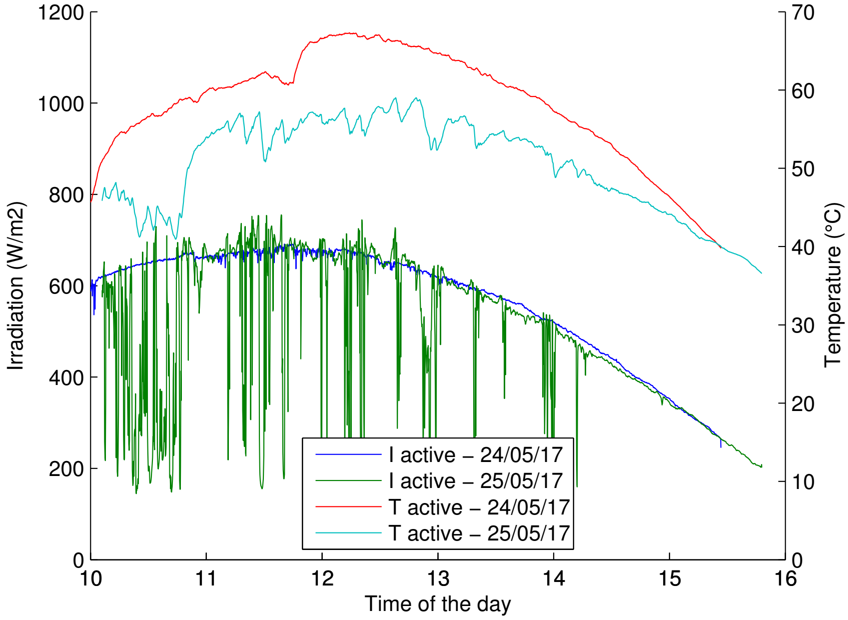

Figure 28: A graph showing a more varied day and a more stable day in Maputo, for the active collector

The graph in figure 28 shows 2 days with larger variations in the incoming irradiation of particular interest due to a large amount of clouds on the 25th of May. The temperature in the dryer is compared with the one on the 24th of May, when the sky was clear. This results in large temperature differences (peaking over 15°C) at similar times during the day.

6.1.5 Insulation study in Mozambique

Table 8: The result of the insulation study of the collectors built in Mozambique

	Top sheet	Bottom sheet	Difference
Active	54.3 °C	38.7 °C	15.6 °C
Passive	68.0 °C	41.4 °C	26.6 °C

The insulation study was done by measuring the temperature on top of the absorber and on the bottom and comparing the two temperatures. The result of this can be seen in table 8. There were no difference in the insulation used between the two dryers.

6.2 Tests in Lund

This section presents all the results from the experiments conducted in Lund for both the active and passive dryer.

6.2.1 Passive dryer in Lund

The results of the drying tests in Lund are presented in figure 29. The first graphs presents the drying rates function of the airflow velocity, and the second the drying rates function of the temperature. The control bags with low irradiation were receiving $550W/m^2$ and the bags with high irradiation $850W/m^2$

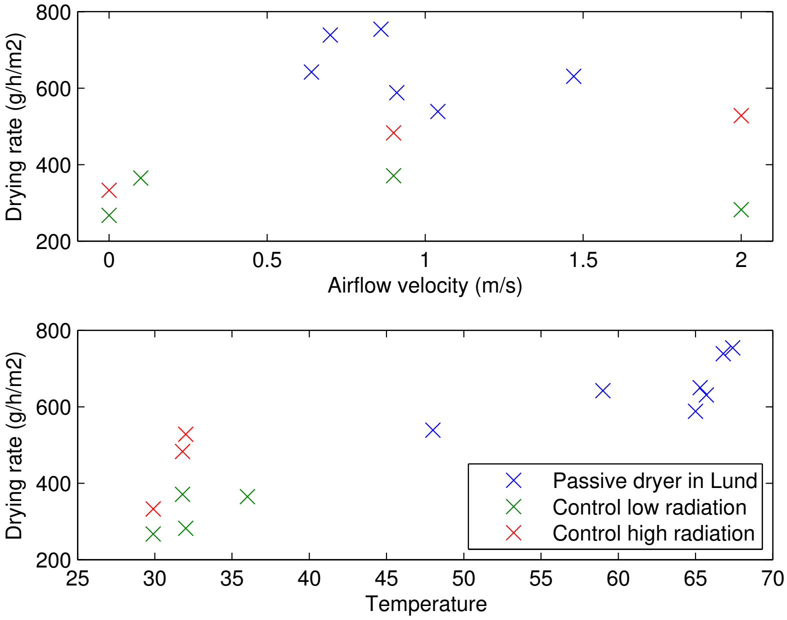

Figure 29: A graph showing the drying rates compared to air speed and air temperature under different conditions and the controls under different conditions

