DEVELOPMENT AND EVALUATION OF A SUSTAINABLE SOLAR COOKER FOR OPERATIONS IN UGANDA

BY

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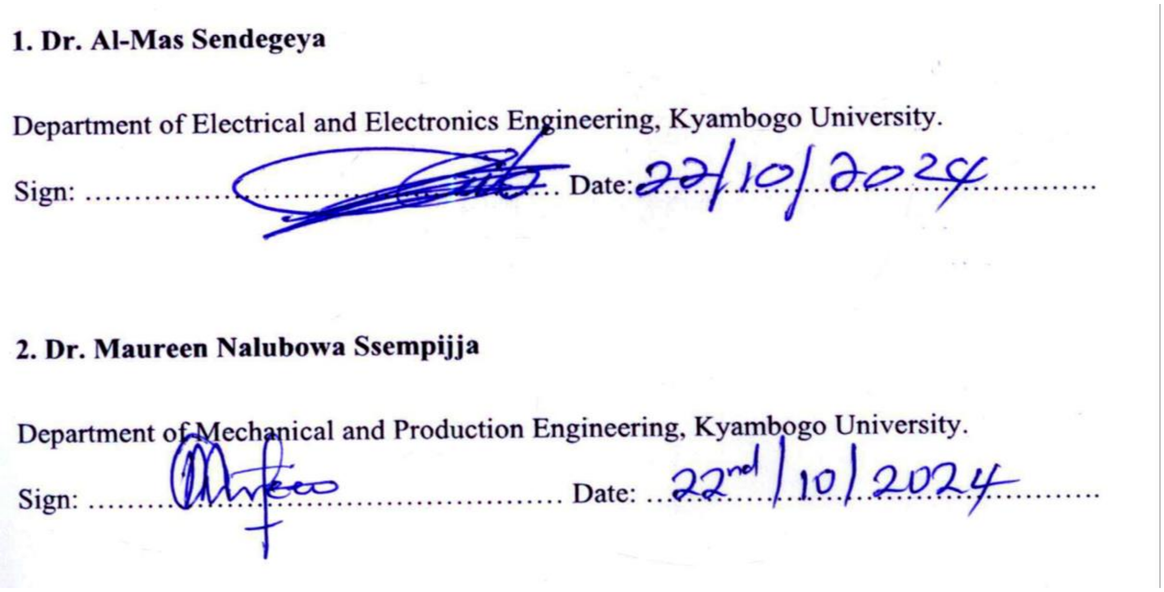
DECLARATION

I, Sebunya Steven, declare that this dissertation is my original work and has never been presented for any award in any tertiary institution.

Sign. .... Date. 18/10/2024.

APPROVAL

This dissertation entitled "*Development and Evaluation of a Sustainable Solar Cooker for Operations in Uganda*", prepared and submitted by Sebunya Steven in partial fulfillment of the requirements for the Masters of Science in Advanced Manufacturing Systems Engineering of Kyambogo University has been under our supervision.



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DEDICATION

I dedicate my research dissertation to my dear mother Ms. Kaisa Sarah, my aunt Ms. Faith Norah Malinga, my sisters, my brother Kakaire Faizo and future family for the inspiration, support and encouragement throughout my pursuit for education. I hope this achievement will fulfill the dream they envisioned for me.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADT	Average Daily Temperature
CPV	Concentrating Solar Photovoltaic
DNI	Direct Normal Irradiation
DSC	Developed Solar Cooker
FS	Fuel Saving
GHI	Global Horizontal Irradiation
GIS	Geographical Information System
IIC	Initial Investment Cost
LPG	Liquid Petroleum Gas
NDPIII	National Development Plan III
NPA	National Planning Authority
PP	Payback Period
SCs	Solar Cookers
SDGs	Sustainable Development Goals
SPM	Savings Per Month
STE	Solar Thermal Energy
UBOS	Uganda Bureau of Statistics
UN	United Nations

ABSTRACT

The high level of increasing technological advancements and human population globally have resulted into escalated energy demands. With cooking accounting for almost 90% of all the household energy consumption in developing countries, traditional firewood stoves and improved charcoal stove are still dominant regardless of their negative impact. In Uganda, there is need of adopting clean and renewable non-depleting alternative energy sources among which includes solar cooking technologies. Many regional areas across Uganda and especially in the Northern and Eastern, receive approximately 4–5 kWh/m² per day of solar energy which is commendable for most solar cooking technologies. This study deals with the development and evaluation of a novel box-type direct solar cooker while putting in to consideration the existing cooking dynamics, solar irradiation and locally available materials for operation in Ugandan. For optimization, the cooking energy requirements for common foods like rice, matoke, and cassava, along with the average solar irradiation in Uganda, were considered to determine the cooker's aperture area, which was calculated to be 0.1897 m². The cooker was further developed with internal side-wall reflectors to improve its performance efficiency and these were calculated as 34^0, 56^0, 43^0, and 43^0 due to south, north, west, and east respectively. Solar data and geographical data for Mbarara city (Having the lowest amount of daily Global Horizontal Irradiation (GHI) among the selected regional areas) were considered in the module design and simulation for performance feasibility. Using COMSOL Multiphysics 5.5 software, thermal analysis and optical analysis were conducted for the systems performance validation. Finally, locally available materials were considered for costing and construction of the developed solar for both economic and manufacturing feasibility. The cooker was costed at 210 USD with a payback period of 1 and 1.3 years while transitioning from cooking using charcoal and electricity respectively.

Keywords: Solar cookers; Sustainability; Solar box cooker; Cooking dynamics; Solar irradiation

CHAPTER ONE: INTRODUCTION

This chapter introduces the study through a presentation on the global status of energy sustainability, the problems escalating from the continuous usage of conventional cooking methods in Uganda, and the purpose of the study. The specific objectives, significance, justification, and conceptual framework are also presented.

1.1 Background of the Study

Universal energy access and a decarbonized climate energy system are crucial global agendas for sustainable development, (Nations, 2021). The use of renewable energy sources with developed technologies is now more than ever being promoted especially in developing countries, (Falcone, 2023). Countries have been encouraged to accelerate electrification and expand investments in renewable energy sources to achieve universal access by 2030 (Assembly, 2023). This is consistent with Sustainable Development Goals (SDGs) 7 and 13, which call for affordable clean energy and immediate action on climate change, (Misra et al., 2023).

Considering a progress report towards the SDGs by the United Nations (UN), 2.3 billion people still cook with unsafe and polluting fuels, (UN Assembly, 2023). The report further states that in sub-Saharan African countries, below 10% of the population has access to clean fuels and technologies. This growing access deficit if not reversed, could affect the increasing trends in global energy access. In the Ugandan context, the energy policy review emphasizes the increase in the use of modern renewable energy technologies, (IEA, 2023). A good consideration is the use of solar cookers which provide heat in a natural and renewable way for cooking through the principles of concentrating the sun's rays, (Soro et al., 2020).

Unfortunately, Uganda still heavily relies on biomass as an energy source due to poor electricity distribution rates across the country, (NPA, 2020). The use of biomass energy fuels (in raw form) is disastrous as these are one of the major contributors to environmental pollution and global warming, (Soro et al., 2020). Charcoal and firewood fuel biomass utilization have led to a lot of deforestation in Uganda and continuously impacts human health, (Bamwesigye et al., 2020). According to statistics, by 2015 Uganda's forest land has greatly reduced due increase in agricultural activities as a result of increased human encroachment, (UBOS - Abstract, 2021). The use of 3 stone stove fire for cooking by Ugandans is at 53.5%, charcoal use at 27.3% while improved cooking stoves stand at 16.9%, (Nsamba et al., 2021). Renewable energy sources like solar energy are hence a clean alternative to worldwide energy requirements and are now being exploited more and more, (Guzman et al., 2014).

On a global scale, it is important and beneficial to have solar cookers of different varieties of geometrical designs, performance, and price, (Akoy & Ahmed, 2015). Hence, improvements in the reflecting surface designs and materials could lead to new developments in solar cookers suitable for different locations. Uganda is among the countries with high solar irradiation throughout the year, (Katongole et al., 2023). However, the use of solar energy for thermal applications in the country has not been well adopted due to continuous use of firewood and charcoal for household consumption, (UBOS, 2021). Most solar cooker designs being adopted are the concentrating types and box type whose performance depends mainly on location, the reflector design, and quality of the reflecting materials among other factor, (Misra et al., 2023).

Comparatively, there are some more limitations in other obsolete technologies of cooking like the electric coils which result to high electric bills. This has limited the economic growth of local communities as households are still burdened with relatively high retail prices for energy, electricity instabilities, and wood shortages, (Mukwaya, 2016). Most solar cookers developed do not take into consideration, the local cooking practices and traditions, (Iessa et al., 2017). The research study therefore centered on developing and evaluating a solar cooker, taking into account Uganda's regional cooking habits, diverse energy demands, and geographical conditions.

1.2 Problem Statement

While solar energy technologies offer extensive potential for enhancing energy sustainability and reducing greenhouse gas emissions, current solar cookers face limitations in addressing local cooking habits, energy demands, and diverse regional geographical conditions in Uganda. Some of the solar cookers developed do not consistently achieve the cooking temperatures (100 ^{0}C - 250 ^{0}C) needed for local foods like matooke or beans, nor do they support the large household sizes (averaging 5 -7 people) typical for rural Ugandan families. Ugandan households, especially rural areas, consume approximately 1.5 kg to 2 kg of firewood per meal and this heavy reliance has increased the cost and crisis of firewood. Furthermore, charcoal production has worsened deforestation and carbon emissions, driven by rising demand in urban and peri-urban areas. Notably, regions like Northern and Eastern Uganda receive approximately 5.5 kWh/m^2/day of solar energy, but this is not fully exploited for solar cooking.

1.3 Research Objectives

1.3.1 Main Objective

To develop and construct a sustainable solar cooker that provides affordable cooking solutions in Uganda, improving livelihoods while reducing environmental degradation.

1.3.2 Specific Objectives

i. To size the components of a solar cooker and select locally available materials that optimize both performance and cost.
ii. To conduct modeling and simulation of the solar cooker to validate its thermal and optical efficiency.
iii. To construct the solar cooker and evaluate its ease of local production, along with its economic feasibility.

1.3.3 Research Questions

i. What components and locally available materials can be used to optimize the performance and cost of a solar cooker for Uganda's conditions?
ii. How can modeling and simulation validate the thermal and optical efficiency of the solar cooker design?
iii. How feasible is the local production of the solar cooker, and what are its economic benefits compared to conventional cooking methods?

1.5 Significance of the Study

On macro level, the research study intends to better prepare communities in Uganda for the challenges of fast urban growth, rising energy costs, resource depletion, health, environmental degradation, and climate change. By reducing the reliance on expensive and unreliable fuel sources, such as firewood or charcoal, sustainable solar cookers could help households save money and reduce their expenses. The research findings could improve energy access and security for households and communities, especially those in remote areas. Also from the academia, the research develops knowledge about solar cooker technology and its adoption in countries with high dependence on traditional biomass. Finally, sustainable solar cookers are consistent with the principles of sustainable development, which are essential for achieving the SDGs. The study also addresses the national development goals on increasing energy access in a sustainable manner.

1.6 Justification of the Study

In line with the National Development Plan III (NDPIII), there is a need to increase the share of clean energy used for cooking from 15% as of 2019 to 50%, (NPA, 2020). This is supported by, (IEA, 2023), which encourages self-generation and adoption of improved energy technologies as vital preconditions to achieving affordable, clean energy and immediate action on climate change. The inefficiencies of conventional cooking and the rising cost of fossil fuels now paves way for solar energy technologies since this is renewable. In Uganda, as in many other developing countries, access to modern energy services is limited, especially in rural and peri-urban areas, which hampers economic development. The development and promotion of sustainable cooking technologies is consistent with the principles of sustainable development and hence the need for more research in this field.

1.7 Scope of the Study

This research aimed at investigating and developing an optimized solar cooker as a sustainable and environmentally friendly solution to meet the escalating energy demand in Uganda. The study assessed the various cooking habits and solar radiation distribution across Uganda to establish cooking energy requirements and regional areas suitable for solar cooker adaptation. Different types of solar cooker designs were studied for the selection one most suitable for Uganda's local cooking dynamics and geographical conditions.

The selected solar cooker type was later on developed in terms of its structure and materials in order to justify its technical and economic feasibility. The study based on literature review data to help evaluate existing local cooking habits, solar radiation distribution and solar cooking technologies. It also adopted an experimental research design to develop and construct an optimized solar cooker prototype, aided by numerical methods and computer aided design modeling and simulation for data collection and analysis.

1.8 Conceptual Framework

The conceptual framework for this research was designed to guide the assessment, optimization, and evaluation of the technical and economic feasibility of solar cookers in Uganda. The study progressed through five interconnected phases: assessment, optimization, modeling, simulation, and construction. This led to the development of an efficient and suitable solar cooker design tailored to local conditions. The research outputs were to greatly contribute to the development of practical and eco-friendly cooking solutions, promote energy sustainability and help mitigate the adverse effects of traditional cooking practices. Figure 1.1 below provides the conceptual framework design used in the study.

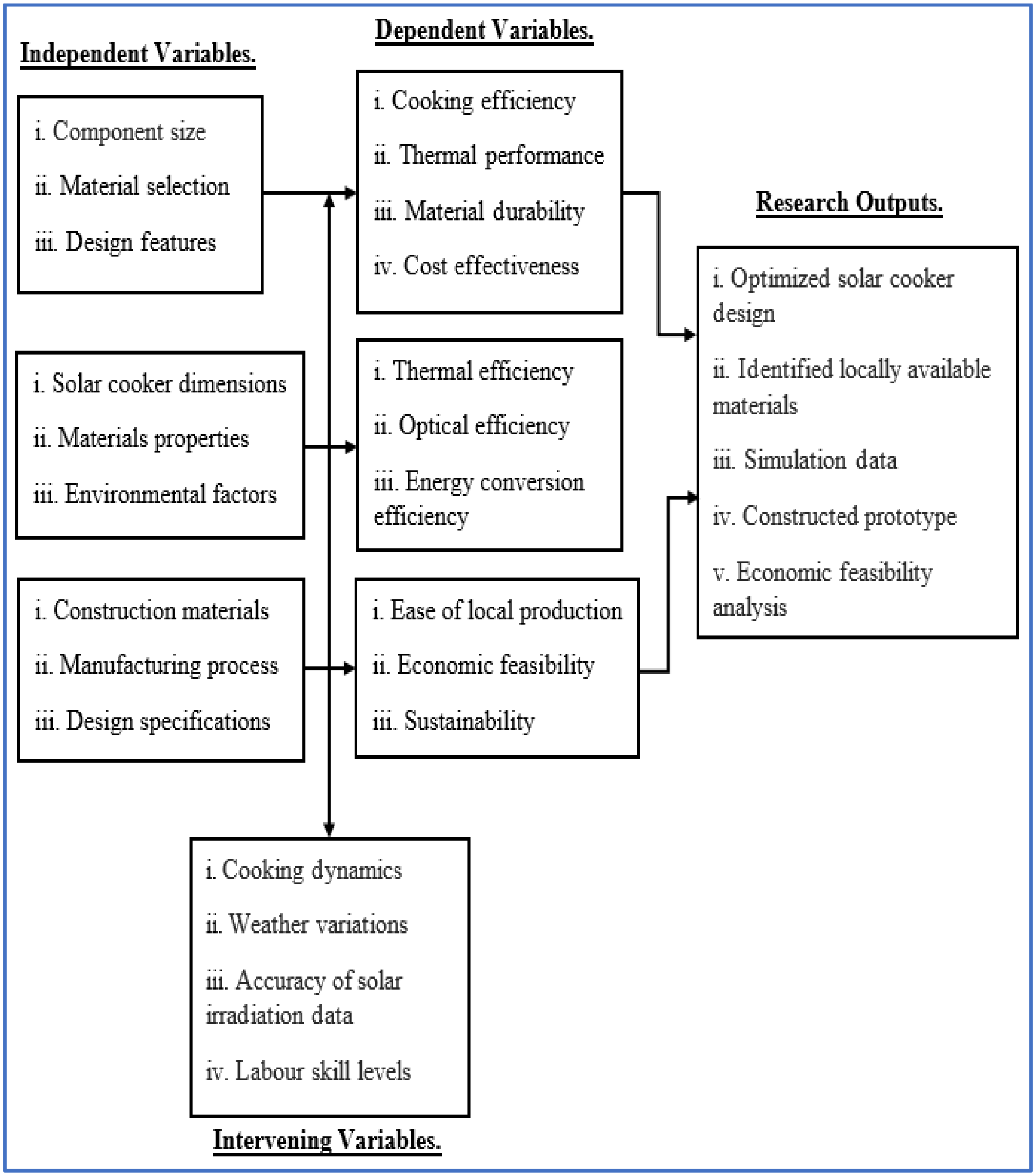

Figure 1.1: Conceptual framework

CHAPTER TWO: LITERATURE REVIEW

This chapter provides literature on cooking habits, cooking methods, and some data on solar radiation distribution in Uganda to justify the need for embracing sustainable clean cooking technologies. The common types of food prepared in different regions of the country have been presented including literature on the different solar cooking technologies available. Finally, it gives a summary of the gaps in the literature.

