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Solar cooking in Namibia

Assessing the performance of a parabolic solar cooker

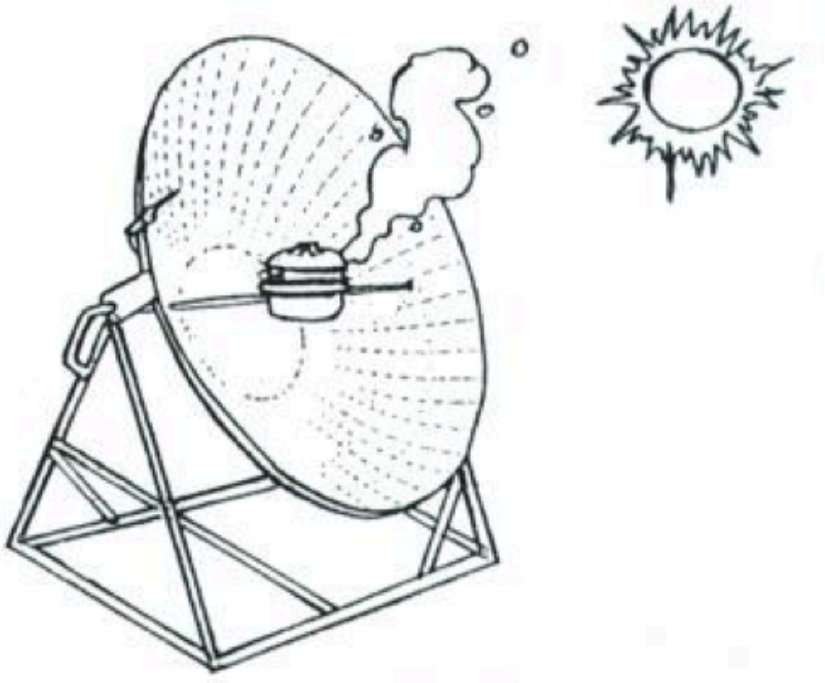
Samantha Nhi Huynh

Bachelor's Thesis
Division of Efficient Energy Systems
Department of Energy Sciences
Faculty of Engineering | Lund University



SOLAR COOKING IN NAMIBIA

Assessing the performance of a parabolic solar cooker



SAMANTHA NHI HUYNH

November 2014, Lund

The forthcoming Bachelor's Thesis has been completed at the Division of Efficient Energy Systems, Department of Energy Sciences at Lund University – LTH and at The Polytechnic of Namibia. Supervisor at The Polytechnic of Namibia: Dr. Al-mas Sendegeya; supervisor at LU-LTH: Professor Jurek Pyrko; examiner at LU-LTH: Professor Christoffer Norberg.

The project has acted as a pre-study and laid the foundation, on behalf of a Master's student at The Polytechnic of Namibia, to enable further work with the particular solar cooker and actual improvements of it. Also, the project has been carried out within the framework of the Minor Field Study programme, funded by SIDA.

Bachelor's Thesis

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To my father, mother and sister

ABSTRACT

A solar cooker is a device that can cook food or boil water using only thermal energy from the sun, which means it is fully emission free during use. The Döbra Solar Development Project (DSDP) parabolic solar cooker – manufactured locally in Namibia – has been tested according to the ASAE S580.1 standard. The aim was to lay a foundation with data that can be used as a benchmark for The Polytechnic of Namibia and their future work on improving the DSDP.

The dimensions of the DSDP were measured manually and the placement of the pot stand was compared to the theoretical focal spot. The field tests were conducted during three days in August between 10AM and 2PM by boiling 11 litres of water in a black aluminium pot. Insolation was measured with a pyranometer, water temperature was measured using two thermocouples and ambient temperature was measured with a temperature probe. The data was recorded every second by a datalogger, which also calculated averages for 10-minute intervals.

The cooking power **P** in relation to the temperature difference $\mathbf{T_\Delta}$ between water and atmosphere was calculated for every 10-minute interval. The cooking power was standardized according to ASAE and a linear regression was found for the data using MATLAB. With the linear regression for the standardized cooking power $\mathbf{P_s = 896.5 - 12.1\ T_\Delta}$ a *single measure of performance* at the temperature difference $\mathbf{T_\Delta}$ **of 50 °C** was established: $\mathbf{P_{s@50} = 290.5W}$. At present, the pot stand of the DSDP is placed approximately 8 cm above the theoretical focal spot.

The purpose of the thesis was fulfilled as The Polytechnic of Namibia can use the results as a benchmark. A study visit to NaDEET centre in Namibia also provided valuable information on other aspects of the DSDP. Evidently, it is essential that a solar cooker does not look like “a device for the poor” – it must have an appealing design if one wants success in increasing the use of it. Recommendations for further work with the DSDP include: source out local reflector materials, stabilize the stand, add two-axis rotation, improve aesthetics and make it easier to transport and store indoors.

Keywords: solar cooking, parabolic solar cooker, ASAE S580.1, Namibia

SAMMANFATTNING

En solvärmespis är en anordning som kan tillaga mat och koka vatten med hjälp av enbart värmeenergi från solen, vilket betyder att den är helt fri från utsläpp vid användning. Döbra Solar Development Project (DSDP) parabolisk solvärmespis – tillverkad lokalt i Namibia – har undersökts enligt ASAE S580.1 standarden. Syftet var att ta fram data som The Polytechnic of Namibia kan använda som utgångspunkt för deras kommande arbete med att förbättra DSDP:n.

Dimensioner hos DSDP:n mättes manuellt och med hjälp av måtten kunde den teoretiska fokuspunkten tas fram och denna jämfördes med placeringen av kokplattan. Fältexperimenten utfördes under tre dagar i augusti månad, mellan kl. 10 och 14, genom att koka 11 liter vatten i en svartmålad aluminiumgryta. Solbestrålning mättes med en pyranometer, vattentemperatur mättes med två termoelement och lufttemperaturen mättes med en temperatursond. Ett dataloggningssystem sparade data varje sekund samtidigt som det automatiskt räknade ut medelvärden för varje 10-minuters intervall.

Effekten **P** beroende på temperaturskillnaden $\mathbf{T_\Delta}$ mellan vattnet och utomhustemperaturen beräknades för varje 10-minutersintervall. Effekten standardiserades enligt ASAE och en funktion som kunde beskriva hur den standardiserade effekten beror på temperaturskillnaden hittades med hjälp av MATLAB. Funktionen för standardiserad effekt $\mathbf{P_s = 896.5 – 12{,}1\ T_\Delta}$ användes till att hitta *single measure of performance* vid temperaturskillnaden $\mathbf{T_\Delta = 50\ °C}$ som blev $\mathbf{P_{s@50} = 290{,}5\ W.}$ Den nuvarande kokplattan visade sig vara placerad ungefär 8 cm högre upp än den teoretiska fokuspunkten.

Syftet med kandidatarbetet uppfylldes då resultaten kan användas av The Polytechnic of Namibia som en utgångspunkt. Ett studiebesök gjordes även till NaDEET centre där värdefull information erhölls angående andra aspekter hos DSDP:n. Det är av stor betydelse att en solvärmespis inte ser ut som ”en manick för de fattiga” – den måste ha ett estetiskt tilltalande utseende för att det ska finnas chans till ökad användning av den. Rekommendationer till förbättringar som bör utredas hos DSDP:n inkluderar: lokalisera material som framställs i närområdet, stabilisera ställningen, tillsätta två-axlig rotation, försköna utseendet och förenkla transport och förvaring inomhus.

Nyckelord: solmatlagning, parabolisk solvärmespis, ASAE S580.1, Namibia

FOREWORD

This thesis is my final project for a Bachelor of Science degree within the Mechanical Engineering programme at Lund University, Sweden. It has been an educational period working on this assignment and I could not be happier with the choice of topic, or the brilliant people who have supported me along the way.

First of all I would like to thank my supervisor at Lund University – Professor Jurek Pyrko at the Department of Energy Sciences – for agreeing to the task of supervising me. Thank you for your knowledge, time and guidance, as it has been truly valuable. Your notes on my draft(s) have aided me enormously.

Thanks to Dr. Al-mas Sendegeya from the Department of Electrical Engineering at The Polytechnic of Namibia, for giving me the opportunity to carry out my field-testing at his university. Thanks to Owen Olivier, Master student and lecturer at the Polytechnic of Namibia, for the collaboration on this project. I wish him all the best with his further work and Master's thesis on solar cookers.