In figure 29, it is very difficult to point out a trend to describe drying rate as a function of either temperature or airflow. The main conclusion of these graphs if that for each test the bags in the dryer were having a higher drying rate than control bags. Notice that the low irradiation with high airflow dries slower than the bag with a lower airflow, but the control with high irradiation dries faster with increasing airflow. [15]

6.2.2 Active dryer in Lund - Test results

Table 9 presents the results of a two day test with the passive collector in Lund. It shows the mean ratio of the drying rate of the bags inside the collector divided by the drying rate of the control bags. During this test, one side of the collector was open, allowing air exchange with the outside to keep the relative humidity low while still maintaining sufficiently high temperature inside the collector. It can be seen that the ratio decreases significantly from the first day of drying to the second. It means that compared to the control bags, the bags inside the collector dry faster during the first day than during the second one. The range of drying speeds achieved with the fans being active was between 630 and 1090 $g/m^2/h$.

Table 9: Tests in Lund with active collector on 2017-04-11 and 12 with only one short side open

	Day 1	Day 2
Mean of bags in dryer *((drying speed ratio to control))*	2.19	1.65
Control (ratio)	1	1

Table 10 shows a summary of the drying speed of all the conditions tested in Lund for the active collector. It uses the same ratio as table 9. Four conditions were tested:

1. Both short sides of the collector open
2. One short side of the collector open, the other closed.
3. Both short sides of the collector closed
4. Both short sides of the collector closed, none of the fans active

For the first three conditions, fans were running on the same power level. This means with a laboratory voltage supply feeding the fans 12V.

Table 10: Tests in Lund with active collector on 2017-04-21 with no fans active

Bag	Both sides open	One short side open	Both sides closed	No fans active
Mean of bags in dryer	2.40	2.19	1.83	1.31
Control (ratio)	1	1	1	1

The first conclusion to draw from table 10 is that closing the active collector, in Lund, impacts the drying rate negatively. This has to be related to the relative humidity study in the active collector, presented in 6.1.3. It can also be seen that a fan failure during drying would almost remove the benefits of putting the bags in the dryer (only 31% increase)

6.3 Tests in Mozambique

6.3.1 Tests in Maputo

The table showing the drying rates for the first day of testing with both dryers at the same time can be seen in table 11 under day 1. It shows a significant increase in drying rates when the bags are placed in the dryers compared to when they are placed outside in ambient conditions.

The table 11 also shows the drying rates for the second day of testing with both dryers. The bags used were the same as on day 1. The increase in drying rate compared to control bags is not as large as during the first day but they still dry faster compared to the control bag. This difference is more clearly shown when comparing day 1 and 2 in the table.

The table 11 finally shows the drying rates for the third day of testing with both dryers. The bags used were the same as on day 1 and 2. The increase in drying rate compared to the first and second day is not as large for the passive dryer and for the active dryer the drying rate is even on occasion slower than the control. The cumulative weight loss for the bags in the dryer is higher than the control bags, this can be seen in the graphs in figure 30 and figure 31.

Table 11: Tests in Maputo, drying rates and ratios compared to control

	Day 1		Day 2		Day 3	
	Sugar	No Sugar	Sugar	No Sugar	Sugar	No Sugar
Active ($g/m^2/h$)	497	609	320	390	187	220
Passive ($g/m^2/h$)	465	457	325	354	216	287
Control ($g/m^2/h$)	293	311	246	264	192	227
Active (ratio to control)	1.70	1.96	1.30	1.48	0.97	0.97
Passive (ratio to control)	1.59	1.47	1.32	1.33	1.12	1.26
Control	1	1	1	1	1	1

On day 1 of testing in table 11 the increase ratio from the controls can be seen. The active and passive increases are an average of the two bags that were tested in each case. The slowest bags saw an increase in drying rate of almost 50% compared to the control bags while the best bags almost double the drying rate. The ratios were calculated using the mean drying speed of the two bags in each dryer and comparing them to the control bag.

On day 2 of testing the increase ratio from the controls can be seen. The active and passive increases are an average of the two bags that were tested in each case. The slowest drying bags changed from the passive with no sugar to the active with sugar and also the overall drying rate decreased compared to the control bags, but only 30 to 50 % increase compared to a maximum increase of almost double on day 1.

On day 3 of testing it can be seen that the drying rate in the active collector is slower than the control bags. This can be further seen in the graph in figure 30 where the cumulative weight loss is much higher in the active dryer compared to the control bags but at the end of the drying the drying rate is slower.