2.1 Cooking Habits and Types of Foods

2.1.2 Cooking Habits

As a country, Uganda has been divided into four regions including the Northern, Central, Eastern, and Western regions, (Katongole et al., 2023). The cooking habits and types of food cooked in these regions can vary due to cultural, geographical, and historical factors, (Kajumba et al., 2020). Uganda is rich in energy resources with physical potentials estimated at 2,000MW for hydroelectric power, 450MW of geothermal, 1,650MW of biomass cogeneration, and, an average of 5.1kWh/m^2 /day of solar energy, (Naluwagga et al., 2022). Like most other sub-Saharan African countries, Uganda heavily relies on biomass as an energy source due to the poor electricity distribution rates across the country, (NPA, 2020). The choices for cooking fuels are categorized into traditional fuel (firewood), transitional fuel (charcoal), and modern fuels (LPG & electricity), (Katutsi et al., 2020). According to Nsamba et al., (2021), forest firewood is the most commonly used biomass fuel for cooking with a percentage of 66.8% followed by charcoal at 27.%. The Ugandan government aims at reducing the use of biomass for cooking purposes from 80% to 50%, while increasing the use of clean energy from 15% to 50% by 2025, (Kajumba et al., 2020).

By advocating for alternative non-conventional energy resources, challenges of pollution, deforestation and increased dependance on fossil fuels will be minimized, (Karande et al., 2017). Studies have also shown that the costs and availability of conventional fuel alternatives are important factors that help in explaining the economic viability of solar cooking in areas suitable for adoption, (Iessa et al., 2017). Table 2.1, summarizes the methods of cooking in the different regions of the country.

Table 2.1: A Summary of the major regions in Uganda and their cooking methods

Region	**Cooking Methods**
Northern	i. Firewood
	ii. Charcoal Stoves
	iii. Electricity (Limited extent)
Central	i. Improved charcoal stoves
	ii. Electrical Cookers
	iii. Firewood (rural communities)
Eastern	i. Charcoal Stoves
	ii. Firewood
	iii. Electrical Cookers
	iv. LPG (In some Urban communities)
Western	i. Charcoal Stoves
	ii. Firewood
	iii. Electrical Cookers

The northern region, particularly the Acholi, Lango, and Alur communities, relies heavily on traditional cooking methods, including the use of firewood and charcoal stoves.

Cooking in some of these places is often communal due to existence of extended families or refugee camps and is done using larger pots, (Nsamba et al., 2021). In the central and eastern regions, cooking methods range from traditional to modern with many urban households using improved charcoal stoves, LPG and electric cookers.

Generally, when considering households that use single fuel, charcoal is the most often and frequently used fuel, (MECS, 2020). This is followed by LPG especially in urban and peri-urban communities. Firewood and charcoal consumption have a lot of negative impacts on both the environment and human health. As such, SDGs 7 and 13 have consistently called for affordable clean energy and immediate action on climate change (Misra et al., 2023). Among the clean energies is solar energy whose distribution in Uganda is satisfactory with an average of 5.1kWh/m^2 /day that supports the use of solar cooking technologies, (Kajumba et al., 2020).

2.1.2 Common Types of Foods in the Major Regions of Uganda

Considering the major regions of Uganda, the quantity of fuel used and the time taken to cook partially depends on the type of food being cooked, (Mainimo et al., 2022). Cereal foods require more fuel compared to fresh foods, (Nsamba et al., 2021). In the northern regions as seen in the Table 2.2, some popular dishes include malakwang (a green leafy vegetable stew) and luru soup (made from groundnuts) which can easily be prepared using solar cookers.

The Eastern region is known for foods like cassava, millet, sorghum, and beans. Popular dishes in the western region include kalo (a millet bread), matooke and ghee – based sauce, (Kajumba et al., 2022). The study findings generally highlight that rice, banana (Matooke or plantain) and cassava are the most common food types while boiling and simmering are the predominant cooking method.

Table 2.2: Cooking dynamics and human household capacities across Uganda

Factor	Result	Sources
Type of food	Banana Rice cassava	Nsamba et al., 2021 Kajumba et al., 2022
No. of people	3 – 5 (Central) 5 – 8 (Others)	Nsamba et al., 2021 Kajumba et al., 2022
Cooking hours	2 – 4	Nsamba et al., 2021
Daily frequency of cooking	≥ 2	Nsamba et al., 2021
Cooking practice	Boiling	Nsamba et al., 2021

From the Table 2.2, it can be noted that the number of household members ranges from 3 to 8 people with an approximated average of 5 members. This is in agreement with the Uganda Demographic and Health Survey (UDHS) report which highlighted that a typical household size in Uganda constitutes 4.7 persons , approximating to 5 people, (Kajumba et al., 2022). Most households cook three times a day with the average total cooking time approximated at 2 hours and 45 minutes. The hard cereal foods require more cooking time compared to fresh foods and hence, a wider cooking pot is recommended to enable a quick and more efficient cooking process, (Kajumba et al., 2022). Therefore, the establishment required a large aperture area of the solar cooker and this also needed knowledge of the available solar irradiations. Additionally, understanding the geographical distribution of solar irradiation was used to justify the development and adoption of solar cooking in different parts of the country.

2.2 Solar Irradiation Distribution in Uganda

The Direct solar irradiation refers to the radiations passing through the atmosphere without any deviation while diffuse solar irradiation are the radiations coming from all the other directions, (Babikir et al., 2018). An important source of solar irradiation distribution for Uganda is the solar resource map presented in the Figure 2.1 below.

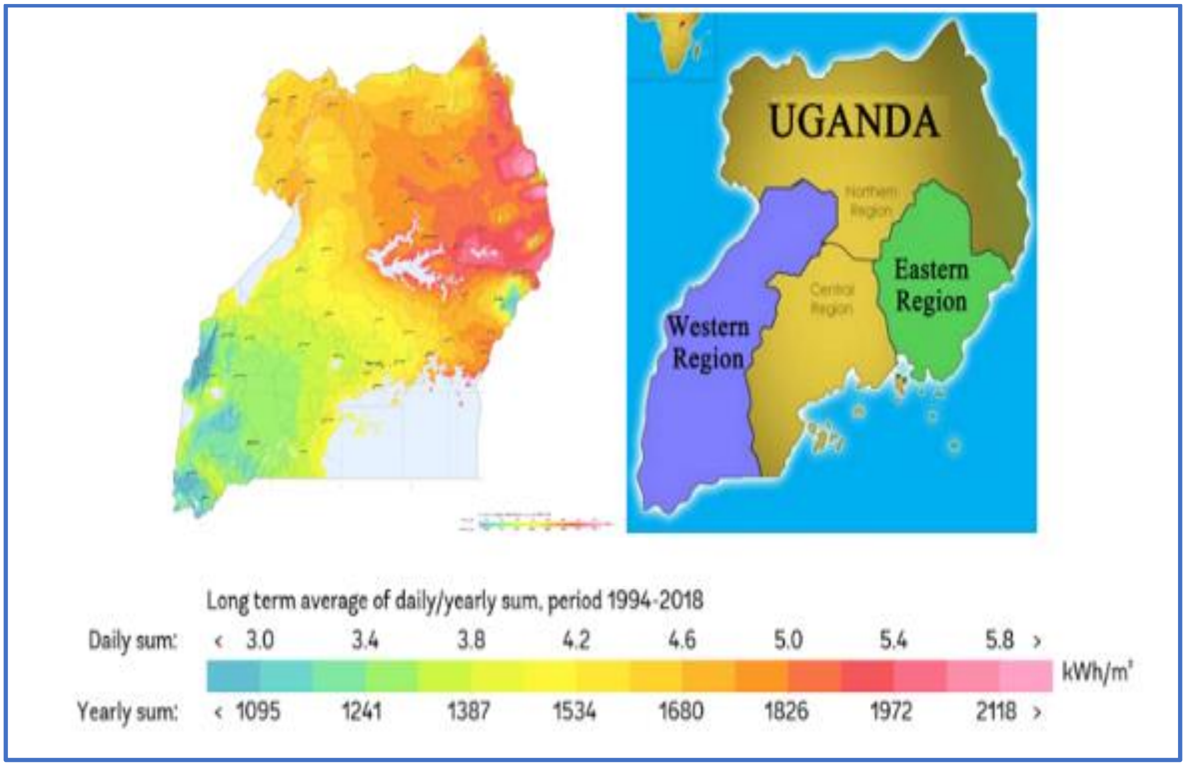

Figure 2.1: Uganda's daily/yearly Sum of DNI (source; Bank, 2023) and Uganda's major regions (Source; Nsamba et al., 2021) .

The Figure 2.1 provides a summary of the estimated solar energy available across Uganda. It represents the average daily/yearly sum of direct normal irradiation (DNI) covering a period of 25 recent years (1992-2018), (Bank, 2023). The DNI is the most important parameter for energy yield calculations and performance assessments of concentrating solar power technologies which includes solar cookers, (Bank, 2023).

The standard requirement of solar radiation for solar cooker applications can vary depending on the type of solar cooker being used and the specific cooking needs of the area, (Kajumba et al., 2022). However, solar cookers are generally most effective in regions with ample sunlight or solar radiation. Solar cooking has great potential in countries which have daily solar radiations of 5-7 kWh/m² and a large number of sunny days per year, (Ali Kakar et al., 2019). A commonly cited minimum solar radiation requirement for effective solar cooking is around 4–5 kWh/m² per day. Studies have also shown that the costs and availability of conventional fuel alternatives are important factors that help in explaining the economic viability of solar cooking in areas suitable for adoption, (Iessa et al., 2017).

Solar resource maps and data sources also reveal the variations in solar energy availability across Uganda, (Katongole et al., 2023). Findings highlight that the eastern and northern regions experience high solar intensities ranging between 823.9 – 831.6 Wm^{-2} and 829.2 – 822.2 Wm^{-2} while western Uganda receives the lowest, (Mundu, 2021). Since effective solar cooking requires regions with ample sunlight typically around 4–5 kWh/m² per day, the regional areas presented in the Table 2.3 were considered in the design process and selected for solar cooking adoption in Uganda, (Katongole et al., 2023). These solar irradiation potential distributions presented were captured at 56 ground meteorological stations across Uganda from January 2015 to February 2022.

From among the selected regional areas, the study considered the western region as the reference location for obtaining numerical data needed in some of the design calculations and module design simulations. This is because Mbarara city possessed the least daily GHI and therefore, the developed solar cooker was expected to longer cooking hours in this region compared to the other regions.

Table 2.3: Solar data for the selected regional areas , (Katongole et al., 2023).

Region	Areas	Avg. daily GHI (kWh m^{-2} day^{-1})	Avg. daily temperature (°C)
Northern	Amolatar	5.25	25 - 25.8
	Gulu	4.95	
	Ngora	5.35	
Eastern	Serere	5.5	23.3 - 25
	NaRo	5.15	
	Serere	4.95	
	Soroti		
Central	Ngoma	4.65	22.4 – 24.1
	Bukalasa	4.5	
	Entebbe	4.3	
Western	Kyenjojo	4.75	20.7 – 22.4
	Mbarara	4.25	

In Uganda, highest ranges are prevalent at the end and beginning of the year (December to February) but these significantly decline in July, (UBOS, 2021). Among the four major regions of Uganda, the northern region receives the highest average temperature as seem in table 2.4, (Katongole et al., 2023).

Table 2.4: Uganda's regional daily average temperatures and the average daily GHI (Source; Katongole et al., 2023)

Region	Daily Average Temperature Ranges (°C)	Daily GHI (kWh/m^2/day)
Northern	25 - 25.8	5.16
Central	22.4 - 24.1	4.30
Eastern	23.3 - 25	4.94
Western	20.7 - 22.4	4.2

2.3 Different Technologies of Solar Cookers

A solar cooker is can provide heat in a natural and renewable way through the technique of concentrating the sun's rays with potential of saving 1 ton of wood per year in sunny regions, (Soro et al., 2020). This makes it a promising option with the capabilities of being one of the main sources of cooking energy sources in the domestic sector of most sub-Saharan African countries. Solar cookers are relatively inexpensive, use no fuel and cost nothing to operate, (Aramesh et al., 2019). Hence, many solar cooking technologies have been developed to suite different geographic locations and climate across the globe, (Ali Kakar et al., 2019). These are divided into two categories as seen in the Figure 2.2, with the direct type focusing sunrays straight onto the receiving area (Absorber plate) while the indirect type utilizes a transient fluid to transport heat from the collector to the cooking unit, (Misra et al., 2023).