Special thanks go to Dr. Daniel Ayuk Mbi Egbe, coordinator of ANSOLE and professor at Johannes Kepler University in Linz, Austria. I have been awfully lucky to make his acquaintance. He has been immensely engaged in my process of finding a suitable thesis project in Africa and thanks to his numerous contacts I ended up exactly where I was aimed to be.

SIDA deserves a million thanks for funding my expenditures throughout this project – through their Minor Field Study Programme – hence enabling me to come to Namibia to carry out my field experiments and at the same time experience the striking nature and wildlife that this country has to offer.

I would also like to thank Andreas and Viktoria Keding, Elizabeth Lammert, Rosemarie Pauly and Rosina Shilungu, for the wholehearted welcome of my study visit to NaDEET centre, prior to my fieldwork. Elizabeth introduced me to my first practical experience with solar cooking; I managed to bake some delicious banana bread in one of the solar ovens with her assistance, using Viktoria's recipe. I have a feeling I will be baking plenty more banana bread in solar ovens in the future.

Finally, I want to express my infinite appreciation to my family and friends for all encouragement and support throughout my thesis work. It has been an exciting journey going to Namibia to study solar cooking. I am incredibly pleased with everything I have learnt, every new friend I have met and all the biltong I have eaten.

Samantha Nhi Huynh Lund, November 2014

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1. INTRODUCTION

1.1 Background

Renewable energy plays a major role in modern life and technology today. To power our lifestyle and secure a sustainable future for our planet and all present and future life on it, new and more efficient technologies are required to harvest energy from renewable sources such as solar. It is not sustainable to rely on fossil fuels, which contribute to both air pollution and global warming (amongst other negative effects) when extracted and exhausted.

Within the area of solar thermal energy comes the technology of solar cooking. It is not a new technology and it is a well functioning one, but in spite of this it is still not widespread enough. Even if solar cookers are used in most countries, there is data stating that fewer than a hundred solar cookers are used in many of these countries (Solar Cookers International n.d.a). Though this number is out-dated, according to Julie Greene at Solar Cookers International (SCI), the 1.3 million solar cookers[1] that are being used worldwide today (SCI 2009) is a rather small number in relation to the 2.5 billion people who cook over open fires.

However, there is another important aspect here. One could think that this should be the grand solution for all the poor families in developing countries that are geographically positioned where the sun shines intensely most of the year, if only they are made aware of solar cooking. Nevertheless, many projects with the main goal of introducing and implementing this technology in these areas – where it is needed the most – has met quite a few setbacks and resistance from the beneficiaries, due to cultural issues and fear of this unknown technology (Ligtenberg 2000).

On top of this, there has been a lack of understanding and communication with the local people when planning and implementing these projects. In a field like this – where information is not as readily available and used methods have not been properly documented – it is important to involve the target group during the whole process (Otte 2013).

In order to make solar cooking more welcomed in rural areas, it first needs to be more welcomed in urban areas. Privileged people, who do not use this technology, have been doing most of the promoting work throughout the years. This approach has led to solar cookers receiving the stamp of a device for poor people only (Radabaugh 1998).

Poor people do not want to be considered poor, as there is the matter of status in every community. Therefore the solar cooking technology needs to be made trendy, desired, and readily used by “the rich” before it can be implemented easily and successfully to “the poor” (Otte 2014). One way towards this goal is to

[1] Julie Greene, Solar Cookers International, 2014-09-24.

improve the efficiency of solar cookers to attract more individuals from the urban population to use them (Noble Grundy 1995).

1.2 Purpose

As assigned by The Polytechnic of Namibia, on behalf of a Master's student at their university, the aim of this thesis is to lay a foundation for further work with a locally manufactured parabolic solar cooker – the Döbra Solar Development Project (DSDP) solar cooker. This entails evaluating the performance of the DSDP, using recommendations from the ASAE S580.1 standard. The geometry of the solar cooker is also studied to conclude potential changes that can improve the efficiency and ease usage.

The questions that this project aims to answer are following:

- What are the dimensional characteristics of the DSDP parabolic solar cooker?
- How accurate is the pot stand placed in relation to the focal spot?
- How is the performance of the DSDP, according to the ASAE S580.1 standard?
- How can the geometry of the cooker be improved?

1.3 Constraints

This thesis has attended to the topic of solar cooking, within the area of solar thermal energy. The focus has been on parabolic solar cookers and only brief information about other types of solar cookers was covered. The ASAE S580.1 standard (2013) was mainly used as a guideline for the performance testing. Methods based on solar cells (photovoltaics) were not studied.

All experiments were carried out at one location – the rooftop of the Engineering building at The Polytechnic of Namibia in Windhoek, Namibia. The field tests were conducted during three occasions in the winter month of August, with no regards to the rest of the year. The performance analysis only concerns a specific model of parabolic solar cookers – the DSDP. No other solar cooking devices were taken into account.

1.4 Namibia

Namibia is situated in Southern Africa with a western coast facing the Atlantic Ocean. It borders with South Africa in the south, Botswana in the east and Angola in the north. After over a century of German rule and colonization since the 1800s, Namibia was later seized by South Africa during World War I. It was called South West Africa during this time and after a 25-year long war, Namibia gained independence on March 21st 1990, with independence fighter Sam Nujoma as their first elected president (BBC 2014).

With a land area of 824 000 km^2 and a population of 2.2 million, Namibia is one of the most scarcely populated countries in the world (CIA 2014). The country is rehabilitating reasonably well from its ferocious past and it is the first country in the world to include environmental protection in its constitution (Stefanova 2005). Namibia is a country with wildlife just as remarkable as it is assorted and landscapes just as stunning as they are diverse.

Namibia has a desert climate and struggles with water scarcity. When it comes to the energy situation, the electricity production in the country is divided between hydroelectric plants and fossil fuels, with a percentage of 68.2 and 31.8 respectively (CIA 2013). In spite of the abundance of free solar energy in Namibia, most households in urban areas make use of the permanent and preinstalled electric water heaters for their domestic hot water (Konrad Adenaur Stiftung 2012).

The yearly average amount of insolation – the amount of solar energy on a surface – for different countries in Africa is shown in Figure 1. It is not too difficult to spot that Namibia is particularly fortunate in this regard, which makes it a country unquestionably favourable for solar applications – solar cooking in this specific case.