The graph in figure 30 shows the mean cumulative weight loss in percentage for the bags in the active collector compared to the control bags for the three days during which the test ran. The bags were weighed at the start and end of each day, this is shown by the crosses in the graph. The two horizontal lines represent what was set as the finished drying. After the experiment, which lasted three day, the bags were left in open air inside the laboratory in Maputo, and then weighed. The cumulative weight loss after three days in the dryers and a week in the open air in the laboratory was set as the final one. This was done because the initial sugar content was not measured, and will be discussed in the next section. Figure 31 presents the same results in the passive dryer.

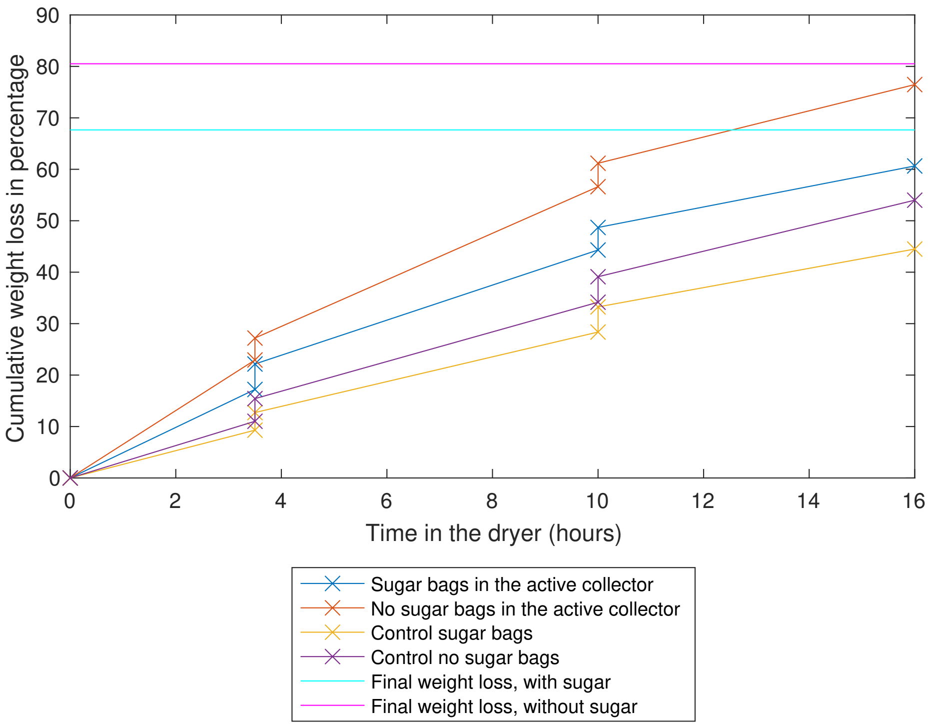

Figure 30: A graph showing the cumulative weight loss in the active dryer

It can be seen in figure 30 that bags with and without sugar dry faster in the dryer than their respective controls. It can also be noted that inside and outside the active dryer, the bags with sugar dry faster than the ones without. Finally, can also be seen that the bags with no sugar inside the active collector are really close to their final drying state after three days.

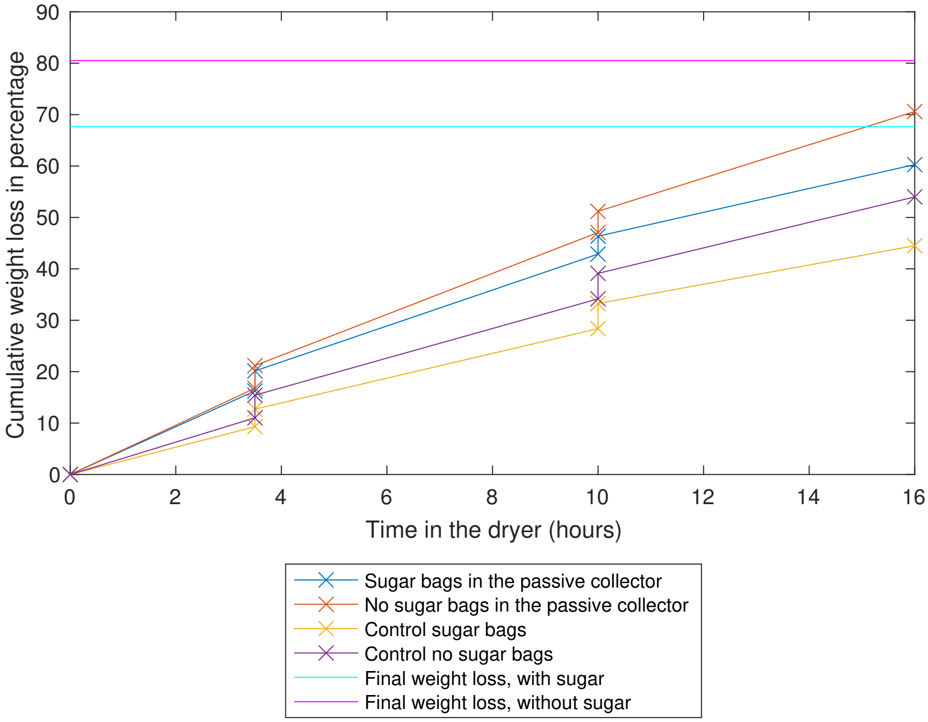

Figure 31: A graph showing the cumulative weight loss in the passive dryer

It can be seen in figure 31, as in figure 30, that bags with and without sugar dry faster in the dryer than their respective controls. It can also be noted that inside and outside the passive dryer, the bags with sugar dry faster than the ones without.