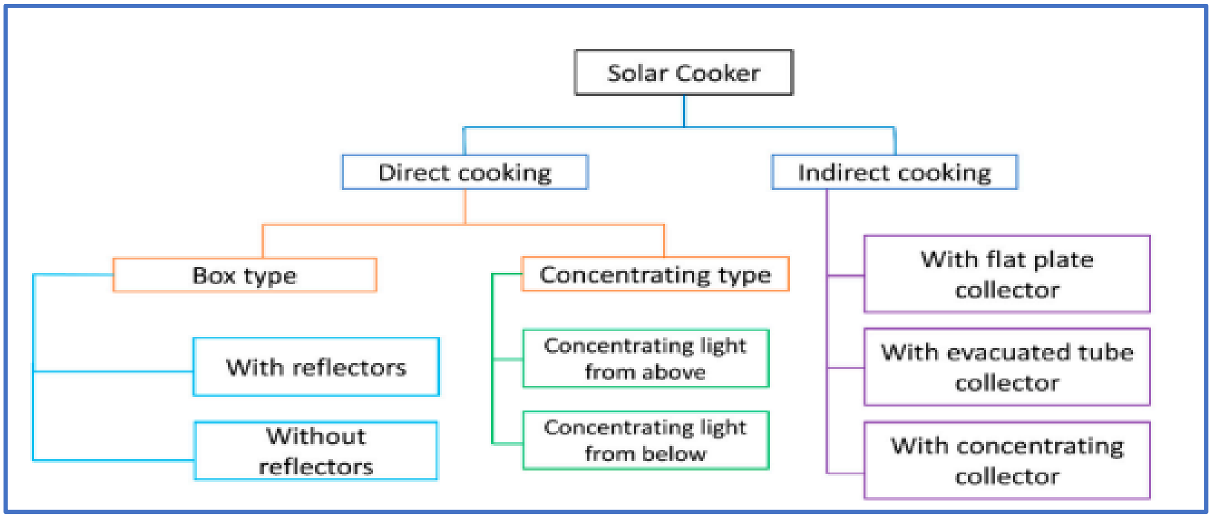

Figure 2.2: A breakdown of different types of solar cookers (Source; Misra et al., 2023).

The study review mainly focused on the direct cooking solar cooker technologies and gave a summary on indirect solar cookers.

2.3.1 Concentrating solar cookers

These employ optics to concentrate the sunrays on the receiver of the cooking unit which results into generation of very high temperatures, (Lentswe et al., 2021). A parabolic concentrator as shown in the Figure 2.3, is mostly used with a cooking vessel at the center, and a stand with adjustable support so that the concentrator always faces the sun, (Misra et al., 2023). Due to high temperature generation (350 ^{0}C to 400 ^{0}C), these are suitable for frying, baking, boiling, and roasting. Cooking can hence be achieved in short time periods. In recent developments, a particular type of lens called the Fresnel lens was used to concentrate sunlight precisely to a focused area and is made from plastic hence, sustaining wear and tear for long durations against UV rays and abrasions, (Engoor, 2020).

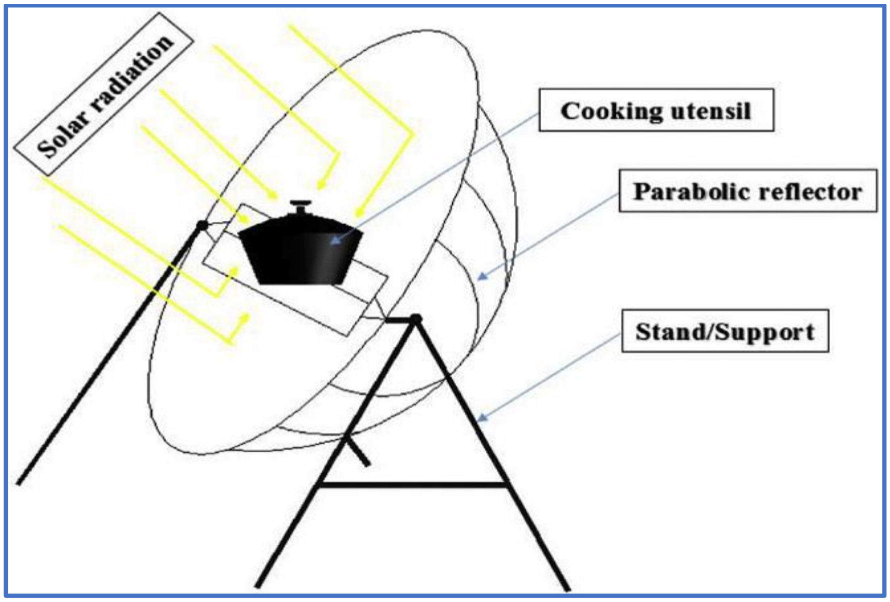

Figure 2.3: A concentrating solar cooker (Source; Lentswe et al., 2021)

The reflector cooker with polished aluminium reflectors have significantly lower performance than those with glass mirror reflectors, under clear sky conditions, (Reddy et al., 2014). The Table 2.5 summarises the advantages and disadvantages of concentrating solar cookers from different sources.

Table 2.5: Advantages and disadvantages of concentrating SCs, (Herez et al., 2018).

Advantages	Disadvantages
i. Can reach very high temperatures (45O^{0}c)	i. They are very costly
	ii. Larger in size
ii. Cook for short periods	iii. Possess risks of fire and burns
	iv. Require continuous tracking of the sun
	v. Need careful attention to prevent food burning

2.3.2 The Box–Type Solar Cookers

According to Aramesh et al. (2019), solar box cookers are third after liquefied petroleum gas (LPG) and stoves (including kerosene stoves) in the adoption rankings. As illustrated in the Figure 2.4, the general operating principle of these solar cookers is that they channel and concentrate sunlight through mirrors to an absorber cooking container, which is then converted to heat and used for cooking, (Iessa et al., 2017).

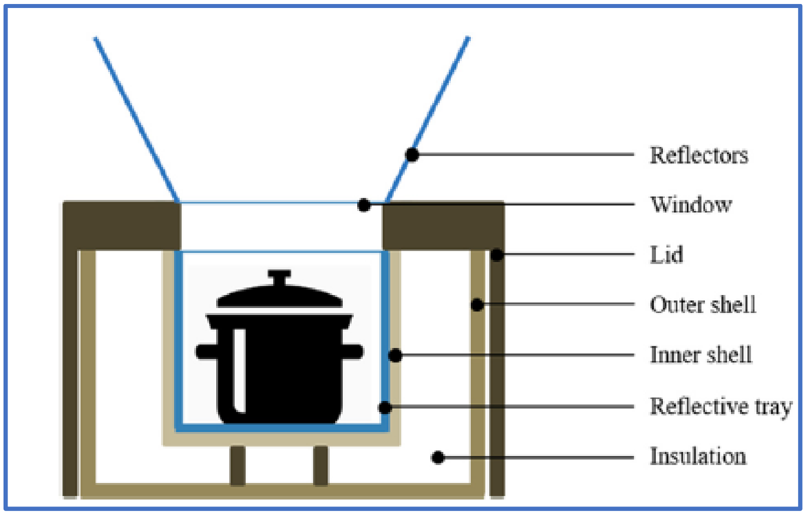

Figure 2.4: Sectional view of a box-type solar cooker, (Schindelholz et al., 2024).

A typical box–type solar cooker is mainly made from plywood sheets, flat mirrors, an absorber made of blackened 0.8 mm thick galvanized sheet metal and is thermally insulated with a layer of glass wool carefully wrapped in a reflecting material like aluminum foil, (Soro et al., 2020).

In order to improve the thermal performance of a box-type solar cooker, it is necessary to have the knowledge of design parameters, optical efficiency and heat capacity of the cooker but also provide a basis for material selection, (Geddam et al., 2015). Box-type solar cookers have numerous advantages associated with highly nutritious food, one-time subsidized cost, almost no maintenance and running cost, and long-term usability, (Misra et al., 2023). Additionally, box-type solar cookers have the ability to keep food warm until evening due to the greenhouse effect created inside the cooker by the glaze covering. Box-type solar cooker also makes use of both diffuse and direct radiation hence, are used in intermittent cloud cover, and low ambient temperatures, (Kulla et al., 2020). Table 2.6 summarizes the main advantages of box – type solar cookers.

Table 2.6: Advantages and disadvantages of Box-type SCs, (Shrivastava et al., 2019).

Box-Type Solar Cookers	
Advantages	**Disadvantages**
i. User-friendly ii. Easy to build iii. Easy to use and operate iv. Safe v. Require little attention.	i. Generate moderate temperatures (150^{0}C) ii. Long cooking hours iii. Can not be used to fry and roasting

Cooking vessels recommended in solar box cookers generally include cylindrical-shaped cooking vessels made of aluminum or copper. Studies also show that cooking time decreases when fins are added to the cooking vessel, (Aramesh et al., 2019). However, some of the drawbacks of box cookers include producing moderate temperatures which lengthens cooking time with the glass cover also causing considerable heat losses. Most box solar cookers can achieve temperatures of around 100 ^{0}C and this enables them to cook foods prepared through boiling, (Yettou et al., 2014a).

2.3.3 Indirect Solar Cookers

Indirect Solar Cookers utilize thermal heat from a heat-transfer fluid, such as thermal oils and molten salts, which come from the focus point of the reflector, (Yettou et al., 2014a). This heat is then transported to cooking vessels for cooking purposes and in these, the heat collection and cooking sections are separated. The heat collection unit is placed outside or on the roof, while the cooking unit is inside or in the kitchen.

Various types of collectors, such as flat-plate collectors or parabolic-trough collectors, are used for heat collection. Kumaresan et al., (2018), conducted an experimental and numerical investigation on a solar flat plate cooking unit for domestic applications and their findings highlight an average heat transfer coefficient of approximately $100\ W/m^2K$ for therminol-55 as the heat transfer fluid (HTF). The Figure 2.5, shows an example of indirect solar cooker design.

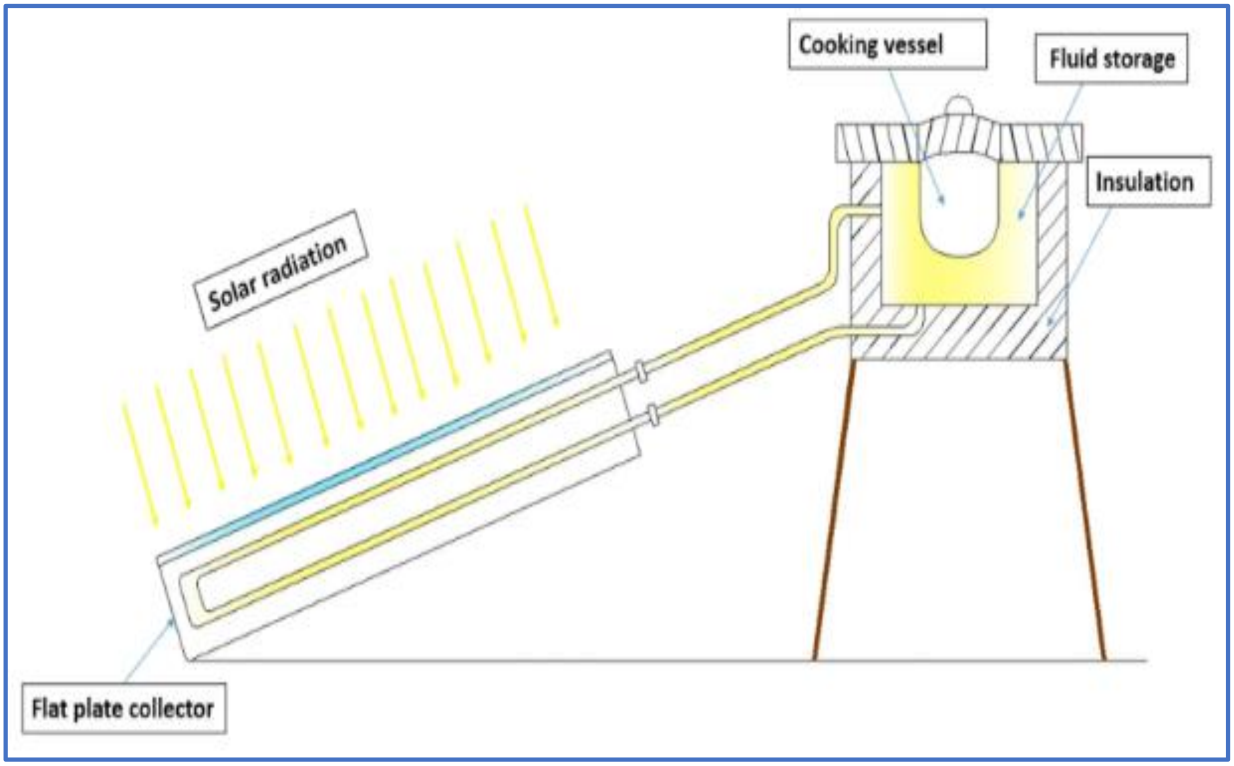

Figure 2.5: Flat-plate collector indirect solar cooker (Source; Misra et al., 2023).

Table 2.7: Advantages and disadvantages of indirect solar cooker, (Misra et al., 2023)

Indirect Solar Cooker	
Advantages	**Disadvantages**
i. Can easily be integrated with energy storage units ii. Can be used during off-sunshine hours iii. Cooking unit is placed indoors	i. Experience heat loss from the thermal transfer fluid ii. construction is expensive iii. Difficult to operate iv. Expensive to maintain

2.4 Summary of Literature Review and Research Gaps

Several studies and developments have been made on solar cookers across the globe and in Africa, especially the sub-Saharan regions of which Uganda is apart. It is imperative to recognize that local factors, such as climate conditions and the extent of sunlight availability considerably impact the overall performance of these cookers, (Aramesh et al., 2019). This calls for more comparative studies on different cooker configurations for development and diverse regional suitability, something that has not been done for the case of Uganda.

With most popular dishes being prepared by boiling and steaming, a box-type direct solar cooker can be diversly adopted if developed while putting into consideration the cooking dynamics and prevailing weather conditions across the major regional areas of Uganda, (MECS, 2020: Kajumba et al., 2022). The study has therefore considered size and shape modification of the absorber plate, and optimizing reflectivity as areas for development in the design of the box-type solar cooker for better cooking efficiency and high temperatures, (Khatri et al., 2021).

The study aims to develop a solar cooker system that will sustainably improve the lives of the people in the both the rural and peri-urban communities which experience sufficient solar irradiations across the year. This study also aims at contributing knowledge to the development, techno-economic and manufacturing feasibility of solar cooker technologies for adoption hence reducing over reliance on biomass cooking fuels.

CHAPTER THREE: METHODOLOGY

This chapter describes the research approaches, design, and procedures used in the study. The methods used to achieve the respective research objectives have been presented. This includes the development processes, material selection, simulation and construction in consideration of Uganda's cooking dynamics, available solar irradiation and locally available materials.

3.1 Research Approaches

3.1.1 Descriptive Research Approach

This approach was used in literature review to assess solar radiation availability, cooking habits, and cooking methods in the four major regions of Uganda. The approach was also used to assess the existing solar cooker designs and gave a basis for the consideration of one for development with suitability for adoption given Uganda's prevailing local conditions.

3.1.2 Experimental Research Approach

This approach was used in the design and construction of the sustainable solar cooker. This involved full development in terms of sizing, shaping and material section of the component parts that make up the considered solar cooker type. The developed system design was modeled and simulated using CAD software followed by a constructed prototype using locally materials.

3.2 Research Design

The research design included determining cooking habits, solar radiation distribution, and types of foods in the four major regions of Uganda. It furthermore assessed the existing solar cooker designs to establish suitability for development and adoption.

Energy requirement for the cooker was established considering cooking needs while the energy input considered the average solar irradiation and suggested efficiencies from the literature. The aperture area was then established with addition improvements made on solar reflectivity into the cooking chamber. A full system design was made using CAD software, simulated and constructed with assessment made for its technical manufacturability and economic feasibility. The economic impact of the sustainable solar cooker was assessed considering factors such as cost-effectiveness and fuel savings.