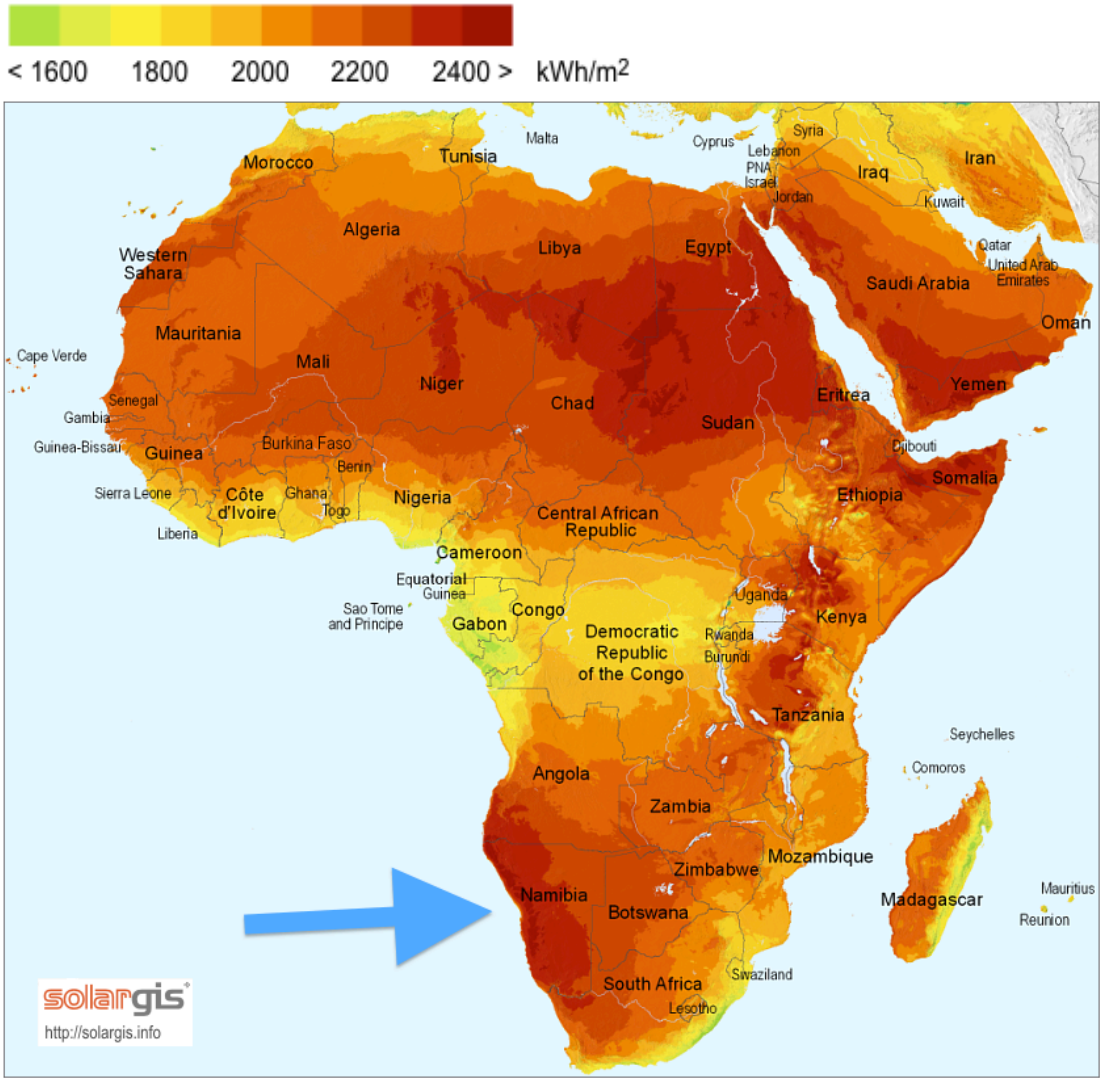


Figure 1. Long-term yearly average sum of Global Horizontal Insolation, measured April 2004-March 2010 (SolarGIS GeoModel Solar 2014).

2. THEORY

2.1 Solar energy

The sun has provided planet Earth with energy since the moment life emerged on it. All fossil fuels that power our vehicles and heat our homes today have materialized thanks to the sunlight that decomposed the remains of dead plants and organisms during millions of years.

Earth obtains solar energy from the sun through electromagnetic waves, also known as electromagnetic radiation or solar radiation. Every hour the sun strikes the planet with more energy (4.3×10^{20} J) than the yearly total energy consumption of 4.1×10^{20} J (Foster, Ghassemi & Cota 2010, p. 4).

Electromagnetic waves can be represented by photons carrying radiant energy or light energy. When photons strike matter, the clash triggers a vibration of molecules and these movements will convert the radiant energy of the photons into heat energy (Reusch 2013).

2.1.1 The electromagnetic spectrum

There are different types of electromagnetic waves and they all move at the speed of light (3×10^6 m/s). They are characterized by wavelength and how they are detected, ranging from long radio waves to short gamma rays. All electromagnetic waves can be represented by the so-called electromagnetic spectrum (Figure 2). Most of the electromagnetic radiation that Earth receives from the sun arrives as visible light and can be detected by the human eye, as opposed to infrared (IR) radiation for example. IR radiation entails wavelengths that are shorter than micro waves but longer than those of visible light. Though the human eye cannot detect IR radiation, a small spectrum of it can be experienced as heat (Connected Earth n.d.).

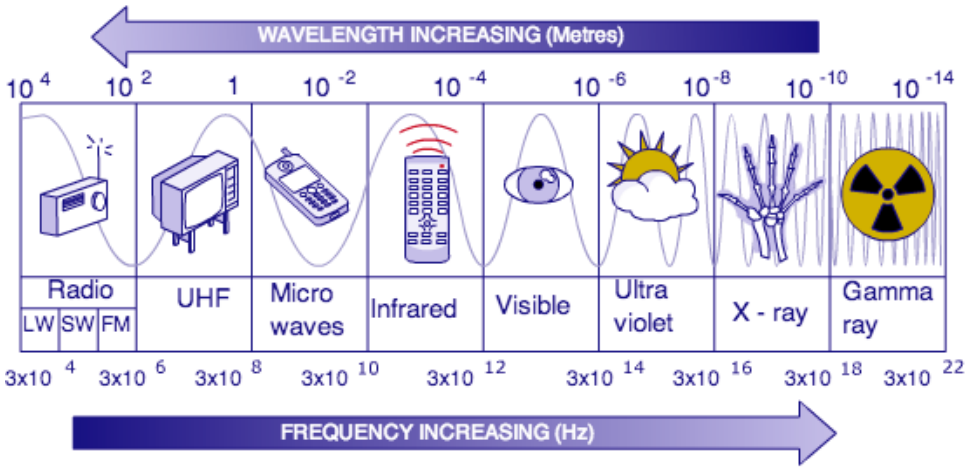


Figure 2. The different types of radiation from the electromagnetic spectrum (Connected Earth n.d.)

The spectrum of IR radiation (Figure 3) is divided into far-, mid-, and near infrared, with near IR being the closest to the wavelength of visible light. The far IR waves have the longest wavelength and those IR waves between 8-15 µm are called *thermal* IR waves. These thermal IR waves are the ones that can be detected as heat, whether they are emitted from the sun or a radiator. The shorter IR waves are not hot at all and are of the sort that television remote controls use (NASA 2007) and generally, they can pass through glass just like visible light. However, glass is opaque to longer IR waves including thermal IR waves and this is how heat can be retained in a greenhouse (Unterman 2012).



Figure 3. The spectrum of the infrared radiation is divided into far-, thermal-, mid- and near infrared radiation (NASA n.d.).

2.1.2 Solar radiation

The total amount of solar radiation on a surface is called global radiation and can be divided into two main categories: *beam radiation* and *diffuse radiation*. Beam radiation – also called direct solar radiation – entails sunrays that have not been scattered by the atmosphere and are received directly from the sun. Diffuse radiation concerns both the radiation that has changed its direction due to clouds and particles in the atmosphere (Duffie & Beckman 1991, p. 10) and radiation that has hit the ground before it is received by a surface (Figure 4). This means that diffuse radiation can be divided into the two subcategories *diffuse sky radiation* and *ground reflected radiation* (Ineichen, Guisan & Perez 1990).

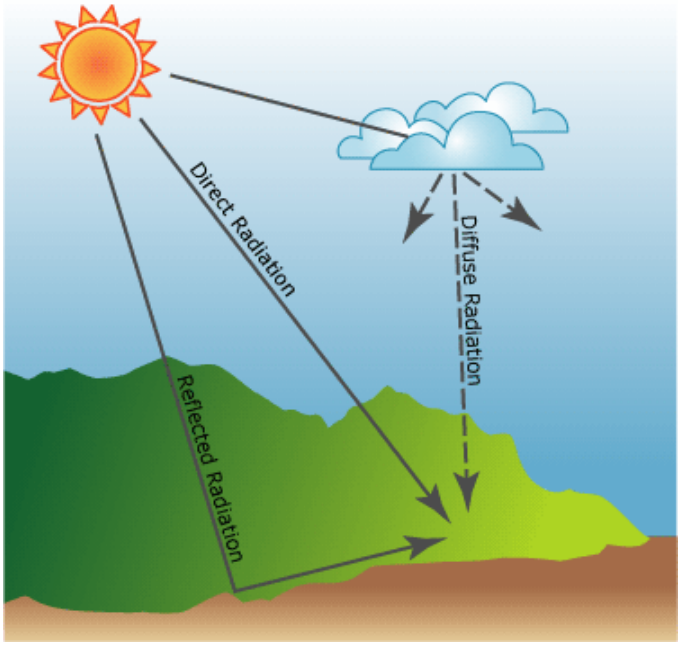


Figure 4. How incoming global radiation is divided into direct solar radiation, diffuse sky radiation and ground reflected radiation (Emax Green Energy n.d.).

2.1.3 Irradiance vs. Insolation

Irradiance is the *rate* at which radiant energy from the sun strikes a surface, per unit area [W/m^2] while irradiation is the *amount* of radiant energy received by a surface, per unit area [J/m^2]. Through integration of the irradiance over a specified time, the irradiation can be found. It is typical to integrate over an hour and therefore express irradiation in Wh/m^2 as in Figure 1. When speaking of *solar* irradiation specifically, it is equivalent to use the expression *insolation* (Duffie & Beckman 1991, pp. 10-11), which is used in this report.