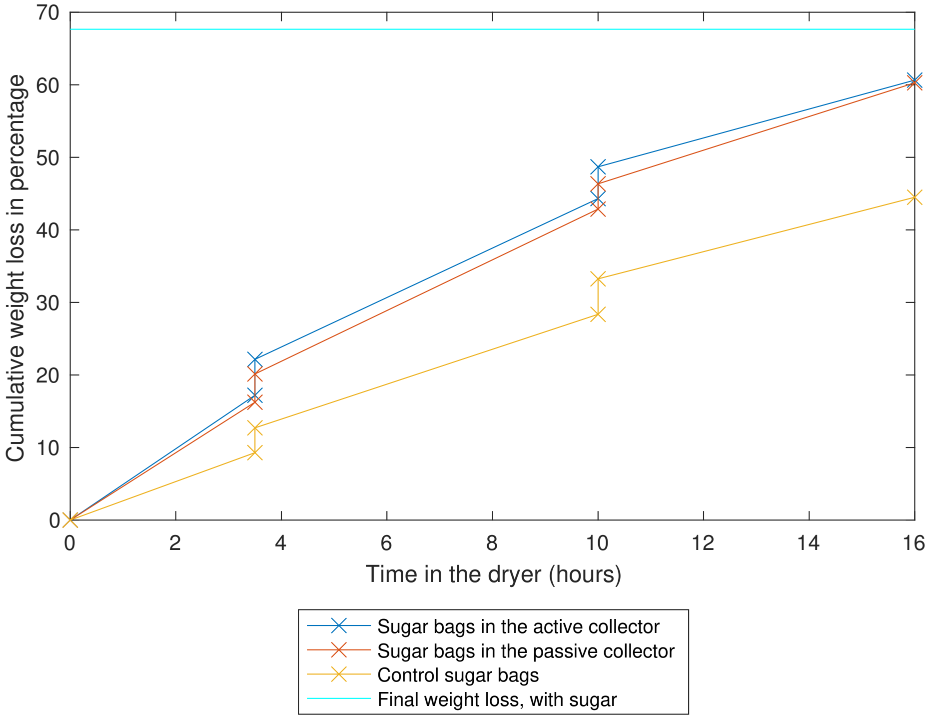

Figure 32: A graph showing the cumulative weight loss for the bags with sugar added

Figure 32 shows the cumulative weight loss for the bags that had sugar added for the three days the test ran. The graph in figure 33 shows the cumulative weight loss for the bags without any sugar added for the three days the test ran. In figure 32, it can be seen that the increase in weight loss in the bag with sugar in the active dryer compared to the passive dryer is really small. This has to be compared with figure 33 where the difference in cumulative weight loss is much bigger. The increase in drying speed going from the passive to active dryer, is then much bigger for bags with no sugar added.