3.3 Determination of Cooking Habits, Types of Foods and Solar Radiation Distribution

Thorough literature review was conducted on cooking habits together with their impact to the families and the environment in the Ugandan context. The common cooking methods in the four major regions in Uganda were identified together with the main foods prepared. All these finding guided the design and decision-making processes during the development of the solar cooker suitable for operations in Uganda. Cooking is dependent on the temperature requirement and the method of application of heat and duration, and is mainly categorized as baking, roasting, boiling, frying, stewing, among others, (Indora & Kandpal, 2018). In Uganda, most popular dishes are prepared by boiling and steaming, (MECS, 2020). Some of these dishes include matooke, potato, rice, cassava, and beans which are among the common dishes across all regions of Uganda, (Nsamba et al., 2021). From the literature study findings, rice, banana (Matooke or plantain) and cassava were confirmed to be the most common food types across all the four major regions of Uganda, (Kajumba et al., 2022; Nsamba et al., 2021; Akumu et al., 2023). Since the quantity of fuel to cook is partially dependent on the type of food being cooked, establishment of the energy requirement for the common types of foods was key for the study design process, (Mainimo et al., 2022).

The literature findings suggested that solar cookers are currently being used in conjunction with various types of cookstoves and retained heat cookers due to the uncontrollable weather conditions, (Ebersviller & Jetter, 2020). This helped to justify the need and suitability of solar cooker adoption especially in regions experiencing high solar irradiations and many sunny days across the year. The study review on solar radiation data highlighted regional areas suitable for solar cooking adoption across the major regions of Uganda. These regional areas were considered because their daily GHI fall within the threshold recommended for solar cooker adoption.

It was noted that Uganda has an average solar irradiation of 5.1 kWh/m^2 /day on a horizontal surface, (Gumisiriza, 2020; Katongole et al., 2023). Northern Uganda receives the highest average daily GHI of 5.38 kWhm^{-2} day^{-1} and Western Uganda receives the lowest daily GHI of 4.16 kWhm^{-2} day^{-1}, the average of these two was to be considered in the design calculations for the establishment of the solar cookers aperture area, (Katongole et al., 2023).

3.4 Assessment of The Existing Solar Cooker Designs

Renewable energy projects are normally aimed at providing solutions based on how clean the energy is, the efficiency of the system, energy saving, time saving, and the cost benefits of using the system, (Kajumba et al., 2022). The in-depth reviews highlighted that the development of existing solar cooking technologies during the past two decades focused on the geometry of the components such as the booster mirror, absorber tray, insulation, glazing system, cooking vessel, and thermal energy storage materials, (Yettou et al., 2014b). The concentrating-type and box-type direct solar cookers were focused on in the study review with consideration based on the merits and limitations of each in relation to Uganda's cooking dynamics and regional geographical conditions.

The review also included technical specifications, cooking efficiency, and materials used. Therefore, factors such as the local conditions, cooking needs, cost-effectiveness, durability, and ease of use were to justify the selection, (Nhabetse, 2015). Concentrating solar cookers (Component A) generate higher temperatures which gives them diverse potentials like frying and roasting numerous types of foods. This is where they had a great advantage over box-type solar cookers as this leads to shortened cooking hours and ability to prepare a wide range of dishes, (Misra et al., 2023). Argumentatively, the study review suggested that box-type solar cookers came in second place in terms of heat generation and highlighted that with good optimization, this could be improved further, (Khatri et al., 2021). Box – type solar cookers are also known for their ability to accommodate many cooking pots, provide moderate temperature which minimizes the risks of burning food, and also having a light weight that simplifies transportation, (Vaidya et al., 2023). It is therefore against this background that a box-type solar cooker was considered for developed and when proven efficient, it can be availed for adoptions in different regions with similar weather conditions across the globe. The limitations that led to the omission of the concentrating-type solar cooker were its material requirements, manufacturability requirements and inefficiencies when the intensity of the sun is low and cloudy weather conditions, (Jacob Aliyu et al., 2021).

3.5 Design and Simulation of the Selected Solar Cooker

The study involved sizing the solar cooker and selecting optimal materials for construction. Simulations were carried out to establish its optical and thermal performances. This involved use of engineering design principles and consideration of the standard structural and material performance requirements for the development of an optimal solar cooker. Below is a breakdown of the design process flow that was formulated and the simulation process description.

3.5.1 Sizing of the Solar Cooker

The design criteria were based on the cooking dynamics and the examined solar irradiation data in the four major regions of Uganda. The common types of foods prepared across the regional areas and the average number of people per household established were considered for calculation of the theoretical energy requirements. The average household size guided the approximation of the food quantities. The cooking hours and the daily frequency of cooking in these regional households were also considered in the design process. Establishment of the energy requirement for preparing selected dishes helped in the determination of the active area of the solar cooker. This was later on used to size the absorber plate from which other components of the solar cooker like the internal reflectors, the glazing and the outer reflector were optimized, (Kajumba et al., 2022). Energy requirements for cooking using electricity and charcoal were established from the study review and compared with those theoretically calculated to justify the selection one for use as the output energy when calculating for the aperture area. The highest of these was considered. The criteria below were developed to help establish the energy requirement for cooking selected food types. Considering three cooking technologies;

1. Electricity (E_{En})
2. Charcoal (E_{Cn})
3. Solar cooker (E_{Sn})

With, n, being the quantity and type of dish prepared, also let;

i. n_2 – 1 kg of food type A

ii. n_3 – 1 kg of food type B

iii. n_4 – 1 kg of meat

Therefore, the energy requirements for cooking the four dishes were to be given as;

i. E_{E2}, E_{C2} and E_{S2} – for cooking food type A

ii. E_{E3}, E_{C3} and E_{S3} – for cooking food type B

iii. E_{E4}, E_{C4} and E_{C4} – for cooking 1 kg of meat

Table 3.3 below summarized the results of energy requirement for preparing different dishes using selected cooking technologies.

Table 3.1: Energy requirement for cooking four dishes using different technologies

	Energy Requirement (MJ)		
Type of Dish	**Electricity**	**Charcoal**	**Solar Cooker**
Food type A	E_{E2}	E_{C2}	E_{S2}
Food type B	E_{E3}	E_{C3}	E_{S3}
1 kg of meat	E_{E4}	E_{C4}	E_{C4}

From the results in table 3.1, the energy requirement for cooking using electricity and charcoal were to be established and used as a basis of comparison and estimation for that of the solar cooker. Using the standard formula for establishing energy requirement for solar cookers, the active area was to be established.

3.5.1.1 Energy Requirement for Cooking Using Electricity

Cooking requires a significant amount of energy which varies depending on the method of cooking, (Pathare & Paul, 2016). The energy requirements for cooking the selected dishes were established from experimental findings of other scholars in the literature. It was noted that the energy requirement for cooking using electricity could be calculated through establishment of the power rating of the cooking stove and the time taken to cook a given quantity of food.

In formular form, the expression for energy requirement for cooking a specific quantity of food (Q_{En}), was given by;

$Q_{En} = P_R \times t_n$ ………………………………………………………………….. (Eqn 1)

Where;

P_R – Power rating of the electric cooker, (KW).

t_n – Time taken to cook a specific type of food (n), (h).

3.5.1.2 Energy Requirements for Cooking Using Charcoal

Charcoal is commonly used on improved cook stoves and as such, the Table 3.2 below gave details on the general heating value and the calorific value of charcoal as established from the literature for use in the calculations. The improved cook stove was quoted to have an efficiency ranging between 23% and 40%, (Ayub et al., 2022). An example of these cook stoves that utilize charcoal are the combined clay/metal stoves which are said to have an efficiency of 30% and more, (Adeyemi et al., 2017). The design calculations considered an assumed efficiency of 35%.

Table 3.2: Parameters for charcoal

S/n	Parameter	Value	Source
1	Heating Value	7170.2 Kcal/kg	Owen et al., 2002
2	Calorific value	28 MJ/kg	Bhattarai, 1998

Here, theoretical methods were used to establish the energy requirements for cooking the selected food types using charcoal. According to Kajumba et al., (2022), the mass of fuel (m_f) consumed by a given fuel technology combination is given by the equation below as;

$m_f = \frac{Q_{input}}{CV \times \vartheta}$ ……………………………………………………………… (Eqn 2)

Where;

Q_{input} – Energy gained by the food (J)

CV – Calorific value of the fuel (J/kg)

ϑ – efficiency of the stove

Also, findings suggested that the calorific value of charcoal was estimated to be in ranges of 2.8 - 29.4 kJ/kg according to Nhabetse (2015). The Table 3.3 below summarizes an establishment of the amount of charcoal used to prepare selected meals using charcoal stoves, (Asada, 2019).

Table 3.3: Amounts of Charcoal consumption for selected meals, (Asada, 2019)

Meal	**Cooking Time (mins)**	**Charcoal Consumption (kg)**
Rice with fresh bean stew	248	2.0
Matooke with fish stew	202	1.2
Rice with cabbage	149	2.0
Matooke with groundnuts paste	64	1.2

3.5.1.3 Energy Requirement for Cooking Using the Developed Solar Cooker

The energy required to cook a specific type of food varies with its properties and ingredients. Theoretical energy for cooking a given food item was established and this was equal to the sensible heat required to cause a temperature change, and for zero energy losses, it was expressed as, (Kajumba et al., 2022):

$$Q = m.c_p.\Delta t, kJ \quad \text{...} \quad \text{(Eqn 3)}$$

Where;

Q – thermal energy requirement for cooking, kJ

m – mass of material taken for cooking, Kg

c_p – specific energy for the selected material, kJ/kg/^{0}C

Δt – difference between initial and final temperature, ^{0}C

Considering 1kg of food type A, the weight of the cooking vessel, the type of material, and the quantity of water used, the required heat energy was given as the sum of the thermal energy required for heating the food, the water, and the cooking vessel material. At ambient temperature - $t_a{}^0$C and with the required cooking temperature being 100 ^{0}C (Boiling method), the total thermal energy required for cooking food type A was given by, (RET, 2014):

$$Q_A = \left(m_A C_{pA} + m_w C_{pw} + m_v C_{pv}\right) \times (100 - t_a) \quad \text{(Eqn 4)}$$

Where:

m_A and C_{pA} – mass of food type A and its specific heat capacity respectively

$m_w and$ C_{pw}– mass of water and its specific heat capacity respectively

$m_v and$ C_{pv} – mass of the cooking vessel material and its specific heat capacity respectively.

To maintain the same temperature throughout the cooking process, a consideration of 30% of the energy was taken, hence the total heat energy required (Q_T), was given by:

$$Q_T = Q_A + 1.3 \quad \text{(Eqn 5)}$$

Notably, high moisture content foods like plantain (Matooke) usually require more energy to boil than to simmer which involves just keeping the food below the boiling point while bubbling gently, (Kajumba et al., 2022).

3.5.1.4 Establishment of the Aperture Area for the solar cooker

To establish the active area which is also referred to as the aperture area, energy input (E_{in}) and energy output of the solar cooker (E_{out}) where established. From the formular for the solar cooker's efficiency, the active area was made the subject leading to its establishment. The equations below were used in the design calculations.

1. Energy Input

The solar input (I) into the cooker was calculated by equation 6, (Kahsay et al., 2014):

$$I = GA_{ap} \quad \text{(Eqn 6)}$$

Where:

- G: Global Solar Radiation (W/m^2)
- A_{ap}: Aperture area of the cooker (m^2)

2. Energy output of the solar cooker (E_{out}) was given by:

$$E_{out} = m_w . C_{pw} . \left(T_f \times T_i\right) \quad \text{(Eqn 7)}$$

Where;

m_w – Mass of what is being cooked (kg)

C_{pw} – Specific heat capacity of what is being cooked (J/kg/K)

T_f – Final temperature attained by what is being cooked (K)

T_i – Initial temperature of what is being cooked (K)

3. The energy efficiency (η_{en}) was therefore given by:

$$\eta_{en} = \frac{E_{out}}{E_{in}} \quad \text{(Eqn 8)}$$

Therefore, from equation 8, the aperture area(A) was to be established as in the equation 9:

$$A_{ap} = \frac{m_w . C_{pw} . \left(T_f \times T_i\right)}{G . \eta_{en}} \quad \text{(Eqn 9)}$$

3.5.1.5 Establishment of Optimum Inclination Angles for the Internal Reflector Walls

The optical efficiency of a solar cooker is an essential design elements and in their study, Kahsay et al., (2014), suggested that making suitable angles of the internal side walls of the box-type solar cooker and incorporating reflectors enhance performance. Among the parameters that affect the optical efficiency of a solar cooker is the angle of incidence of solar radiation as shown in the Figure 3.1, (Vaidya et al., 2023). This affects how the rays get reflected onto the absorber plate and the reflector surfaces. For optimization of the four side wall reflectors, the angle of incidence of the solar radiations was to be altered in such a way that the rays get reflected horizontally and hence, remain parallel to the base of the absorber plate as shown in the Figure 3.1. This implies that the surface of the side walls, need a tilt so that $\theta = (90 - \beta)$, hence the side-wall inclination angles were given by β.

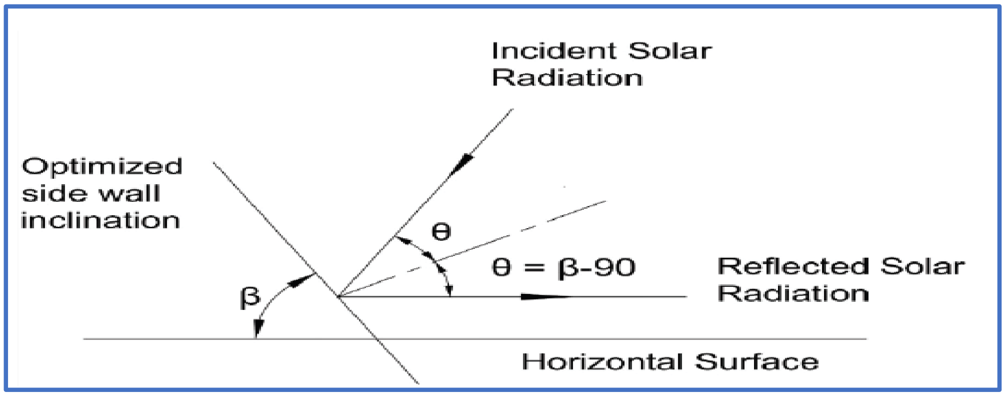

Figure 3.1: Reflection of incident ray onto the internal side walls, (Vaidya et al., 2023).

Therefore, cosine of angle of incidence of the solar radiations, θ, was given by equation 10, (Vaidya et al., 2023; Mundu, 2021).

$$cos\theta = sin\varphi\ (sin\delta\ cos\beta + cos\delta\ cos\gamma\ cos\omega\ sin\beta) + cos\varphi(cos\delta\ cos\omega\ cos\beta\ - sin\delta\ cos\gamma\ sin\beta) + cos\delta\ sin\gamma\ sin\omega\ sin\beta. \ldots\ldots \text{(Eqn 10)}$$

Where;

θ – Angle between the incident beam of flux (G) and the normal to the absorber plate surface

φ – Latitude angle of the selected regional area

β – Optimized side wall inclination angle

ω – Hour angle at solar noon (As at the date of establishment)

δ – Declination angle (As at the date of establishment)

γ – Angle given for each of the side walls facing due north, south, west and east respectively.