2.1.4 The apparent path of the sun

The path of the sun in the sky differs depending on the day of the year and from which hemisphere it is observed. In the Northern hemisphere the shortest day of the year (the winter solstice) is on December 21st, which is when the path of the sun in the sky is the lowest. After this day, the sun follows a higher and higher path for every day and on 21st of March it will reach the *spring equinox*, which is when the sun rises exactly in the east and sets exactly in the west (Figure 5). This day lasts exactly 12 hours and the days will become longer until the summer solstice on 21st of June – the longest day of the year in the Northern hemisphere.

From here the sun will start following a lower path again and head towards the same equinox, which (in this direction) is now called the *fall equinox*. In the Southern hemisphere the same cycle follows but in the opposite direction. Therefore the winter solstice is on 21st of June, fall equinox on 21st of March, spring equinox on 21st of September and summer solstice on 21st of December (Foster, Ghassemi & Cota 2010, pp. 9-10).

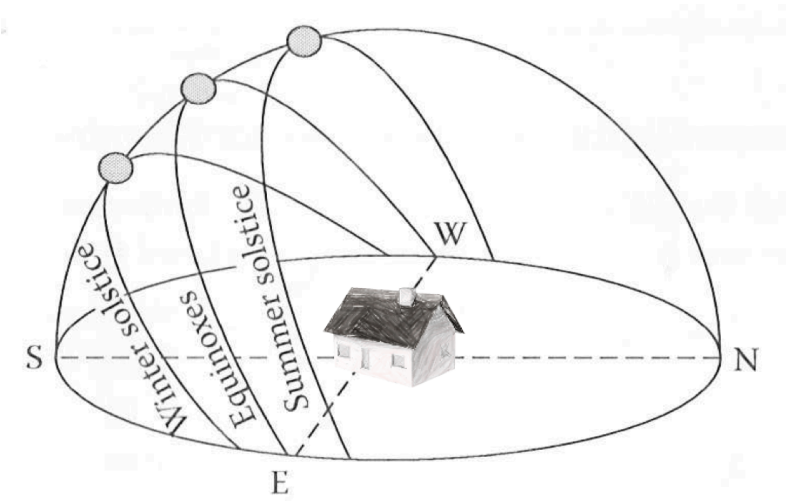


Figure 5. The apparent path of the sun throughout the year seen from the Northern hemisphere (Duffie & Beckman 1991, p. 10).

Due to the apparent path of the sun, permanent solar energy collectors in the Northern hemisphere are recommended to face south while in the Southern hemisphere they should face north to receive as much sunshine as possible.

2.2 History of solar cooking

A solar cooker is a device used for cooking food and boiling water. It is fully powered by solar thermal energy. The history of solar cooking dates back to the 1600s during which a German physicist, Tschirnhousen, allegedly boiled water in a clay pot by focusing the sunrays with a large lens (Halacy & Halacy 1992). Horace de Saussure, a Swiss scientist, reported this event when he published his studies of solar cookers in 1767.

De Saussure was inspired by the greenhouses, which were used only to raise tropical plants and fruits in Nordic climates at the time. He built a small-sized greenhouse by putting five glass boxes (with the bases cut out) inside of each other and on top of a black wooden table. He measured the temperatures in each box and the bottom of the smallest box reached the highest temperature of 87.5 °C (Buttin & Perlin 1980).

When de Saussure put fruit in the smallest glass box (which was inside the four bigger glass boxes) it cooked satisfactorily under the sun and that is how solar cooking was born. De Saussure continued to experiment on this "solar heat trap" by using different materials, adding insulation and even cooking at different altitudes. He ended up building a wooden box with three separate layers of glass as a lid. The bottom of the box registered 108 °C when exposed to the sun. This wooden box became "the hot box" and modern solar box cookers today are all variations of this design (SCI 2011a).

During the same era lived the French scientist Ducarla who worked on improving de Saussures primitive hot box. He added reflective mirrors, insulation and two extra layers of glass for the lid. With these improvements Ducarla managed to cook meat in an hour. A century later Augustin Mouchot, a French mathematician, wrote the first book about solar cooking – *Solar heat and its industrial applications*[2]. Mouchot successfully baked bread in three hours and in 1877 he developed solar cookers for French soldiers in Africa. The French government were highly pleased and gave Mouchot a big cash reward for his efforts (Halacy & Halacy 1992).

The M.I.T. scientist Maria Telkes – who worked on solar thermal energy technologies to heat buildings (among other things) – constructed a solar box cooker that did not have a regular shape of a rectangular parallelepiped. Instead of a horizontal top, Telkes gave her box cooker an inclined top and covered it with two layers of glass, with a layer of air in between them. The box cooker was insulated, made of plywood, included a door and Telkes had not only added four large flared reflectors to it but also 4 triangular shaped reflectors to cover the corners (Figure 6). Even today, this exact design from the late 1950s (and variations of it) is being built and used (Knudson n.d.).

[2] French title: La Chaleur solaire et ses Applications industrielles (1869).

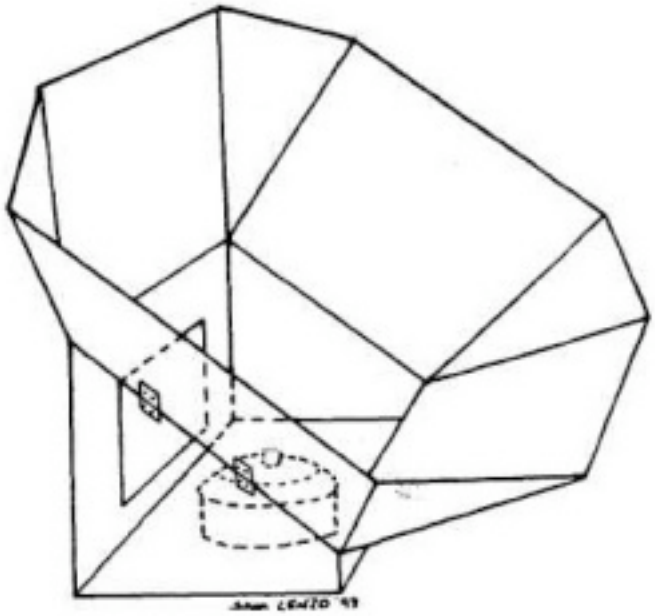


Figure 6. The solar oven design by Maria Telkes (Still & Kness 1999).

In 1987 Barbara Kerr and Sherry Cole wanted to share the promising technology of solar cooking with the world. Therefore they founded Solar Cookers International (SCI), a non-profit network in USA. Together with a handful of other solar cooking enthusiasts they produced manuals of how to build solar cookers and educated other people in the construction and usage of the devices. The SCI Wiki webpage contains plenty of useful material for anyone interested in solar cooking. Today, SCI is the biggest international network for solar cooking and have introduced the technology to 30.000 families in Africa[3].

[3] Retrieved from the official Solar Cookers International webpage on July 10th 2014.

2.3 Solar cookers

There are many different types of solar cookers and according to Solar Cookers International (2011a) most solar cookers can be divided into three main categories: box cookers, parabolic cookers, and panel cookers. Below is a brief description of the three. Characteristics of the parabolic disc will be mentioned further in section **2.4**. It is significant to keep in mind that not all solar cookers can be strictly placed in one of the three categories.

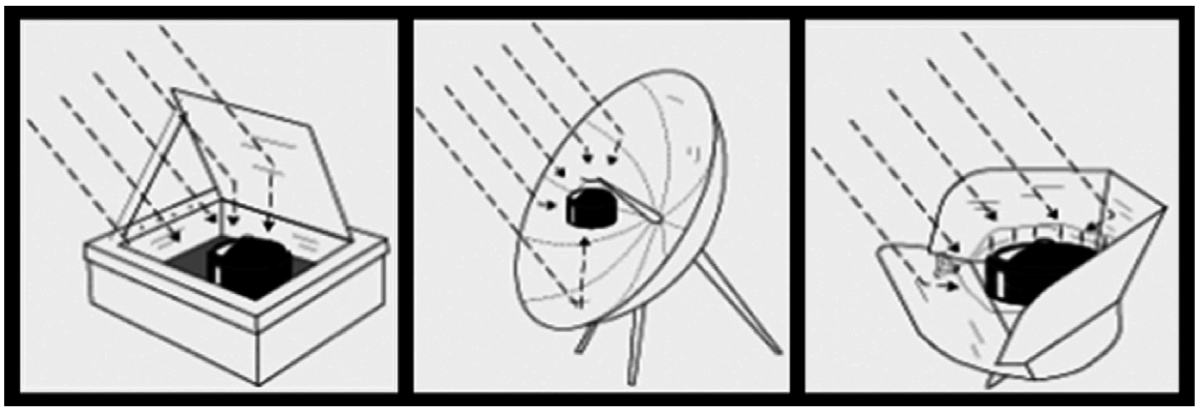


Figure 7. The three main types of solar cookers. From left: box cooker, parabolic cooker, panel cooker (Courtesy of Solar Cookers International).