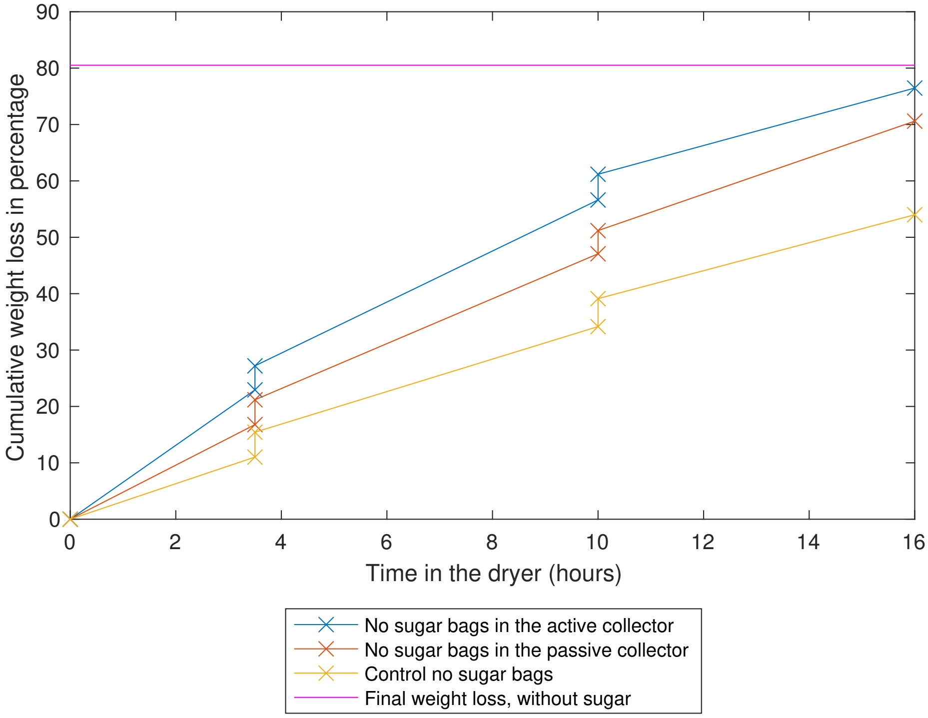

Figure 33: A graph showing the cumulative weight loss for the bags without sugar added

6.3.2 Tests in Inharrime

In Inharrime one complete drying process was completed for two big bags in each dryer. In four days, all the bags had achieved a water activity of below 0,7. It represented four pots of jam of 330ml. It was the first time the water activity measurement was made to check if the drying was complete. The set goal at the beginning of the project, two to three days to complete drying, was not achieved. It has to be noted that the weather conditions were not optimal.

6.3.3 Issues with the bags

The bags were not as resistant enough to UV and therefore the bags started to deteriorate inside the dryer in the high temperature environment there.

7 Discussion

In this section, the results from Lund and Mozambique are discussed, as well as the dryers' performances. A comparison between the dryers will also be made.

7.1 Relevance of the dryers' parameter study in the laboratory in Lund

After the first collectors were built in Lund, we focused on trying to identify the influence of the different parameters (temperature, relative humidity and airflow) on the drying rate. The results of this study are shown in figure 29. To do so we used the Testo 435-2 probe, which measures all three of these parameters in one point. It was placed just before the bag in the direction of the flow. Therefore it is not representative of the conditions in the rest of the dryer. The measurements does also not take into account the effect the probe has on the flow. It is then complicated to find a correlation between airflow, temperature and drying rate. This could be due to the fact that the measurements are not representative of the dryer's behavior or due to the lack of of a simple relation between all of these factors.

We had first assumed that measuring these parameters so close to the bag would give us some insight into the drying conditions but the sensitivity study presented in figure 24 showed that the measurements were too sensitive to the position of the probe in all three directions. It is then very complicated to relate the drying rates in the dryer to the parameters in one point.

These studies, even though they did not give the result that we hoped for, did give us a better understanding of the driers. First of all, it confirmed shortly after the first collector was built that the required temperature interval could be reached. In Mozambique, the incoming irradiation varied along the day so these studies could not have been conducted there. Finally, broached our questioning on how to approach a dryer's characteristics and performances.

7.2 Results in Lund compared to results in Mozambique

7.2.1 Conditions comparison

In order to compare the performances of the dryers in Lund and in Mozambique, a lot of parameters have to be considered. First of all, the orange juice used in Lund was bought in the supermarket, in Mozambique we prepared it ourselves. The main difference were the ambient conditions. The temperature is usually lower as are the relative humidity and wind (because the tests in Lund are conducted indoors). The use of a fan to simulate the wind stays very approximative as it is blowing very regularly, unlike the wind. A second very important thing is the use of the lamp to simulate the sun. The use of a glass in front of the bulbs prevents any UV radiation from reaching the dryer. The impact of this is very complicated to measure and predict. The laboratory also prevents other problems due to weather conditions, such as the ones shown in figure 28. The most important difference with our use of the lamp is that the angle is stable. In Mozambique, the sun moved, changing the incidence angle of the sun on the collectors. If the irradiation had been similar with the same incidence angle, it would still not have been possible to compare both conditions. That is because the irradiation on the collector varies during the days as shown in figure 27. This has a huge influence when comparing the performance of the dryers. Each hour spent in the collector in Lund is the equivalent to the peak hour of the day in Mozambique. For example if a bag stays in Mozambique from 9 to 16 in the collector, the mean irradiation is very different from the peak irradiation. But a bag staying from 9 to 16 in the laboratory in Lund will receive a constant irradiation, meant to simulate the peak irradiation of the day in Mozambique. This suggests that the drying rates in Lund should be significantly higher, as they represent only the peak drying rates in Mozambique. A better way of measuring this difference would have been to leave the bags for only two hours in the dryers in Mozambique, from 11 to 13.

7.2.2 Performance comparison

This section focuses on the first day of the testing in Mozambique for the bags with no sugar, comparing them to the tests in Lund. The same trends were observed in Lund and and in Mozambique.