Taking the months of June to be experiencing the lower daily GHI in Uganda and the western region to be experiencing the least average daily GHI, the number of days needed for calculating the declination angle, the latitude and hour angle were established. The declination angle , δ, was calculated using the equation 11, (Vaidya et al., 2023);

$$\delta = 23.45 \, sin\left[\frac{360}{365}\,(284 + n)\right] \text{ ………………………………………………….. (Eqn 11)}$$

Where;

n - The number of days from the beginning of the year to the date of establishment.

The hour angle (ω^0) is given by the equation 12 below, (Mundu, 2021):

$$\omega^0 = 15 \times [Solar\ time - 12] \text{ ………………………………………………… (Eqn 12)}$$

The solar time is a measure of the position of the sun relative to a locality and at noon.

3.5.2 Material Selection for Optimal Optical and Thermal Performance Efficiency

The main constituent parts of a box-type solar cooker include the box frame, the insulation material, an absorber plate, a cooking vessel, a glazer, and a reflector. Material selection for the respective component parts was based on Uganda's local suitability in terms of availability, climate sustainability and economic feasibility in addition to the optical and thermal performance characteristics as shown in the Table 3.4.

Table 3.4: Design elements for thermal and optical performances in solar cookers

Parameter	Design Elements
Optical Performance	i. Angle of incidence of the solar radiation ii. Number of covers for the glazing iii. The material of the covers for the glazing iv. The coating of the absorber plate v. The reflector material
Thermal Performance	i. Heating capacity

3.5.2.1 Insulating Material

Insulating materials used in solar cookers include air, vacuum in a thermos flask, and rock wool, (Ayub et al., 2022). Other alternative materials that were to be considered depending on market availability included Kapok wool and glass wool, (Nébié et al., 2022; Da Rosa et al., 2015). The insulation material is normally 50 mm thick for most of the solar cooker designs, (Ambe, 2019).

3.5.2.2 Glazing Materials

The common types of glazing used in the solar market were identified as low iron glass and fiberglass reinforced polyester (FRP) with transmission rates of 87-92% and 87% respectively, (Kahsay et al., 2014). Double glazing has proved to improve performance efficiency of box cooker, (Badar et al., 2015). This was also considered for the study design. It should also be noted that transparent insulation materials for the glazing were greatly recommended in order to minimize heat loss from inside the box to the outer environment, (Yettou et al., 2014a). This well suited the moderate solar conditions in Uganda for maximum efficiency.

3.5.2.3 Reflecting Materials

Direct solar cookers with internal reflectors prove to be more efficient compared to those without, (Vaidya et al., 2023). Reflecting materials commonly used in solar cookers include aluminium sheet/foil, glass mirrors or polished steel, (Indora & Kandpal, 2018). Glass mirror is also used due to its high optical reflectance, (Iwuoha & Ogunedo, 2021). The Table 3.5 gave a summary of reflective materials used in solar cookers and their properties.

Table 3.5: Reflective materials and their properties from different scholars

Material Type	Properties	Sources
Aluminum Foil	i. High reflectivity ii. Low weight and flexible iii. Corrosion resistant	(Soro et al., 2020)
Mylar (Reflective polyester film)	i. Excellent reflectivity ii. Light weight and flexible iii. Resistant to moisture	Cuce & Cuce, 2013
Flat mirrors	i. High reflectivity ii. Rigid and durable	Lessa, 2017
Polished aluminum reflectors	i. High reflectivity ii. Good durability	Misra et al., 2023
Glass mirrors	i. High reflectivity ii. Good optical durability	Yettou et al., 2014
Metalized Polyester	Resistant to oxidation and scratching	Sater & Tolly, 2021

3.5.2.4 Absorber Plate Materials

Examples of absorber plate materials used in solar cookers include copper flat-plates and aluminium plates, (Bouhdjar et al., 2021). To increase sunlight absorption, the absorber plate of the box cooker is normally painted black, (Yettou et al., 2014a).

Aluminium painted with Abro black has been tested and it proved to be very efficient, (Filli et al., 2018). This also imported is locally available at friendly costs and can be accessed in form scrap material in the market.

3.5 .2.5 Cooking Pot Materials

For the cooking vessel, Goswami et al,. (2019) highlighted that most households use aluminium pots for cooking due to their low cost. These conducted a comparative analysis of cooking using a normal aluminium pot and using an aluminium activated carbon coated pot. Their findings showed that the solar cooker performance of activated carbon coated aluminium pot in terms of efficiency was high and had a lower cooking time. Locally available aluminium and stainless cooking vessels are recommended for the study design, (Vaidya et al., 2023). This is intended to minimize limitations in regards to the use of the developed cooker but also avoid the cost implications that come with customized components.

3.5.3 Design Modeling and Simulation for Optimization

This involved development of a design concept for the selected solar cooker type and considered factors like size, shape and material selection from the sizing stage. With dimensions for the different component parts of the solar cooker established, SolidWorks, a computer-aided design (CAD) software was used to model the developed design. For the assessment of the optical and thermal performance of the developed model design of the box solar cooker, SOLIDWORKS, ANSYS, COMSOL Multiphysics, and TRNSYS (for thermal performance simulation) were the software considered for the simulation process.

Input data included the following:

- I. Geometric data
- II. Material properties of the reflective surface and absorber plate
- III. Environmental data
- IV. Operational data

Geometric data included the dimensions of the developed solar cooker that were to be obtained from the design calculations and the modeled system design in SOLIDWORKS software. Material specifications for the major component parts of the developed model design were to be established from the software's material database. The environmental data was considered from the selected regional areas presented in the Table 2.3 so the study review. The simulation results included temperature profiles inside the solar cooker, the time taken to reach specific temperatures and maximum temperature achieved. Figures showing heat flux through different parts of the cooker and the efficiency of heat absorption were produced. For optical performance, distribution of solar irradiation inside the model design were also considered for presentation and hence, the overall thermal efficiency of the model established. Some to the equations used in the thermal and optical analysis included the following;

1. Energy radiated (E)

Energy radiated (E)= $A\delta T^4$ ……………………………………………………. (Eqn 13)

Where:

E - The total amount of energy radiated (N/m^2)

A - The area of the absorber plate (m^2)

δ – The Stefan constant of value 5.7×10^{-8} $W/m^2/K^4$

T_{am} - The temperature (K)

2. Heat transfer rate (q)

From Fourier's law of heat conduction;

$q = -k - A.\frac{\Delta T}{L}$ ………………………………………………….…………….. (Eqn 14)

Where;

k – Thermal conductivity of the material (W/m. K)

A – Cross-sectional area through which the heat is conducted (m^2)

ΔT – The temperature difference across the materials (K or ^0C)

L – Thickness of the material (m)

3. Heat Exchange between the Glass and the Outside Environment ($Q_{p,\ av1}$)

The heat exchange between the glass and the external environment ($Q_{p,\ av1}$) is mainly due to the transfer of heat by convection and by radiation. It was given by, (Soro et al., 2020);

$Q_{p,\ av1} = (h_{c,\ v\text{-}am} + h_{r,\ v\text{-}sky})\ (T_v - T_{am})$ …………………………… (Eqn 15)

Where:

$h_{c,\ v\text{-}am}$ - The coefficient of exchange by convection between the glass and the ambient

$h_{r,\ v\text{-}sky}$ - The radiation exchange coefficient between the glass and the sky

T_v - Temperature of the window (K)

T_{am} - The Ambient temperature (K)

In this, $h_{c,\ v\text{-}am}$ and $h_{r,\ v\text{-}sky}$ were given by:

$h_{c,\ v\text{-}am} = 5.67\ 3.86\ V_{wind}$, …………………………………………......…………. (Eqn 16)

Where; V_{wind} was wind speed less than 5m/s.

$h_{r,\ v\text{-}sky} = \frac{\sigma \varepsilon_v \left(T_v^4 - T_{sky}^4\right)}{T_v - T_{am}}$, ……………………………………………….….…………… (Eqn 17) where; σ is the Boltzmann constant ($m^2\ kg/s^{-2} \cdot K^{-1}$), ε_v is glass emissivity, and T_{sky} is the sky temperature which was to be determined by: T $T_{sky} = 1.5\ 0.0552\ T_{am}^{1.5}$ … (Eqn 18)

Therefore, $Q_{p,\ av1}$ was given by:

$Q_{p,\ av1} = h_{c,\ v\text{-}am}\ (T_v - T_{am}) + \sigma\varepsilon_v\ (T_v^4 - T_{sky}^4)$ ……………………………… ….. (Eqn 18)

4. Heat Exchange between the Glass and the Absorber ($Q_{p,\ av2}$)

The heat exchange ($Q_{p,\ av2}$) between the glass and the absorber is by convection and by radiation. It was given by the equation 19, (Soro et al., 2020):

$Q_{p,\ av2} = (h_{c,\ p\text{-}v} + h_{r,\ p\text{-}v})\ (T_p + T_v)$ ……………………………………………….. (Eqn 19)

Where:

$h_{c,\ p\text{-}v}$ - is the coefficient of heat transfer by convection between the glass and the absorber

$h_{r,\ p\text{-}v}$ - is the coefficient of heat transfer by radiation between the glass and the absorber

T_p - is the Absorber temperature (K)

T_v - is the Glass temperature (K)

3.6 Construction and Evaluation of the Economic Performance Feasibility

A bill of quantity for the selected locally available materials was made and this was used as a basis for cost analysis but also procurements for the system construction. For economic feasibility, payback period and fuel saving were calculated with comparison between the developed solar cooker and the traditional cooking methods which included use of electricity and charcoal. The equations following were used in the evaluation process:

a) Initial Investment Cost (IIC)

This involved the summation of the cost of the solar cooker and the Installation cost. It was hence given by the equation 19:

$$\text{IIC} = (\text{Cost of Solar Cooker}) + (\text{Installation Cost}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eqn 19)}$$

b) Payback Period (PP)

To calculate the payback period, the amount of savings per month (S) needed to be first calculated by considering any other conventional cooking method and then related to the initial investment cost of the solar cooker. It was therefore calculated by, (Misra et al., 2023);

$$\text{pp} = \frac{\text{Total cost of the cooker}}{\text{Monthly Saving (S)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eqn 20)}$$

c) Fuel Savings

This refers to the percentage reduction in fuel consumption achieved by using the solar cooker compared to traditional cooking methods. It was given by the equation 21, where FC represented fuel consumption:

$$\text{Fuel Savings (\%)} = \frac{\text{FC with traditional cooking} - \text{FC with solar cooker}}{\text{FC with traditional cooking}} \times 100 \quad \ldots\ldots\ldots\ldots \text{(Eqn 21)}$$

Fabrication of the prototype was conducted in Kyambogo University engineering workshops. At this level, the product was ready for performance testing, a step considered for future works in this study. Additionally, any modifications or adjustments in the finalized design were to be based on construction challenges or technical limitations and these were to be given as recommendations.

3.7 Proposed Solar Cooker Design

The box-type direct solar cooker design was considered for development with optimization performed on the absorber plate and the solar reflectors. The absorber plate was sized putting into consideration the prevailing cooking dynamics and solar irradiations in the four major regional areas of Uganda. The energy requirement (Output energy) used in sizing the aperture area was theoretically established with consideration of the popular food types, the cooking method and the food quantities in relation to the average household population size across the identified regional areas.

The daily GHI used was an average from the considered regional areas having satisfactory solar irradiations for solar cooking adoption. The design considered the incorporation of internal side wall reflectors in the box-type solar cooker to increase the optical and thermal efficiency. Solar data regarding the design and the system's simulation was bases on Mbarara city from among the considered regional areas. This was because it possesses the least daily GHI hence, believed to take longer cooking hours while using the developed cooker compared to other regional areas. The sun's declination angle was calculated considering the month of June which experiences the least solar radiation across the year. These considerations aimed at optimizing the side wall inclination angles for maximum solar energy capture.

With the developments highlighted above, a full system was modeled using SOLIDWORKS software and later simulated to assess its optical and thermal performance feasibility. A prototype was constructed to evaluate local manufacturability using locally available materials but also the cooker's economic feasibility in relation to cooking with electricity and charcoal in Uganda

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.0 Introduction

This chapter presents the solar cooker development, design and simulation processes. A box-type solar cooker design was considered for development and simulation to assess its technical performance feasibility. The design process begun by establishment of the energy requirements for use in the calculation of the solar cooker's aperture area. The inclination angles for the internal side walls of the box cooker were also established. With a full system developed, a detailed construction process is presented to justify manufacturability using locally available materials.

4.1 Sizing the Solar Cooker

4.1.1 Energy Requirement

To estimate the theoretical energy requirements for cooking selected dishes using the solar cooker under development, design calculations were made and literature review conducted on cooking using electricity and charcoal. The established energy requirements were also used in the economic feasibility analysis of the developed solar cooker.

4.1.1.1 Energy Requirements for Cooking Using Electricity

These energy requirements were established from literature review considering the common types of foods prepared in all the four major regions in Uganda and the findings are hence presented in the table 4.1 below. From the Table 4.1, it can be observed that meat requires the highest amount of energy when cooking using electricity followed by rice. Cooking matooke requires less amounts of water than cooking rice which results into a slightly lower energy requirement.

Table 4.1: Energy requirements for cooking some foods using electricity

Food Item	Energy (kWh/kg)	Source
Rice (1kg)	0.64	Kajumba et al., 2022
	0.53	Kanyama, 2016
	0.1575	De et al., 2014
Matooke (1kg)	0.60	Kajumba et al., 2022
	1.06	MECS, 2020

4.1.1.2 Theoretical Energy Requirements for Cooking Using a Solar Cooker

The specific heat capacity (C_p) of rice and matooke were highlighted by Kajumba et al. (2022), during their experimental assessment of energy needs for cooking some of the major food types in Uganda. The Table 4.2 below summarizes both the established model specific heat capacities and those from other experimental reports reviewed.

Table 4.2: Specific heat capacities of rice, matooke and meat, (Kajumba et al., 2022)

Food Item	**C_p (Model), KJ/kg/K**	**C_p, KJ/kg/K**
Rice	1.80	1.65
Matooke	3.62	……
Meat (Beef)	……..	3.44

The study design process also assumed the following:

1. The cooking vessel used was made out of Aluminium whose specific heat capacity as given by RET (2024), was 0.90 kJ/kg/K. Another alternative consideration was 0.896 kJ/kg/K and this was considered in the design calculations, (De et al., 2014).

2. The initial ambient temperature considered was 25 ^{0}C and the required cooking temperature, 100 ^{0}C since all the selected food types had the same cooking method (boiling).

3. The amount of water required to cook 1kg of rice and 1kg of matooke were approximated at 2 litres and l litre respectively, (Kajumba et al., 2022).

4. To maintain the same temperature for thorough cooking, the study assumed that 30% of the energy was required throughout the period of cooking.