2.3.1 The box cooker

The box cooker (solar oven) is easy to construct and can also be made sturdy. The simplest version can be built within the hour with recycled materials, such as two shoeboxes, aluminium foil and a sheet of glass (or even plastic) for the lid. However, it is typically made of wood for durability and the base on the inside is usually painted black for better heat absorption. Walls can also be painted black or covered with reflective material (aluminium sheets or mirrors) to reflect more incoming sunrays towards the cooking vessel (Solar Cookers International 2011a) and often, one or more booster mirrors are also added for this purpose. It goes without saying that the cooking vessel should be black for ideal heat absorption.

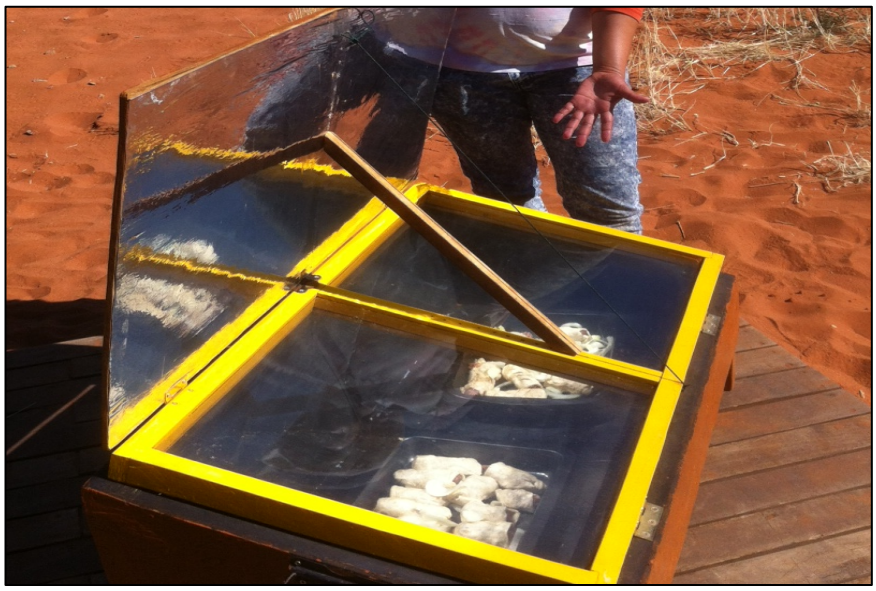


Figure 8. One of the larger sized wooden solar box cookers at NaDEET (June 2014).

Essentially, the box cooker works like a greenhouse. The light energy that passes through the glass will convert into heat energy when striking the base or the cooking pot. The glass cover will retain the heat, which will cook the food or boil the water. It is quite similar to how the inside of a car warms up during a sunny day. Nonetheless, a box cooker needs to face the sun to stay hot, which means it needs to be moved every 30-60 minutes. During days with a clear sky, the box cooker will work just as good as a conventional oven (Halacy & Halacy 1992).

This type of solar cooker is the most widespread one globally (Solar Cookers International 2011a) and it has an advantage of accommodating more than one pot, depending on the size of the cooker (Figure 8). Basically, there is no chance of burning food in a box cooker and it is much cheaper than the parabolic cooker and less sensitive to winds than the panel cooker.

2.3.2 The parabolic cooker

The parabolic cooker (curved concentrator disc) is the most efficient type but also more expensive and complex to build. Commonly, they are constructed using polished aluminium sheets or plates for the reflective surface while the stand can consist of other metals or even wood. Nonetheless, a few simple designs of parabolic solar cookers do exist. Halacy & Halacy (1992) constructed one with only an umbrella, aluminium foil and a simple stand. Another example – a quite environmentally friendly approach – is Paul Webb in Australia who used old aluminium printing plates (that were on the way to the dump) to build his parabolic solar cooker (Solar Cooker at CantinaWest n.d.).



Figure 9. The DSDP parabolic solar cooker (Döbra Solar Development Project n.d).

When a parabolic solar cooker is directed towards the sun, all incoming sunrays striking the parabolic disc will be reflected into one point called the focal spot, which is where the pot stand and cooking vessel should be placed. This concentrated sunbeam will heat up a pot or pan within minutes on a clear and sunny day.

However, as only beam radiation can be concentrated, a parabolic solar cooker cannot make use of any diffuse radiation (Lund 2012). Another disadvantage is that the cooker needs to be moved according to the sun more often than a solar box cooker (at least every 10 minutes) and the cooking process must be monitored frequently to prevent burnt food. There is also a risk of harming the eyes, in case of looking straight into the focal spot, if they are not protected appropriately.

2.3.3 The panel cooker

The panel cooker is simple, cheap, and portable. It is typically made of cardboard with a surface finish of aluminium to reflect incoming sunrays. It is however more sensitive to wind and therefore not as durable as the other two types of solar cookers. This type is favourable for its lightweight and portability. Solar Household Energy (SHE) has developed the HotPot[4], which is foldable and made of heavy cardboard bonded to either aluminium foil or anodized aluminium. According to SHE, both reflector materials are equally efficient though the one with anodized aluminium is more durable.



Figure 10. The foldable HotPot with the specially designed cooking pot that comes with it (Solar Household Energy n.d.)

[4] Manufactured by Energía Portátil S.A. de C.V. in Monterrey, Mexico.

2.4 The parabolic concentrator

A parabola is a symmetrical two-dimensional curve with a point of focus on the axis of symmetry, a vertex – the point where the parabola intersects with the axis of symmetry and a directrix – a line that is perpendicular to the axis of symmetry and does not intersect with the parabola (Khan Academy 2009).

The distance from a given point on a parabola to the directrix is the same as the distance from this point to the focus. This goes for all points on the parabola (Figure 11) and the vertex, directrix and focus are all fixed for every unique parabola (ibid.). In the context of parabolic solar cookers, the point of focus can be referred to as *focal spot*.

When revolving a parabola around its symmetry axis it becomes the three-dimensional *paraboloid*. However, when speaking of a solar concentrating device with a shape of a paraboloid it is common[5] (in informal language) to use the terms *parabola* and *parabolic*, hence the labels "parabolic concentrator disc" and "parabolic solar cooker". This thesis also tends to these informal expressions.

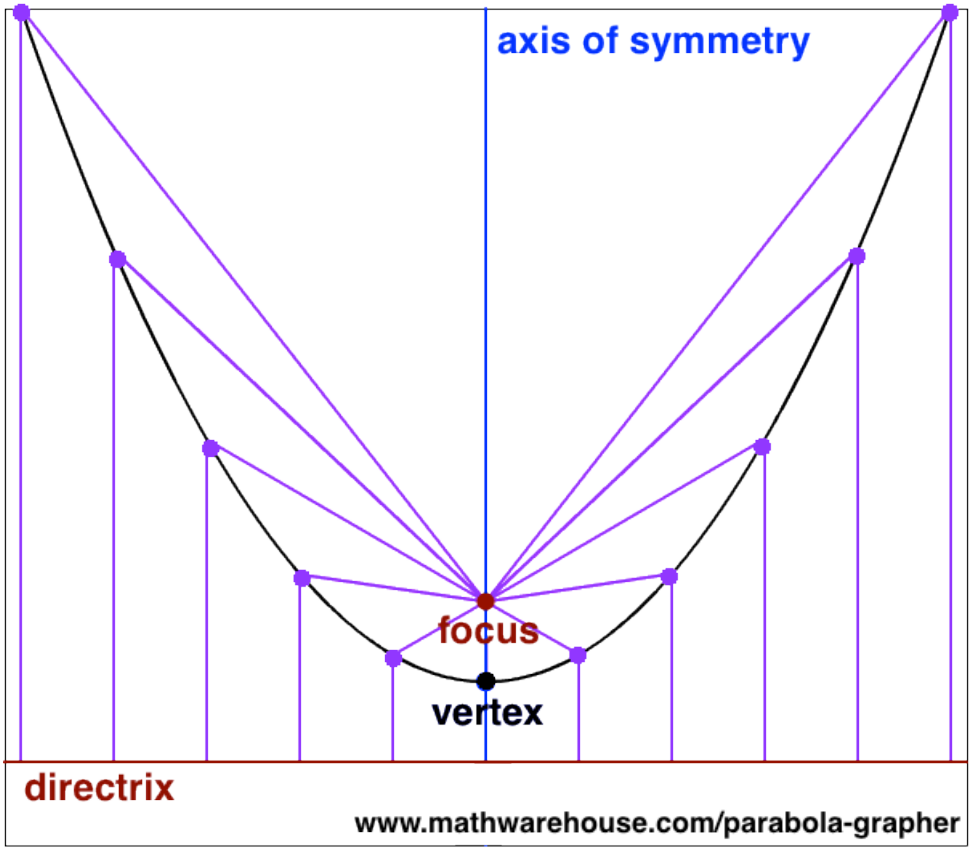


Figure 11. The distances from different points on a parabola to the directrix and the distances from these points to the point of focus (focal spot) are exactly the same (Math Warehouse 2014).