Table 12: Summary of the maximum and mean drying rates achieved, presented in section 6.2 and 6.3

		Mean drying rate achieved ($g/m^2/h$)	Maximum drying rate achieved ($g/m^2/h$)
Lund	Passive	678	754
	Active	924	1090
	Control	411	528
Mozambique	Passive	457	462
	Active	609	652
	Control	311	311

The drying rates achieved in the active collector were greater than the ones achieved in the passive collector, themselves greater than the drying rates of the control bags. A summary of these values is presented in table 12. Another interesting trend can be seen. For each category (control, active or passive) the drying rates achieved are bigger in Lund than in Mozambique. Some possible explanations for this have been listed in the previous paragraph.

It can be concluded that even if the drying rates achieved in Lund and in Mozambique are significantly different, the simulations made in Lund were good to investigate trends and to compare dryers.

7.3 Results in Mozambique

In real conditions, in Mozambique, very good drying rates were achieved compared to the control bags. It almost peaked at twice the drying rate for the active collector, for bags with no sugar, on the first day of drying. The passive dryer performed very good as well, achieving very high temperatures (highlighting the influence of the tilt) and good drying rates.

The biggest achievement was the success of the drying in Inharrime. Four bags of over 1.5 kilograms each were dried in the collectors. This represents a 330ml pot of jam of final product for each bag. This was achieved in four days, with the weather not being ideal for drying. The goal of two to three days was not reached, but this remains very satisfying as the weather conditions were not ideal for drying.

7.4 Reflection on performance evaluation

The graphs in section 6.3, presenting the results in Maputo, highlighted the limits of using drying rate to evaluate the dryers' performances. It is summarized in table 11. During day 1, the drying rates ratios to control for the active and passive are significantly over 1, ranging from 1.47 to 1.96. During day 3 they only range from 0.97 to 1.26. The drying process was still more advanced for the bags in the dryer than for the control bags. This is seen in the cumulative weight loss curves.

As the drying process progresses the drying rate decreases. This means that drying speed is a good tool to predict which dryer will end the drying process first, but not how long it is going to take. Another way to to do this needs to be found.

It was not easy to imagine, from the start, all the challenges that would have to be faced. At the beginning of our thesis, our focus was on the challenges the students before us had faced. As they did not manage to completely dry bags and because the bags in their dryer were drying slower than the control bags, their main problem having been reaching a high drying rate in their dryer. We started our thesis with a similar method as they had used (weighing the bags and calculating drying rates at the beginning of the drying process). But only when arriving in Mozambique did we considered what happens for a complete drying. We then realized that using the drying rate as a baseline for comparison of the dryers' performances would be a problem for us, but we did not have time to adjust. The methods to be ready to transition from drying rate to drying time should already have been implemented earlier in Lund. In addition to weighing the bags, the sugar contents in the bag should have been measured. In fact, the only requirement to know if the drying was finished was to measure the water activity (below 0.7). So the studies were based on a perspective where the drying would not run until its end, but when it happened the measurement to determine if the drying process was complete were not made.

7.5 Choosing a dryer

7.5.1 Influence of sugar

The influence of the sugar on drying rate can be seen in figures 30 and 31. These figures show that the weight loss is smaller in the bags with sugar compared with bags with no sugar in similar conditions. This supports the conclusion from table 11, showing that the drying rates are lower for bags containing sugar compared to bags containing no sugar in similar conditions. Here, the conclusions from the reflection on performance evaluation are very important. To conclude that drying would be longer we would need to evaluate drying time, using water activity measurements. Adding sugar to the bag would create a bonding reaction involving sugar molecules and water molecules. These water molecules would then no longer be available anymore, hence making the water activity in the orange juice decrease. We can then conclude that sugar should lower the drying rates, but not that it would increase drying time. This is another reason for using sugar content measurements.

We can still compare the performances of the bags if sugar is used. To do so, figures 32 and 33 are used. In figure 33, we can see that the weight loss process is faster for bags without sugar in the active collector than in the passive collector. But in figure 32, it can be seen that the weight loss curves are really close. It can be concluded that choosing the active collector would make more sense if the recipe without sugar is chosen. Considering the extra cost of the active collector, the passive collector is a better choice if the recipe with sugar is chosen.