The formular for calculating energy requirement for cooking was as below, (Kajumba et al., 2022);

$$Q_R = \left(m_R C_{pR} + m_w C_{pw} + m_v C_{pv}\right) \times (100 - \ t_a)$$

Where:

m_R and C_{pR} – mass of food type A and its specific heat capacity respectively

$m_w and$ C_{pw}– mass of water and its specific heat capacity respectively

$m_v and$ C_{pv} – mass of the cooking vessel material and its specific heat capacity respectively

$$Q_R = ((1 \times 1.8) + (2 \times 4.2) + (1.2 \times 0.896)) \times \left((100 - 25)\right)$$

$$Q_R = \ 845.64 \text{ kJ}$$

Assuming that 30% of the energy was required throughout the period of cooking for a maintained temperature, the total heat energy requirement (Q_{RT}) was therefore given as;

$$Q_{RT} = 845.64 \times 1.3$$

$$Q_{RT} = 1099.332 \text{ kJ}$$

The theoretical energy requirement for cooking 1 kg of rice using a solar cooker was established as **0.3054 kWh/kg**.

Similarly calculating for the theoretical energy requirement for cooking 1 kg of matooke and 1 kg of beef meat gave the following results as summarized in table 4.3.

Table 4.3: Established theoretical energy requirements for cooking using a solar cooker

Food type	Water used (ltr)	C_p (kJ/kg/K)	Energy requirement (kWh/kg)
Rice (1 kg)	2	1.8	0.3054
Matooke (1 kg)	1	3.62	0.2409
Beef – Meat (1 kg)	0.8	3.44	0.2133

4.1.1.3 Theoretical Energy Requirement for Cooking Using Charcoal

Considering the following details;

1. The assumed mass of charcoal required to cook 1 kg of rice and 1 kg of matooke was taken as 0.8 kg and 0.6 kg respectively, (Asada, 2019).
2. The efficiency of the improved charcoal stove considered as 35%, (Ayub et al., 2022).
3. The calorific value of charcoal considered as 28 MJ/kg, (Miranda et al., 2020).

If therefore 1 kg of rice approximately takes up 0.8 kg of charcoal for its preparation using modern charcoal stoves, the energy requirement was established using equation 2:

$Q_{in-Rice} = 0.8 \times 28 \times 0.35 = 7.84\ MJ$

Therefore, cooking 1 kg of rice theoretically required an approximate of **2.178 kWh**, of energy on a modern charcoal stove.

Also, for 1 kg of matooke approximately taking up 0.6 kg of charcoal for its preparation, the energy requirement was also given as below:

$Q_{in-Matooke} = 0.6 \times 28 \times 0.35 = 5.88\ MJ$

Therefore, cooking 1 kg of matooke on a charcoal stove theoretically required an approximate of **1.633 kWh**, of energy.

Table 4.4: The energy requirements for cooking using different technologies

	Energy Requirement (kWh/kg)		
Type of Dish	**Electricity**	**Charcoal (Theoretic)**	**Solar Cooker (Theoretic)**
1 litres of water	0.10278	———	0.1429
Rice (1 kg)	0.64	2.178	0.3054
Matooke (1 kg)	0.60	1.633	0.2409
Meat (1 kg)	2.54	———	0.2133

From the Table 4.4, it can be observed that cooking with charcoal consumes a lot more energy than cooking with electricity and the solar cooker. Meat requires more energy for its preparation while matooke requires the least energy among the three selected food. From the theoretical calculations, rice required more energy when cooking using a solar cooker and hence was considered for the design calculation of the aperture area. This was attributed to the fact that it requires more amounts of water for its preparation, (Kajumba et al., 2022).

4.1.2. Establishment of the Active Area of the Solar Cooker.

For establishment of the active area (aperture area), the following assumptions were made;

1. The energy efficiency of the solar cooker is 35%, (Taylor et al., 2006).
2. The average daily GHI for Uganda stands at 4.60 kWhm^{-2}, (Katongole et al., 2023).

From the equations 6,7 and 8, for the establishment of the solar input energy, output energy and the energy efficiency (η_{en}), the aperture area was given as below. Where E_{out}= 0.3054 kWh (Theoretical energy required to cook 1 kg of rice), G= 4.60 kWhm^{-2} and η_{en}= 35%;

$A_c = \frac{0.3054}{4.60 \times 0.35} = \mathbf{0.1897\ m^2}$

Since for non-concentrating solar collectors, the aperture area is defined as the area that absorbs the solar radiation, this was considered as the absorber plate area for the box-type solar cooker under development. With the solar cooker developed expected to accommodate two cooking vessels having an average diameter of 200mm and two side handles with an approximated length of 100mm, the total length of the absorber plate was considered as 600mm. From the formula for calculating area (A) of a rectangular base, where A = 0.1897 m^2 and length = 0.60 m, the width was established as 0.32 m. Therefore, the absorber plate was as **0.60m** and **0.32 m** by length and width respectively.

4.1.3 Establishment of Optimum Inclination Angles for the Internal Reflector Walls

The date 1st June, 2024, was the approximated date for the developed box cooker design simulation since it is in this month that solar irradiations are lowest annually considering Uganda's weather conditions,(Katongole et al., 2023). The number of days of the year, n, considered for calculation of the solar declination angle were established as 153 days. Also considering the time at solar noon, hour angle, $\omega = 0^0$, the declination angle was calculated as:

$$\delta = 23.45\, sin \left[\frac{360}{365}\ (284 + 153)\right]$$

$$\boldsymbol{\delta = 22.17^0}$$

From the equation 10 and letting $\theta = (90 - \beta)$, the side wall inclination angles were calculated as below considering the location of Mbarara city with latitude (φ), - 0.6110^0. The Table 4.5 summarizes all the established side wall inclination angles at the solar noon hour.

Table 4.5: Internal side-wall inclination angles due to the four directions

S/N	Directional angle (γ)	Inclination angle ($\boldsymbol{\beta}$)
South	0^0	34^0
North	180^0	56^0
West	270^0	43^0
East	90^0	43^0

The design considered the above angles for the sizing of the side wall reflector surfaces and thereafter, the dimensions for the rectangular glazing system were taken from the top edges of the inclined reflector walls as modeled in SOLIDWORKS design software. The establishment also led to the sizing of the outer reflector during the modeling process. The Figure 4.1 shows a diagrammatic illustration of how the angles were represented.

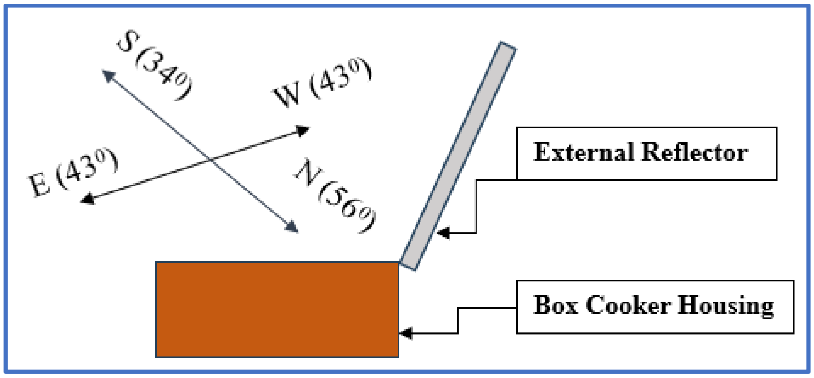

Figure 4.1: Side view of the box type solar cooker showing positions of the angles

Notably, the medium size saucepan diameters are normally in ranges of 180 mm to 280 mm and with heights ranging between 80 mm and 150 mm, (UNHCR, 2022). For convenience of accommodation therefore, the design considered an internal box height of 200 mm from the horizontal surface of the absorber plate to the glazing as shown in the Figure 4.2. This was to also ensure a commendable spacing between the cooking vessel and the glazing system.

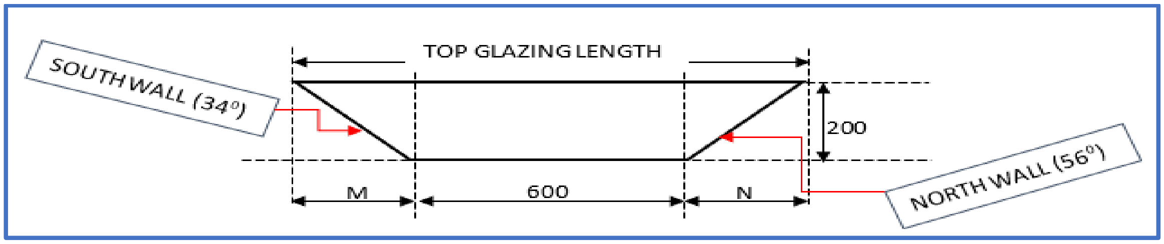

Figure 4.2: A crossection through the east end and west end directions of the cooker

To establish the length and width of the top surface of the reflector walls, mathematical computations gave 1031 mm and 751 mm respectively. This therefore implied that the side of the rectangular glazing were approximated as 1030 mm and 750 mm by length and width respectively. Calculating for the surface area of the glazing gives 0.7725 m^2. Since the study review highlighted that most solar cookers for household-use receive solar radiation over an area in ranges of 0.5 – 1.5 m^2 and , the calculated glazing surface area of 0.7725 m^2 was satisfactory, (Africa, 1987). Using SOLIDWORKS design software, the internal side wall reflectors were modelled as shown in the Figure 4.3.

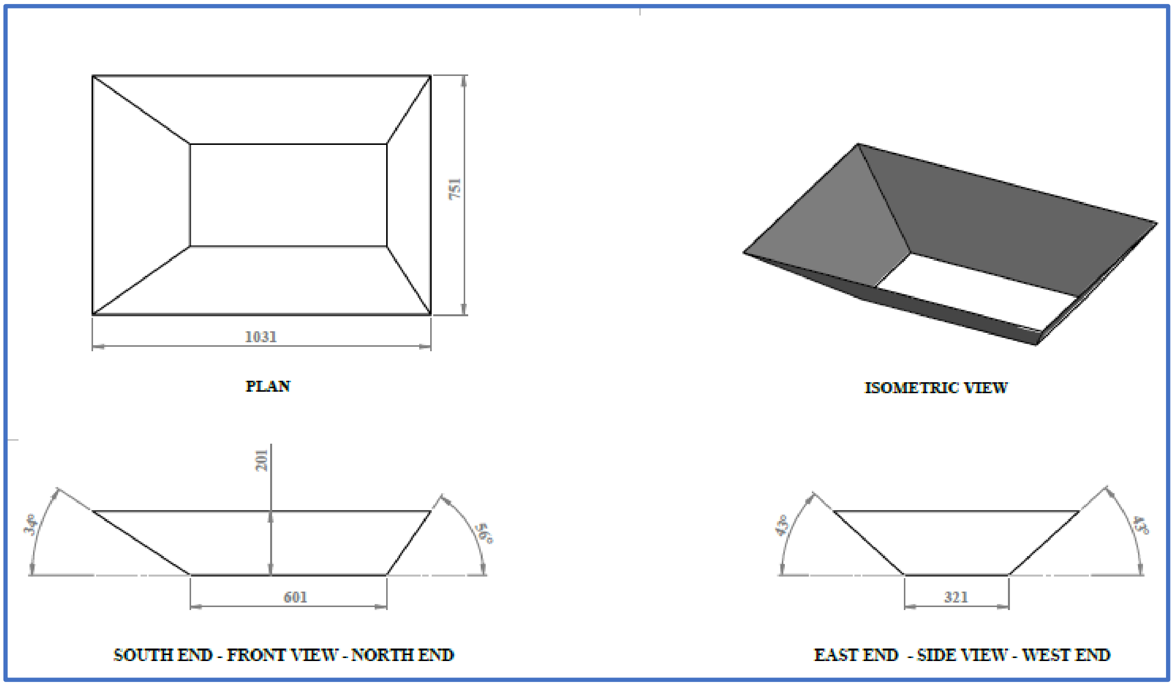

Figure 4.3: Views showing the internal side - wall reflector angles

From the Figure 4.3, the dimensions of each of the internal side wall reflectors were established. An insulation spacing of 20 mm between the glazing and the wooded box frame was considered and a 50 mm insulation from the bottom of the absorber plate to the outer box frame. Also given that the wood frame was of thickness 20mm, the outer length, width and height of the box were computed as 1120 mm, 1005 mm and 300 mm respectively. The 30 mm extension from the top of the internal side wall reflectors was considered so as to accommodate the glazing assembly system designed to slide horizontally. This enabled the ease of loading and unloading without dismantling anything. The Figure 4.4 gave the full modeled design assembly of the developed box-type solar cooker.

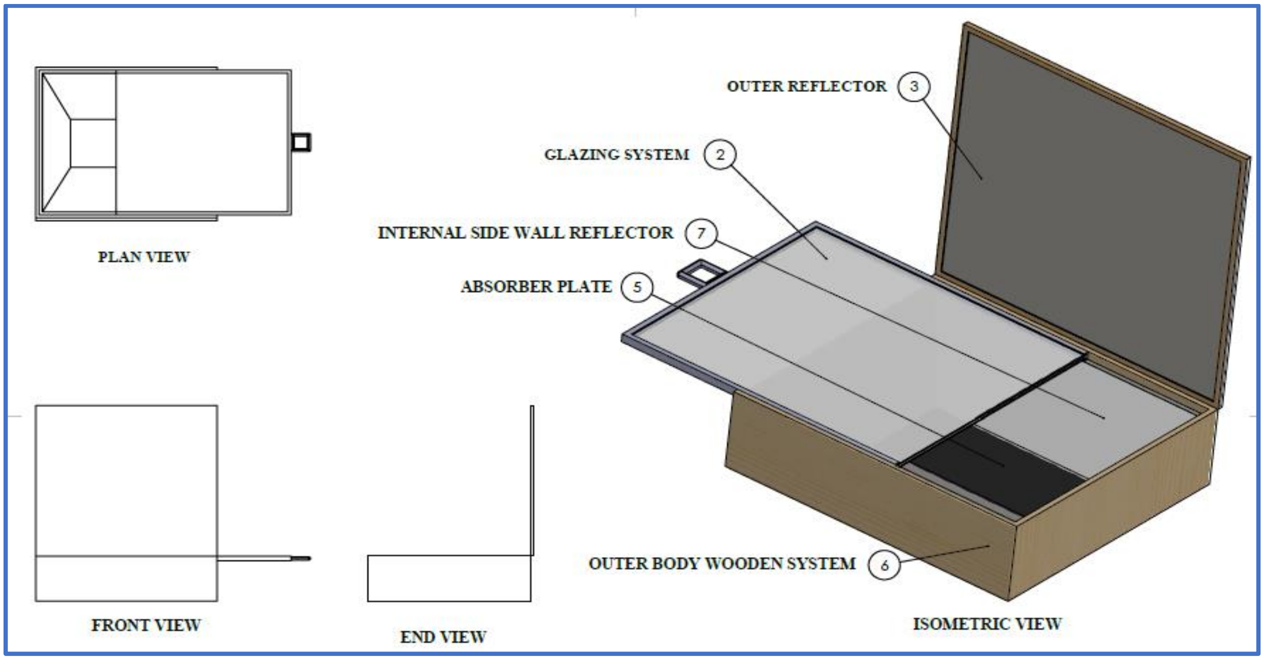

Figure 4.4: Full assembly drawing of the DBSC

The Table 4.6 below gives a summary of the established main design specifications for the DBSC and from this establishment, material selection for each of the component part was conducted.