[5] Noted in multiple reports and articles regarding parabolic solar concentrators.

The geometry of a parabola (Figure 12) has the characteristics of reflecting all incoming sunrays – that are approximately parallel to the axis of symmetry – to the point of focus (Stine & Geyer 2014). This means that if an object is placed in this spot, the concentrated light energy striking it will convert into heat and that is how parabolic concentrators work. How to calculate the focal length – the distance from vertex (**V**) to the focal spot (**F**) – is mentioned in section **3.1** (Equation 1).

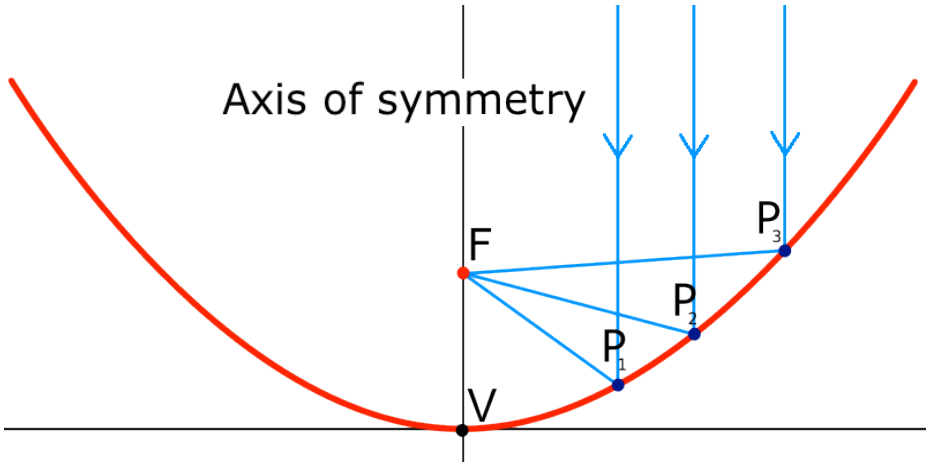


Figure 12. A parabola reflecting incoming sunrays to the focal spot F. V is vertex while P_1, P_2, P_3 are arbitrary points on the parabola.

2.5 Benefits of solar cooking

Solar cooking is fuel free, emission free and it is also a rather simple technology, which is of a great importance. It can be used, at nearly no cost, to pasteurize water and therefore prevent deadly diseases caused by unsafe drinking water (Solar Cookers International n.d.b). On top of this, solar cooking even fulfils the United Nations (UN) Millennium Development Goals (Solar Cookers International 2014a). It is astonishing how solar cooking still is not widely adopted or extensively researched upon, bearing in mind all the benefits that comes with it.

2.5.1 Environment

2.5 billion people – 52% of the population – in developing countries rely on biomass fuels such as wood, charcoal and animal dung for cooking. In many parts of Sub-Saharan Africa, more than 90% of the rural population relies on wood and charcoal and the burning of these fuels results in local air pollution. However, the biggest concern is not that biomass fuels are being used but the way that these resources are being harvested; at an unsustainable pace and through inefficient technologies. The production of charcoal is typically not energy efficient and can lead to local deforestation and land degradation (International Energy Agency 2013).

2.5.2 Health

According to the World Health Organization (2012), burning of biomass fuels in poorly ventilated spaces is the major reason to indoor air pollution such as small soot particles and methane[6], which in turn kills more people yearly than AIDS and malaria combined (Kopman 2013). 4.3 million deaths per year are caused by illnesses linked to indoor air pollution. From pneumonia to lung cancer, the ratios of the lethal illnesses due to household air pollution are presented in Figure 11 (WHO 2012). Cooking food should not involve dangers to your respiratory system and health. Solar cooking prevents the inhalation of smoke, since there is no fire or smoke involved in the cooking process.

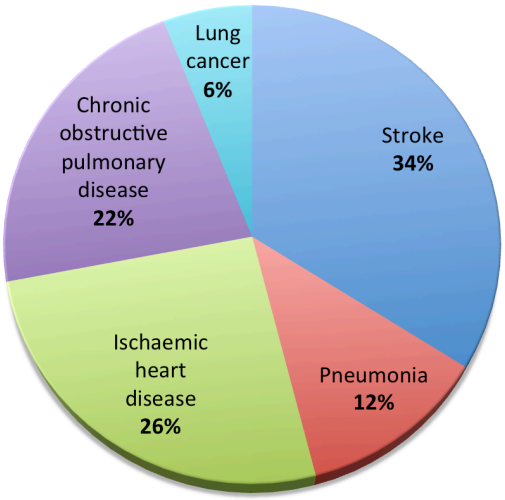


Figure 13. Percentage of illness due to indoor air pollution (World Health Organization 2012).

[6] Only dangerous when excessive amounts are inhaled, which occurs when there is no ventilation or poor ventilation (Health Protection Agency 2010).

2.5.3 Women's empowerment

Women and girls predominantly carry out the task of gathering wood, which is not considered as valuable labour because it does not produce income. As trees are becoming scarcer, the distances they have to walk to collect wood become longer. It is a physically tiring task just as it is time consuming. Additionally, these walks on foot expose these women and girls to dangerous and violent treatments (International Energy Agency 2013). Solar cooking can aid women's empowerment efforts in the sense that instead of collecting wood, these women and girls can use this time for more enriching activities, such as learning a new skill that could generate income or/and develop their personal growth (Green 2001).

2.5.4 Economics

Many poor families in developing countries spend more money on cooking fuels than they spend on food. This compels a vicious cycle of poverty, as this money cannot be used for more beneficial purposes such as education (Sperber 1990). Solar cooking can also create business opportunities, e.g. solar restaurants, solar bakeries and solar cookers manufacturing and repair services.

There is a solar restaurant called Delicias del Sol in the village of Villaseca in Chile where all food is cooked by solar ovens (Figure 14). The food is reportedly delicious and the well-run solar cooking restaurant has produced profits. It started in the year 2000 with a seating of 16 and since 2013 it can seat 120 people. This proves that it is possible to produce income through solar cooking (Solar Cookers International 2014b).



Figure 14. Solar ovens at the solar restaurant Delicias del Sol in Villaseca, Chile (AstroTravel Chile n.d).

3. METHOD

3.1 Field experiments

The fieldwork consists of measuring the dimensions of the DSDP parabolic solar cooker, calculating the focal spot, testing and reporting the performance of the cooker as suggested by the ASAE S580.1 standard (2013). The American Society of Agriculture and Biological Engineers formed this testing standard for solar cookers, with the aim to enable comparison between different types of solar cookers despite being tested at different locations and during different times of the year.

Equipment:

- DSDP Parabolic Solar Cooker
- CR1000 Datalogger system
- Kipp&Zonen CMP3 Pyranometers
- R.M. YOUNG Anemometer
- Humidity sensor
- Temperature probe
- Thermocouples type K (special limit of error)
- Black cooking vessel of aluminium
- Tape measure
- Electric kettle
- Microsoft Office
- Mathworks MATLAB

The performance testing was carried out in Windhoek, which – according to One World Nations Online – is positioned approximately 1700 metres above sea level, with the following coordinates: **22°34′12″S 17°5′1″E** (Google Earth). The area around the Engineering building of The Polytechnic of Namibia can be seen in Figure 15. The center of this particular map has latitude φ = -22.57 (South) and longitude λ = 17.07 (East).



Figure 15. The area around the Engineering building (yellow arrow) on Wagner Street.