7.5.2 Influence of the season

The dryers and tests in Lund and in Mozambique were planned and conducted for the use of oranges. It was then necessary to consider the conditions during the harvest of tangerines and oranges. In Maputo it appeared that a lot of studies with other fruits had been conducted (mangoes, bananas) or even on vegetables (casava, also called manioc). This triggered a reflection about the use of the dryers at other periods of the year. Using the inclination study, and figure 10, we were able to quantify these effects. During mango season (December to January) , at noon, the sun peaks at a solar height of almost 90 degrees. This means β would then be 0 for the active collector and 45 for the passive collector. It then appears that the active collector would benefit from being used during the mango season rather than during the citrus season. It is not the case for the passive collector. We can't conclude this as it hasn't been tested. Furthermore, the temperature in the active collector could rise very high. But the controllable openings, paired with the angle reflection allow us to strongly expect that the active collector would be the best choice during the wet season in Mozambique (winter in Europe).

7.5.3 Influence of the prices

The prices of both collectors built in Maputo are presented in table 4. To make an accurate economic study several things are needed: the price of the collector, the production costs, the productivity, the selling price of the finished product, etc. To simplify this, it will be considered that everything is the same for both collectors except for the price of the collector and productivity. To evaluate productivity accurately the drying time and amount of product given by the collector after one drying session are needed. As it has been already discussed, the drying time has not been determined for the collectors. But neither has the capacity of the dryers (the maximum amount of juice in the dryers). This probably also has an impact on drying time in the active collector, as the absorber surface decreases with the quantity of juice.

It is then really difficult to estimate if the increase in price induced by the transition from the passive collector to the active is worth it. We can only conclude it requires a good evaluation of drying time, an investigation of the quantities of juice that can be dried at once, and a better understanding of the potential use.

However, the compared prices of the collectors presented in table 4 seem to suggest that the active dryer, being almost 2.5 times more expensive, could be too expensive compared to the passive. This highlights the important of further investigation for the sourcing of the fans and PV panel.

7.6 Difficulties

The juice used in Lund was pasteurized and the first tests done in Maputo were not conducted with pasteurized juice but when problems with fermentation was discovered, as can be seen in figure 34, this was changed. This showed the necessity of pasteurizing the juice in the bags before drying when the juice is made and not bought.

It was discovered in Maputo, then later in Inharrime that the bags could not resist 5 days of drying. It could be that they are not UV resistant. This will need to be further investigated at the food technology department as it has a crucial importance for the dryers' designs.

Sourcing rock wool in Mozambique is not possible. Glass wool was found in Maxixe, 85 km away from Inharrime, but not in Maputo. A solution was found using Styrofoam and expanding foam.

7.7 Impact of the project

The impacts of the thesis will hopefully be positive on the research project. It was shown that it was possible to dry decent amounts of juice in four days with these designs. We hope this will push to keep investigating the possibilities of

Figure 34: A picture showing a bag with fermented orange juice

using solar dryers with semi permeable pouches and to keep making the process better for the farmers.

8 Conclusion

The objectives were to further investigate the possibility of designing a cheap and easy to use solar dryer for small scale use by farmers in rural Mozambique. The objective was also to compare the two different dryer designs that were to be used, the passive and active dryers.

Two dryers were successfully built and tested under laboratory conditions and later under real conditions in Mozambique. One passive dryer and one active dryer were built and tested. The active dryer had fans that were powered by a photo voltaic modules. Both of the dryers achieved the target temperatures of above 50 C° and lowered the relative humidity significantly. The PV and fan system also worked as expected.

The results from the laboratory conditions showed a large increase in the drying speed of the bags compared to the control bags. An increase in drying rate of at least 50 % in some cases an increase of 190 % could be seen. These results were very promising when looking ahead towards the field testing in Mozambique.

The results from the field testing in Mozambique also showed a large increase in drying speed compared to the control bags, not as large as the laboratory tests conducted in Lund. Increases in drying speed of 50 % and up to an increase of close 100 % in the best case for the active dryer when drying the bags with no sugar added.

The trends observed during the laboratory tests in Lund were confirmed in Mozambique, even though the increase of drying rate compared to the control bags were smaller than in the laboratory. The results were not directly comparable when using absolute numbers but the field testing showed that the laboratory was a reliable testing tool for these kinds of experiments.

It couldn't be concluded which dryer is the best as numerous parameters influence this discussion: price, season, etc. Moreover the drying area of the passive is limited by the size of the horizontal part while the drying area of the active dryer is limited by the absorber area that will also be used as the drying area.

The most promising achievement was the success of the drying process with the farmers in Inharrime. It still needs to be improved as it took four days, and the objective was two to three days. Nevertheless, this thesis proved that solar dryers reduce the drying time of the bags compared to open air drying.

The biggest issue still to be solved is to find a better method to evaluate the progress of the drying process. The maximum capacity of each dryer still has to be investigated.

9 Suggestions for further development

The drying process could be investigated further in terms of water activity rather than drying rate to get a clearer vision of the drying time. This would help to know exactly when the drying is finished.

The only rock wool available in Mozambique was glass wool, and was not available in Maputo. It could be worth considering other methods of insulation, or plan the sourcing of rock wool before going to Mozambique.