Table 4.6: Summary of the design specifications for the DBSC

S/n	Parameter	Values
1	Outer dimensions of cooker	1120 mm x 1005 mm x 300 mm
2	Insulator thickness	20 mm
3	Inner height	200 mm
4	Area of the absorber plate	0.1897 m^2
5	Area of the glazer (Glass plate)	0.7725 m^2
6	Thickness of the glazer material	4mm each

4.2 Material Selection

The Table 4.7 shows material section that was made on basis of high-quality material performance properties and experimentations from the study review.

Table 4.7: Material selection for the DBSC component parts

S/n	Part	Material Used	Reasons
1	Outer Frame	Wood	- Availability - Good manufacturability - Weight factor
2	Insulation	Rose Wool	- law thermal conductivity ≤ 0.044 - Combustion performance (no burning class A) - Density Tolerance ± 15%
3	Absorber plate	Aluminium painted with black matte paint	- Good thermal conductivity - Corrosion resistant - Cost friendly
4	Glazing	Fiberglass reinforced polyester	- Good thermal insulation - Temperature resistant - High mechanical strength
5	Reflector	S – Reflect (Non – adhesive)	- High reflectivity > 90% - Very light, flexible and does not wrinkle

4.3 Simulation of the Developed Solar Box Cooker Design Model

4.3.1 Input Parameters

The Tables 4. 8 gave a summary of the input material properties for the different component parts of the DBSC that were used in the model simulation.

Table 4.8: Material properties of the specific component parts

Part	**Properties**	**Values**
Reflector (mirror polished stainless steel plate 0.8 mm)	i. Thermal conductivity ii. Specific heat capacity iii. Density iv. Emissivity v. Absorptivity	- 16.2 W/mK - 500 J/kg. K - 8000 kg/m^3 - 0.07 - 0.2
Absorber plate and (aluminium pate 2mm thickness)	i. Thermal conductivity ii. Specific heat capacity iii. Density iv. Emissivity v. Absorptivity	- 273 W/mK - 1200 J/kg. K - 1200 kg/m^3 - 0.9 - 0.9
Cooking vessel (Stainless steel grade 304 oxidized)	i. Thermal conductivity ii. Specific heat capacity iii. Density iv. Emissivity v. Absorptivity	- 16.2 W/mK - 500 J/kg. K - 8000 kg/m^3 - 0.4 - N/A
Rose wool	i. Thermal conductivity ii. Specific heat capacity iii. Density iv. Emissivity v. Absorptivity	- 0.03 W/mK - 840 J/kg. K - 100-200 kg/m^3 - N/A - N/A

The environmental and operation data that were considered in the model simulations are summarized in the Table 4.9 and in this context, Soroti, Entebbe and Mbarara were the selected districts. Among these, the simulation considered data values for Mbarara as justified in the design process. For the loading, 1 litre of water, 1 kg of rice and 1 kg of plantain (matooke) were considered since these are common in most of the established regional areas for the DBSC's adaptation. According to the clarifications for ASAE S580.1 wind velocity specification, an average of ≤ 1.5 m/s is normally recommended for solar cooker technologies, (Ebersviller & Jetter, 2020). On the contrary, most areas in Uganda have moderate wind speed ranging from 2 m/s to about 4 m/s with an average of 3 m/s, (Gumisiriza, 2020).

Table 4.9: Environmental data and operation data for simulation

Data	Specification	Values
(Mbarara – Uganda)	i. Solar irradiance ii. Ambient temperature iii. Wind speed and direction iv. Location coordinates	- 400 W/m^2 - 27 ^{o}C - 13 km/h - Lat: 0.6587 & Long: 30.6587
(Entebbe – Uganda)	i. Solar irradiance ii. Ambient temperature iii. Wind speed and direction iv. Location coordinates	- 500 W/m^2 - 23 ^{o}C - 14 km/h - Lat: 0.0500 & Long: 32.4600
(Soroti – Uganda)	i. Solar irradiance ii. Ambient temperature iii. Wind speed and direction iv. Location coordinates	- 700 W/m^2 - 30 ^{o}C - 10 km/h - Lat: 1.71500 & Long: 33.6111
Operation data	i. Initial temperature ii. Cooking duration	- 27 ^{o}C, 23 ^{o}C and 30 ^{o}C - 2 hr - 1 L water, 1 kg rice and 1

4.3.2 Simulation Results

SOLIDWORKS software was used to analyze the initial ambient conditions of the model DBSC upon its exposure to the atmosphere with Mbarara city considered for boundary conditions. Here the ambient temperature at the non-solar hour was considered to be 297 K as shown in the Figure 4.5. It was observed that the entire system was at ambient conditions of 297 K (Dark blue zone) with slight variations in the interior of the DBSC (Light blue zone) due to the reflections from the reflector walls into the space within the box cooker.

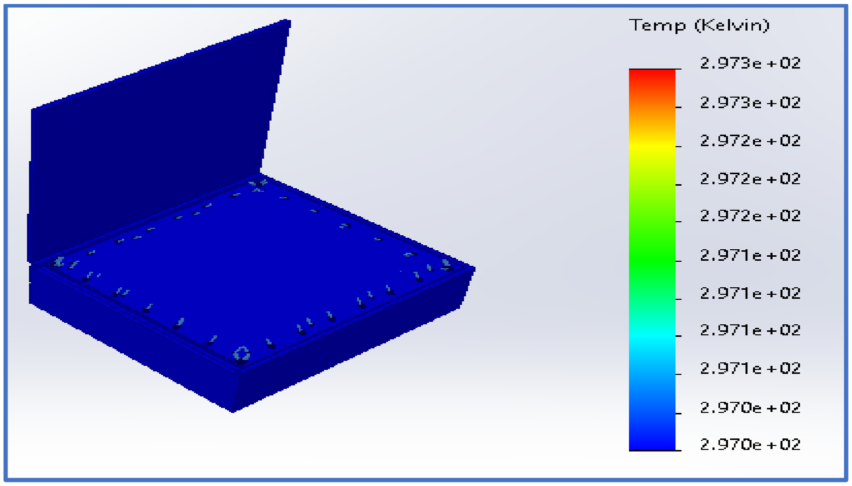

Figure 4.5: Ambient temperature distribution in the DBSC at solar exposure

Using COMSOL Multiphysics 5.5 software, thermal analysis was conducted between the absorber plate and the internal side wall reflecting surfaces. The Figure 4.6 shows that thermal temperature kept building up within the system and as time went on, the absorber plate gained more temperature of up to about 4600 K (Dark red zone) due to concertation of solar heat energy onto it. This justifies the efficiency in reflectivity of the side wall reflector and the outer reflector which both serve the same purpose. In terms of heat transfer, it was also be observed that conduction rates are high between the absorber pate and the bottom areas of the side wall reflector’s material (Dark red colour).

This is attributed to the high thermal conductivity of the absorber plate material (Aluminium -237 W/mK) in relation to that of the reflector material (Polished stainless steel – 16 W/mK) which was used in the construction of the DBSC prototype. Both the glazing system and the wooden outer frame of the box cooker were seen to experience slight temperature increments of about 20 ^{0}C from the initial value of 300 K (Light green zone) hence justifying the insulation efficiency.

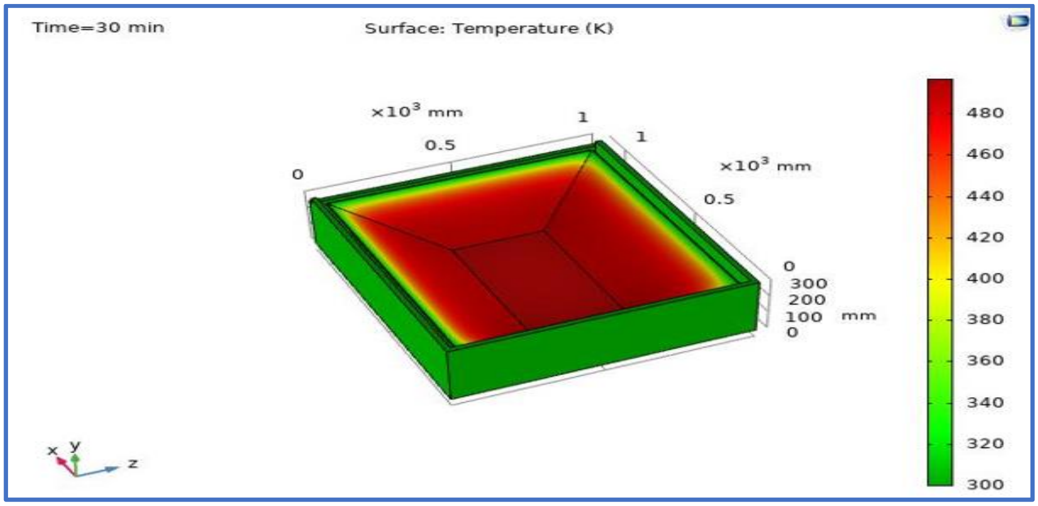

Figure 4.6: Simulated heat transfer distribution with in the interior of the DBSC

Similarly, the Figure 4.7 shows the surface radiosity in the interior of the system and here it can also be observed that there is high radiosity (red brownish zone) from the absorber plate onto which the cooking vessel is placed but also on the internal side-wall reflecting surfaces. This is due to the fact that the absorber plate material has a high heat transfer rate while the internal reflectors were designed to reflect solar rays in a horizontal way making them to both reflect and radiate. Simulation results highlighted that the surface radiosity on the two component parts increased from 2.0 x 10^3 W/m^2 to 2.8 x 10^3 W/m^2 at the 15th and 30th minute time of exposure which indicates satisfactory performance efficiency of the materials.

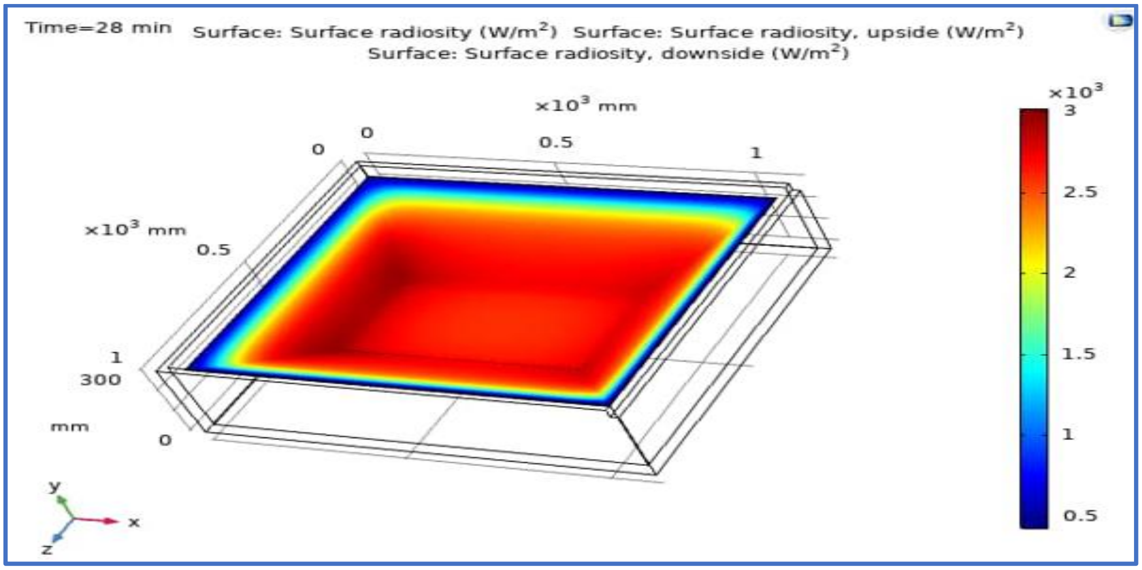

Figure 4.7: Surface radiosity of the absorber plate and the internal reflectors

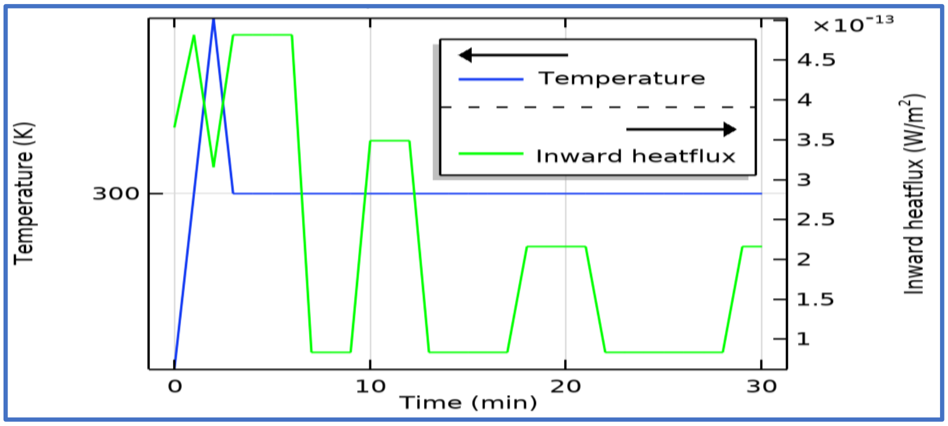

Figure 4.8: Relationship between the solar radiosity and temperature with time

From the Figure 4.8, it is observed that the temperature (Blue Line) starts at around 300 K and experiences a sharp rise within the first few minutes and after the initial spike, the temperature stabilizes at around 300 K for the remainder of the time. Also, the inward heat flux (Green Line) starts with an initial fluctuation, stabilizes for a short period, and afterwards shows periodic spikes and drops, oscillating between approximately 0 W/m² and a peak value slightly below 4.5×10^{-13} W/m².

The initial spike in temperature suggests a rapid heating phase which could be due to the initial exposure to sunlight. stabilization of temperature at 300 K indicates the attainment of thermal equilibrium where the rate of heat input balances the rate of heat loss. The oscillating pattern of the inward heat flux signifies periodic changes in the heat input due to environmental factors like changes in solar intensity, wind speed, or shading that periodically affect the heat input to the system. The lack of a direct correlation between the temperature and inward heat flux after the initial spike suggests that the system quickly reaches thermal equilibrium. Once equilibrium is reached, the temperature remains relatively constant despite the periodic changes in inward heat flux, indicating the system's good thermal stability and insulation.

4.4 Cost Analysis of the DBSC

This included the establishment of the bill of quantity of single unit of the DBSC to enable material procurement and product construction. The materials considered were those which were locally available in Ugandan markets or could be availed through import dealers within the country. Additionally, economic analysis of the DBSC were conducted and presented to justify its competitive advantage over other cooking technologies like charcoal stoves, electric appliances and LPG burners.

4.4.1 Bill of Engineering Measurement and Evaluation (BEME)

This was aimed at establishment of the initial investment cost of the DBSC and in this context involved the summation of the total project cost and the installation/ indirect costs. For cost evaluation while basing on the materials selected for the construction of the DBSC, the table 4.10, presents the bill of engineering measurement and evaluation (BEME) for the dissertation design.