3.1.1 Dimensional characteristics

The dimensions of the parabolic solar cooker: the diameter of the rim, the depth of the parabola and the distance from vertex to pot stand, were measured with a tape measure. All dimensions were measured four times.

The intercept area **A** is defined as the reflector area projected onto the plane perpendicular to the beam radiation. In this case – where it concerns a parabolic solar cooker – it is the area covered by the circle of the rim. The intercept area **A** can be calculated with the equation for the area of a circle: $\boldsymbol{A = \pi R^2}$ where **R** is the radius of the rim.

3.1.2 Focal spot VS. Pot stand

With the dimensions of the parabola measured, the theoretical focal spot was calculated with Equation 1 (Duffie & Beckman 1991, p. 358).

$$\boldsymbol{F = \frac{R^2}{4D}} \qquad \textbf{(1)}$$

where:

F = focal length from vertex [m]
R = radius of the rim [m]
D = depth of the parabola [m]

3.1.3 Performance analysis

First of all, the boiling point for water at the test location was determined by boiling water in an electric kettle while measuring the water temperature with a thermocouple. The performance tests were conducted during three days, between the hours of 10:00 and 14:00, as the ASAE standard suggests.

The weather requirements that should be fulfilled for the test data to be ranked as valid, according to the ASAE standard, are presented in Table 1. Regarding the maximum wind, only if it is exceeded for a period over ten minutes will the test data be discarded. If the variation in insolation is greater than 100 W/m^2 over a ten-minute period then that test data shall be discarded as well.

Table 1. Weather requirements for conducting the efficiency tests

Ambient temperature	**20 - 35 °C**
Insolation	**450 - 1100 W/m^2**
Average wind	**< 1.0 m/s**
Maximum wind	**< 2.5 m/s**

The cooking pot was made of aluminium and painted black with heat-resistant spray paint. The pot should carry a water load of 7000 gram per square meter intercept area. During the tests, the frequency of the manual tracking of the sun – how often the cooker is moved – was noted.

Water temperatures were measured with two thermocouples passing through the lid, out of which one was placed right below the water surface and the other just above the bottom of the pot. The average temperature of these two thermocouples was used in the calculations. The hole in the lid was insulated with silicone. Ambient temperature was measured with a temperature probe, due to greater accuracy[7] when measuring ambient temperature.

The datalogger was set on a frequency of 1 Hz, meaning both water and air temperatures were recorded every second, to the nearest one hundredth of a degree Celsius. Insolation [W/m^2] and wind speed [m/s] were also measured with the same frequency. The CR1000 datalogger calculates the average (of 600 recordings) for every 10-minute interval. These averages were then downloaded and opened through Microsoft Excel. From here all calculations were made using the following instructions.

1. CALCULATE COOKING POWER

The first step is to calculate the cooking power $\mathbf{P_i}$, for every 10 minute interval ***i*** with Equation 2 (Funk 2000, p. 3). Use Microsoft Excel for this purpose.

$$\boldsymbol{P_i = \frac{(T_2 - T_1) \cdot M \cdot C_v}{\Delta t}} \qquad \textbf{(2)}$$

where:

$\mathbf{P_i}$ = cooking power for interval ***i***	[W]
$\mathbf{T_2}$ = final water temperature	[°C]
$\mathbf{T_1}$ = initial water temperature	[°C]
M = water mass	[kg]
$\mathbf{C_v}$ = heat capacity of water = 4186	[J/(kg · °C)]
Δ**t** = time of interval ***i*** = 600	[s]

2. STANDARDIZE COOKING POWER

Standardizing the cooking power will enable the comparison of results from different locations and dates. The average cooking power for each interval will be corrected to the set standard insolation of 700 W/m^2, using Equation 3 (Funk 2000, p. 3).

[7] Recommended by technician at Campbell Scientific (South Africa) though ASAE suggests thermocouples for measuring ambient temperature.

$$P_s = P_i \cdot \frac{700}{I_i} \qquad (3)$$

where:

$\mathbf{P_s}$ = standardized cooking power for interval ***i***	[W]
$\mathbf{P_i}$ = cooking power for interval ***i***	[W]
$\mathbf{I_i}$ = average insolation for interval ***i***	[W/m^2]

3. FIND TEMPERATURE DIFFERENCE

Find the temperature difference for each interval by subtracting the average ambient temperature from the average water temperature (Equation 4).

$$T_\Delta = T_w - T_a \qquad (4)$$

where:

$\mathbf{T_\Delta}$ = temperature difference for interval ***i***	[°C]
$\mathbf{T_w}$ = average water temperature for interval ***i***	[°C]
$\mathbf{T_a}$ = average ambient temperature for interval ***i***	[°C]

4. PLOT DATA

Plot the standardized cooking power $\mathbf{P_s}$ against the temperature difference $\mathbf{T_\Delta}$ for each interval and find a linear regression for the plotted points. MATLAB can be used for this purpose, using the command `reggui`[8] (not a standard MATLAB command). At least 30 observations from three different days should be used in the plot.

The linear regression for the standardized cooking power can be expressed as a function $\mathbf{P_s = A + B \times T_\Delta}$ where **A** is the intercept [W] and **B** is the slope [W/°C]. The coefficient of determination (r^2) found by regression should be higher than 0.75 or particularly noted.

5. REPORT PERFORMANCE

A *single measure of performance* ($\mathbf{P_{s@50}}$) for the temperature difference of 50 °C can be calculated using the found linear regression. This value is meant to function as a quick and helpful tool for whoever wanting to compare different types of solar cookers.

[8] Command written by Joakim Lübeck, Dep. of Mathematical Statistics at Lund University, Sweden (1999). The full code package is required in order to use the operation. It can be downloaded for free at: http://www.maths.lth.se/matstat/staff/joa/ [2014-08-03].

Reporting of results from the performance testing should consist of a plot presenting the relation between standardized cooking power $\mathbf{P_s}$ and temperature difference $\mathbf{T_\Delta}$. Include the regression line and its equation and the coefficient of determination r^2 in the same plot. The cooking power at the temperature difference of 50 °C $\mathbf{P_{s@50}}$ should also be listed.



Figure 16. The DSDP solar cooker during testing on day 2 (29/8-2014).

3.2 Study visit

NaDEET[9] centre is a non-profit organization that provides education in the area of nature conservation and sustainable living, including solar cooking. A study visit was carried out to this centre, which is located in the NamibRand private reserve. The intent was to gain some practical experience regarding solar cooking, prior to the field tests at The Polytechnic of Namibia.

[9] Namib Desert Environmental Education Trust

4. RESULTS

4.1 Dimensional characteristics

Table 2 presents the averages of the manually measured dimensions, radius and depth, which were both measured four times. The calculated intercept area (**c**) of the circle of the rim is based on the radius (**a**).

Table 2. Relevant dimensions of the DSDP parabolic solar cooker

a. Radius	**0.71 m**
b. Depth	**0.54 m**
c. Intercept area	**1.58 m^2**

4.2 Focal spot VS. Pot stand

The distance from vertex to the theoretical and the distance from vertex to the pot stand are presented in Table 3. The two differs approximately 8cm.

Table 3. The distance from vertex to the theoretical focal spot and pot stand respectively

Distance from vertex to (theoretical) focal spot	**23.3 cm**
Distance from vertex to pot stand	**31.5 cm**

4.3 Performance analysis

The intercept area (**4.1c**) corresponds to a water load of 11 kg. Manual tracking of the sun was noted to be every 6-7 minutes. The boiling temperature of water at the testing location was determined to be 94 °C.

Table 4. The found linear regression and single measure of performance for the standardized cooking power.