Simplify the use and construction of the dryers even further, especially concerning the plastic sheet used in both dryers. The plastic sheet was a good solution for a prototype but for long term use the plastic will not last and would need replacing. Another problematic part when building the dryers is the need for power-tools. A cheap hand-drill could replace the power tools or, ideally, a process with no drilling could be found.

Integrating a pasteurization method using the dryers in the procedure would be of great help. This would remove the need to heat the juice in pots before it is put into bags. To test this, a way to measure the temperature of the juice inside the bags will have to be developed. Wireless Testo probes could be used. If the dryers can't achieve it, an extra very small collector capable of achieving high temperatures could be built, and the bags would be placed in it for a day to ensure pasteurization before transitioning to the big dryers.

The dryers should be tested during the wet season to investigate precisely how the different conditions during this time of the year affects the drying.

A controllable angle to adapt the dryer to different fruits at different seasons of the year would be very interesting if the dryers were to be used all year long. This is more applicable to the passive dryer than to the active, where controlling the angle of the leaning part could be interesting.

It would be interesting to try to find a solutions to not have to move the driers in and out every morning and night. This was done to avoid theft of the dryers and PV-cell and also to minimize the amount of dew in the collectors in the morning.

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A Matlab code for inclination study

```
%%%%%%% This programme is made to calculate the overall sun radiation
%%%%%%% received by a collector depending on its inclination over
%%%%%%% a given period of time.
%%%%%%% Change d1 and d2 to choose the time period (correponding to
%%%%%%% harvesting season for example).
%%%%%%% Change the vector b in the first loop to chosse the inclinations
%%%%%%% you want to study. The outputs are a curve with the percentage of
%%%%%%% sun received depending on the day number, and a vector F regrouping
%%%%%%% the mean for each inclination.



clear all
%close all


% set(0,'DefaultTextFontname', 'CMU Serif')
% set(0,'DefaultAxesFontName', 'CMU Serif')



d1 = 90;                          % Second day of the study
d2 = 180;                         % First day of the studyd


Lt = -24.5;                       % Latidtude
Md = -35;                         %Local Meridian
St = -30;                         %Standard Meridian



a = 0;                            % azimuth of the collector

F=[];

```

```
D=[d1:d2];
for b=-60:10:0                      % choice of the inclinations of the collector
f=[];
for d=d1:d2                         % Loop on the day
Dc = 23.45*sin(pi*2*(284+d)/365);
B = 360*(d-1)/365;
E = 229.2*(0.000075 + 0.001868*cos(B*pi/180)-0.032077*sin(B*pi/180)-0.014615*cos(2*B*pi/180)-0.04089*sin(2*B*pi/180));
TC= 4*(St-Md)+E;                    %Time correction
T=[];
for iii=1:4800
    T=[T iii/200];
end
 T=T+(TC/60);                       % Time vector
 W=(T-12)*15;
 SA = (180/pi)*asin(cos(Dc*pi/180)*cos(W*pi/180)*cos(Lt*pi/180)+sin(Dc*pi/180)*sin(Lt*pi/180));
                                    % Solar height
 Beta = 180/pi*acos(cos(Dc*pi/180)*sin(W*pi/180)*sin(b*pi/180)*sin(a*pi/180)+cos(Dc*pi/180)*cos(W*pi/180)*sin(Lt*pi/180)*sin(b*pi/180)*cos(a*pi/180)-sin(Dc*pi/180)*cos(Lt*pi/180)*sin(b*pi/180)*cos(a*pi/180)+cos(Dc*pi/180)*cos(W*pi/180)*cos(Lt*pi/180)*cos(b*pi/180)+sin(Dc*pi/180)*sin(Lt*pi/180)*cos(b*pi/180));
                                    % Incidence on the collector
 En = cos(Beta*pi/180);             % Energy received in percentage of sun's radiation
```

```

 c=0;                               %initalizing first counter

 for ii=1:length(En)
     if(En(ii)<0)
         En(ii)=0;                 % negative values are replaced by 0
     elseif(SA(ii)<0)
         En(ii)=0;      % When the sun is not up, En values changed to 0
     end

     if(En(ii)==0)
         c=c+1;
     end

 end


 %f1=sum(En)/(length(En)-c);    % percentage of the daily sun radiation received by the surface
 f1=sum(En)/(length(En));     % Amount of sun received compared to a 24h direct irradiation
 f=[f f1];



end
F=[F ; f];

end

set(0,'defaultfigurecolor',[1 1 1])
plot(D,F)


legend('60','50','40','30','20','10','0','Location','southwest')
xlabel('Day number')
ylabel('Percentage of the suns radiation received in one day')




```

```
O=sum(F,2)/(d2-d1+1)
```