Linear regression	**$P_s = 896.5 - 12.1\ T_\Delta$**
Single measure of performance	**$P_{s@50} = 290.5$ W**

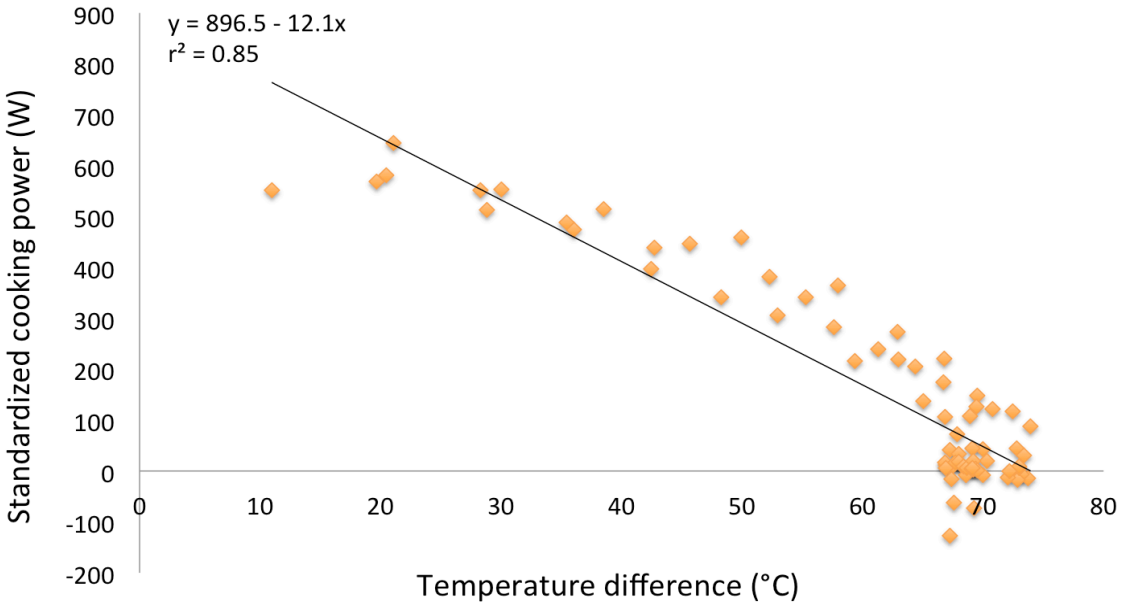


Figure 17. A plot of all 72 recordings from the three days of testing, with regression line and coefficient of determination.

5. DISCUSSION

5.1 Dimensional characteristics

The local community at Döbra in Namibia constructs all DSDP solar cookers. There is no advanced equipment available and all dimensions are approximate as precision is difficult to achieve. This means that all DSDP solar cookers do not have exactly the same dimensions. Even if the differences might be small there is no statistics on the variation. Therefore the measurements (**4.1**) do not reflect the dimensions of all DSDPs until there is data that states that the variation is insignificant.

The dimensions of the DSDP were measured manually and to reduce the possible errors, each dimension (diameter, depth and distance from vertex to pot stand) was measured for times and the averages of these were used for the calculations that followed. However, it is difficult to determine whether the possible errors were reduced or not.

5.2 Focal spot VS. Pot stand

The equation for calculating the focal length is strictly theoretical. It is complex to build the ideal parabolic solar cooker with the exact shape of a paraboloid, especially without high-precision machinery and proper expertise.

Data from Table 3 states that the pot stand is placed above the theoretical focal spot with a distance of approximately 8 cm. This number entails certain insecurities as it is based on the dimensions that were measured manually (discussed in **5.1**). On top of this, there is the lack of information of where the actual focal spot is located.

5.3 Performance analysis

For simplicity, 11 litres of water were used and measured with a measuring bucket, for the performance tests. The boiling temperature of water at the test location was only measured once and the number was approximately 94 °C. There was a day of trial to ensure the equipment was working and it all seemed fine though the water only reached 60 °C. The reason for this was probably that the pot had not been painted black and it was also too big for the 11 litres. A smaller pot (which was half the height of the previous one) was obtained for the three coming days of performance tests.

On the first day of testing (August 28th) the lid for the new pot had not dried from painting and therefore the lid for the previous pot was used. It had the same diameter as the new pot but the fit was not perfect which led to vapour loss. Also, it had not been painted black, which means that most sunrays that hit the lid were reflected instead of absorbed (Figure 16).

There was a major issue on this day concerning data logging. When the water temperature was on the border to 88-89 °C degrees (and possibly higher),

"NOT A NUMBER" (NAN) was registered instead of the water temperatures. The explanation from the supplier was that the temperatures close to 90 °C (and higher) must had been out of the voltage range (2.5 mV) specified in the programme for the data logger. The program was updated and upgraded (to 7.5 mV) for the next two days of testing hence this problem did not occur again. However, many of the numbers from day 1 had now already been lost. Random numbers from the real-time data were recorded manually and every "NAN" was replaced with approximated temperatures around 88-91 °C for the calculations. These 15 numbers are depicted in **Appendix A** as red squares. Full Excel spreadsheets of all collected data from all three days can be found in **Appendix E**.

The boiling temperature of 94 °C was reached only on day 3 (August 30th) due to extreme winds (see **Appendix B**). On all three days of testing, the average wind speed and maximum wind speed were exceeded way over the boundaries suggested by ASAE. This could mean that these results are not doing the DSDP justice and therefore should not be used for comparison with other solar cookers that have been assessed with the ASAE S580.1 successfully.

On the contrary, The Polytechnic of Namibia can indeed (and as aimed) use the results as a benchmark, when working on improvements of the DSDP, though it would be favourable to have an idea of the performance of the DSDP during summer time, too.

5.3.1 ASAE testing standard

Regarding the ASAE standard, using linear regression to depict the collected data may not be the best option as the lower temperature differences are being overestimated while some of the higher temperature differences are being underestimated (Figure 17). The single measure of performance was calculated to be 290 W but when looking at the data points in Figure 17 I think this number should be higher.

The confidence interval for the linear regression, which is the interval where the regression line can be found, is included in **Appendix C** (95% accuracy). **Appendix D** presents the prediction interval, which means that if someone were to carry out these experiments again, the linear regression would be found within this interval, with 95% accuracy.

The ASAE standard was assigned for these particular experiments, with results being reported by a linear regression and a single measure of performance at 50 °C. It is possible that it could be beneficial to only use the data surrounding the temperature difference of 50 °C to find the linear regression. In this specific case it is not too reliable to do this, as more data points would be required. However, this is something that could be considered for coming experiments.

5.4 Study visit

During my meeting with Andreas and Viktoria Keding and my study visit to NaDEET, I was informed about their encountered problems with the DSDP: instability of the stand, lack of two-axis rotation, theft and social issues. The problem with the stand was confirmed during my days of testing; not only the parabolic part of the cooker was wobbly when the wind was strong but even the stand was shaking too.

Concerning the lack of two-axis rotation, this is something that The Polytechnic of Namibia has an interest of looking further into, which is encouraging to hear as this would most likely both improve the efficiency of the DSDP and make it easier to use. I do not think it is desired that the user should have to lift one end of the DSDP to move it. Though the cooker itself is not too heavy it is not lightweight either and added to this is often a large-sized pot filled with food.

Theft is evidently a problem with the DSDP as it is quite large and therefore cannot be taken inside the house during the night, without dismantling it. And even if the doorway were big enough, it would take up too much space in the house. Furthermore, when assembling the DSDP, I found it would be quite a hassle if one was to assemble it alone and dismantling it would be equally troublesome. At present, there is not much portability to the DSDP and this is definitely something to take into consideration when looking into improving the geometry of this solar cooker.

Additionally, speaking further about the social problems (mentioned shortly in section **1.1**) with Viktoria, Andreas and staff at NaDEET, I have understood that it is imperative to offer more than just an efficient and user-friendly solar cooker; it also has to look good, although this is largely for the neighbours' admiration.

6. CONCLUSION & FURTHER WORK

6.1 Conclusion

The purpose of this thesis was fulfilled as the assessed performance (**4.3**) can be used, by the intended Master student at The Polytechnic of Namibia, as a benchmark for the upcoming work with the DSDP.

6.2 Further work

- **Determine where the actual focal spot is located**
  Moving the pot stand closer to the theoretical spot could improve the performance. However, it is wiser to first make sure if the actual focal spot is located where the theoretical focal spot is.

- **Reconsider size and weight vs. performance**
  Could the size/weight of the DSDP be reduced? And if it were to be reduced – how would the performance of the DSDP be affected? Is it a fair deal?

- **Enable two-axis rotation**
  Today, it is only possible to rotate the parabolic part of the cooker around one axis. If it were possible to rotate it around a second axis, then it would not be necessary to lift the stand and the whole cooker ever 6-7 minutes, to follow the sun.

- **Source out local materials**
  This is an important aspect as the present reflector material is imported from Germany, which mirrors in the prize of the final product. If a manufacturer in Namibia or Southern Africa could provide polished aluminium plates it could lower the price.

- **Improving aesthetics of the DSDP**
  Due to evident social matters, The DSDP does not only need to look good – it has to look good. This could also give solar cooking a push towards added popularity, which is very much required today.

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