Table 4.10: Bill of Engineering Measurement and Evaluation

ITEM	DESCRIPTION	QUANTITY	UNIT COST(UGX)	TOTAL COST(UGX)
Timber (Musizi)	2400 x 1200 x 20	2 pc	40,000	80,000
Plywood	2400 x 1200 x 6	1 pc	80,000	80,000
Aluminium plate	2400 x 1200 x 2	1/8 pc	300,000	37,000
Sheep wool	Standard	10 kg	100,000	100,000
Mylar reflective	15000 x 1200 x 2	1/6 pc	400,000	70,000
Plastic glass	2400 x 1200 x 4	3/4 pcs	180,000	135,000
Drawer Handle	Ordinally	3 pcs	4,000	12,000
Hinges	50 mm	1 pair	3,000	3,000
Locks	Padlock type	1 pc	4,000	4,000
Nails and glue	Normal	1 pc	5,000	5,000
Finishing	Normal	1 set	15,000	15,000
	Total material cost			**541,000**

Labour cost = 30% of the total material cost = 162,300 UGX

Therefore, total project cost = 703,300 UGX

Indirect costs = 10% of the total project cost = 70,330 UGX

Therefore, Capital investment required = **773,630 UGX**

Therefore, the initial investment cost for the DBSC considering the best locally available materials in the Ugandan markets was calculated as 773,630 UGX. In relation to the cost ranges of improved small-scale box-type solar cookers lying between 120 USD and 130 USD as stated by Herez et al., (2018), the cost of the developed solar cooker was 0.5 times greater.

This was attributed to that fact that purchases were made for a unit product but with butch production of the DBSC, the unit cost definitely reduces. Additionally, the cost of mylar reflective and plastic glass was locally high due to the fact that these are imported and not locally made in Uganda.

4.4.2 Payback Period (PP)

This was calculated basing on the initial investment cost of the DBSC and the saving per month (S) considering when cooking using charcoal or electricity.

$$\text{pp} = \frac{\text{Total cost of the cooker (IIC)}}{\text{Monthly saving (S)}}$$

The daily food consumption per person is averaged at 300g, 200g and 227g of rice, matooke and beef meat respectively, (Kajumba et al., 2022) and (Adam, 2024). Therefore, in a typical household of 5 people, the total amount of rice, matooke and beef meat consumed daily was computed as 1 kg, 1.5 kg and 1.135 kg respectively. The energy requirement was hence obtained as a product of the energy required for cooking per kilogram and the amount of food cooked. From the table 4.4, the energy requirement per kilogram for cooking using electricity, charcoal and solar cooker were established and by relating them to the quantities of the selected foods and sauce respectively, gave the following amounts in the Table 4.11.

Table 4.11: Summary of the energy requirements for daily cooking

	Energy Requirement (kWh)		
Type of Food	**Electricity**	**Charcoal**	**Solar Cooker**
Rice	0.64	2.178	0.3054
Matooke	0.90	2.449	0.36135
Meat	2.883	2.472	0.242

A combination of each food and beef meat as sauce gave a total energy requirement summarized in the table 4.12.

Table 4.12: Energy requirement for a selection of dishes using different cooking technologies

Meal	**Energy Requirement (kWh/ day)**		
	Electricity	**Charcoal**	**Solar Cooker**
Rice & Meat	3.523	4.65	0.5474
Matooke & Meat	3.783	4.921	0.60335

For monthly electricity costs, the total electric energy requirement consumed in a month was related to the cost per kWh of electricity. This gave a total amount of 43544.28 UGX for a rice meal and 46757.88 UGX for a matooke meal since the domestic cooking tariff in Uganda is at 412 UGX for unit ranges of 81 kWh to 150 kWh, (UMEME, 2024). For monthly charcoal cost, an approximate of 1.4 kg of charcoal use per day was considered, (Asada, 2019). This computed for 30 days and multiplied by a cost of 1500 UGX for I kg of charcoal gave a total cost of 63,000 UGX, (Kajumba et al., 2022). Therefore, the monthly saving for cooking using electricity and charcoal were given as 46,757.88 UGX and 63, 000 UGX respectively. Payback period switching from electricity to solar cooking was computed as:

$$\mathrm{pp} = \frac{\text{Total cost of the solar cooker (IIC)}}{\text{Monthly saving with electricity}} = \boldsymbol{16.55\ Months}$$

Additionally, payback period switching from charcoal to electricity was computed as:

$$\mathrm{pp} = \frac{\text{Total cost of the solar cooker (IIC)}}{\text{Monthly saving with charcoal}} = \boldsymbol{12.28\ Months}$$

4.4.3 Fuel Saving (FS)

The fuel saving was also calculated putting into consideration a comparative analysis of the energy requirement for cooking using electricity, charcoal and a solar cooker for an average number of 5 people per day as highlighted in Table 4.11. Fuel saving of the developed solar cooker in relation to cooking using electricity or charcoal was computed using equation 21. Considering cooking using the solar cooker to using electricity when preparing a rice meal on a given day, the fuel saving was calculated as 84.46 %

Therefore, computations relating cooking using electricity to the solar cooker and using charcoal to the solar cooker gave fuel savings of 84.46% and 84.05% for rice meal, and 88.23% and 87.74% for matooke meal respectively. An 84.46% saving for rice meals when using solar energy instead of electricity leads to a drastic cut in monthly electricity bills. Similarly, an 87.74% saving for matooke meals indicates a significant decrease in expenses on charcoal.

4.5 Construction of the Developed Solar Cooker

Construction of the DBSC was carried out at the carpentry workshop – School of Art and Industrial Design, Kyambogo University. Maesopsis eminni locally known as musizi and plywood were used for the fabrication of the DBSC frame and assembling the internal side wall reflectors respectively as shown in the Figure 4.9.

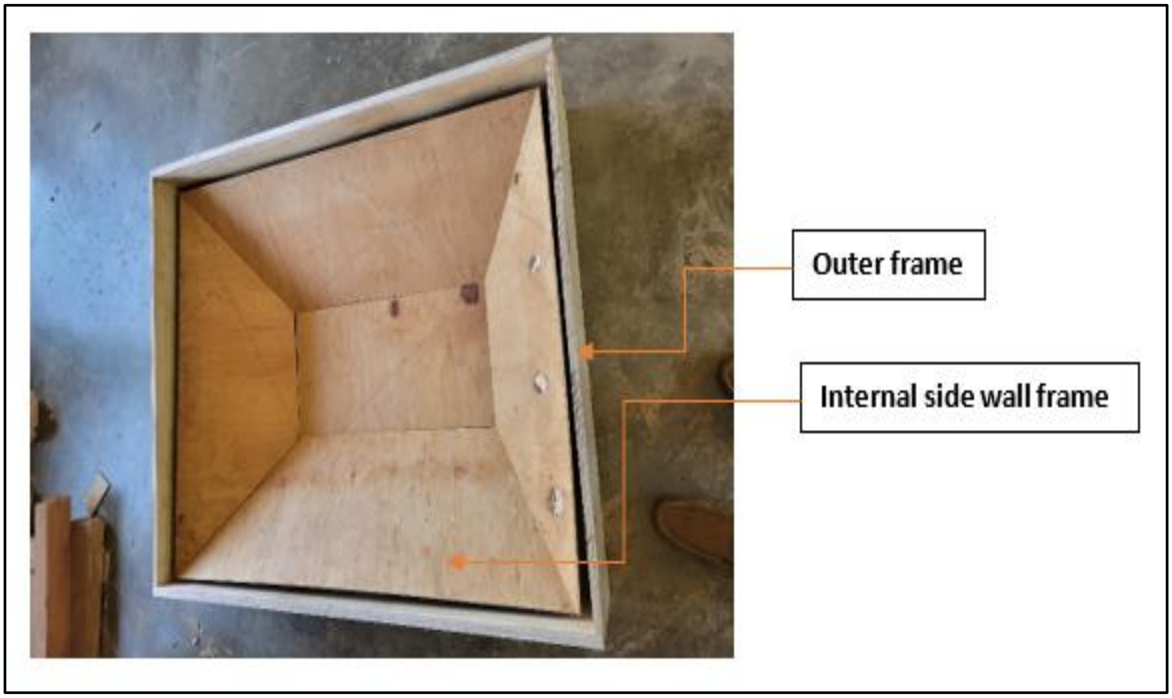

Figure 4.9: Assembly of the outer frame and internal side wall frame of the DBSC

Mirror polished stainless steel plate of 0.8 mm thickness was used as the reflector material due to its availability in the market instead of mylar a reflective sheet which required importation. However, with mass production of the DBSC, it would be the most efficient and economical to use mylar reflective material.

Plexiglass of 3 mm was also used for the glazing surface with the ability to transmit up to 92% of visible light. The Figure 4.10 shows a partial assembly of the DBSC consisting of the outer box frame and the internal reflectors. Rose wool as the insulating material was packed in the space between the interior of the outer box frame and the exterior of the internal slide wall reflector surface frame.

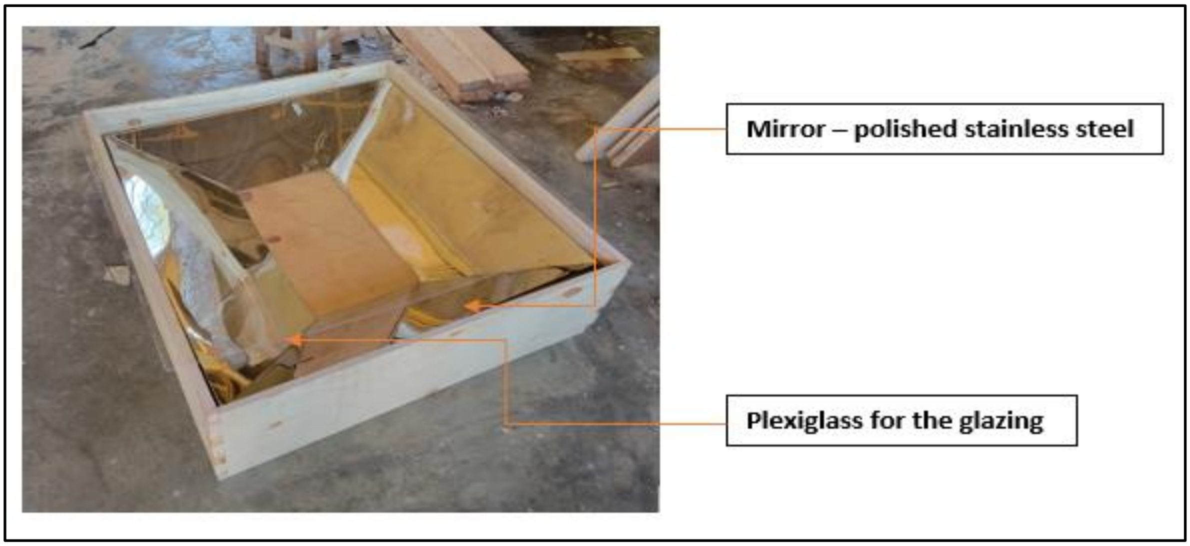

Figure 4.10: Incorporation of the internal reflectors and the glazing material

The final stages of construction included assembling of the glazing system into the main frame of the box cooker by a sliding mechanism to enable easy opening and closer. The outer reflector system was also hinged on to the main box cooker frame using hinges and the finishing works were performed on the cooker to provide aesthetics and durability. Figure 4.11 shows the incorporation of the double-glazing system onto the cooker box assembly.

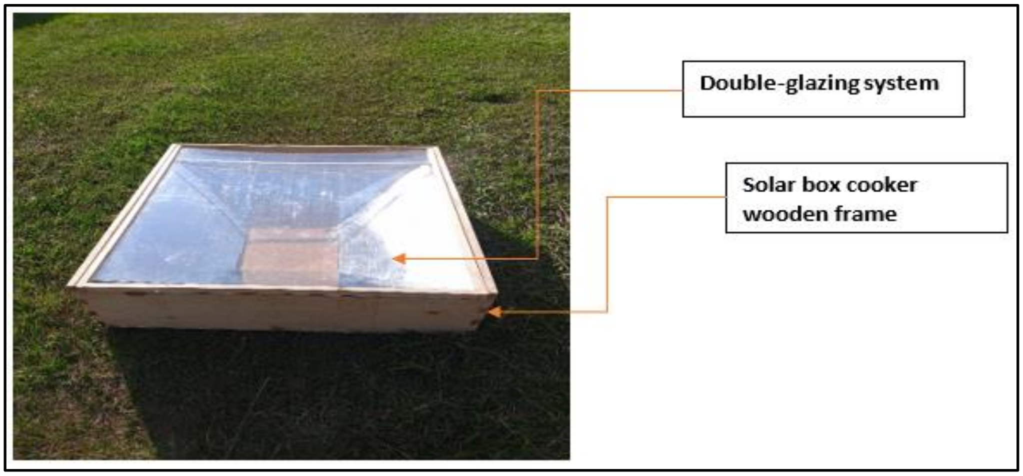

Figure 4.17: Glazing assembly onto the box system of the DBSC

The Figure 4.18 shows the full assembly of the finished product with the outer reflector incorporated.

Figure 4.14: Full construction of the developed box-type solar cooker.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

This chapter presents conclusions derived from the results discussed and provides recommendations and areas for further research.

5.1 Conclusions

The DBSC presents a viable alternative to traditional cooking methods in regions with high solar irradiance. Its expected performance in cooking common foods, combined with its cost-effectiveness and environmental benefits, makes it a suitable option for reducing reliance on non-renewable energy sources such as charcoal and electricity. While considering Uganda's cooking dynamics, the box cooker's aperture area was calculated to be 0.1897 m^2. The cooker was further enhanced with internal side-wall reflectors to improve on its performance efficiency and these were calculated as 34^0, 56^0, 43^0, and 43^0 due to south, north, west, and east respectively.

The feasibility of the DBSC has been increased with the use of locally available materials for construction to promote widespread adoption at moderate costs. A single unite of the developed cooker costed 210 USD and gave a payback period of 1 and 1.3 years while transitioning from cooking using charcoal and electricity respectively. With batch production, this cost is expected to go down and also, its manufacturability requirements are for semi-skilled at local workshops with basic fabrication tools. Therefore, the switching to the developed cooker not only offers substantial monthly savings but also supports environmental sustainability efforts in Uganda in terms of reduced deforestation and carbon emissions.

From the model simulations and with consideration of Mbarara city, a regional area experiencing one of the lowest daily GHI among the selected regions, the design exhibited quick temperature buildup of about 135 ^{0}C in the glazed cooking space within 30 minutes of exposure at the solar hour of noon. This supports cooking of most of the common foods in Uganda. These results support the adoption of solar cookers as a viable, efficient, and eco-friendly alternative for households in Uganda.

5.2 Recommendations

From the study finding, the inclination angles of the internal side-wall reflectors greatly affect the general size of the box-type solar cooker and this is dependent on the selected geographical location. Designs should be developed considering specific regional areas to maximize performance efficiency but also ensure reduced manufacturing cost. Further research should be conducted to investigate the performance of the DBSC under different regional areas in Uganda and for cooking a wider range of foods for validity and adoption.

5.3 Areas for Further Study

Research into alternative materials for constructing solar cookers could further reduce costs and improve performance. Long-term studies are needed to assess the durability and maintenance requirements of the DBSC in real-world conditions. Additionally, studying the social acceptance and user satisfaction of the DBSC in different communities can help identify potential barriers to adoption and ways to overcome them.

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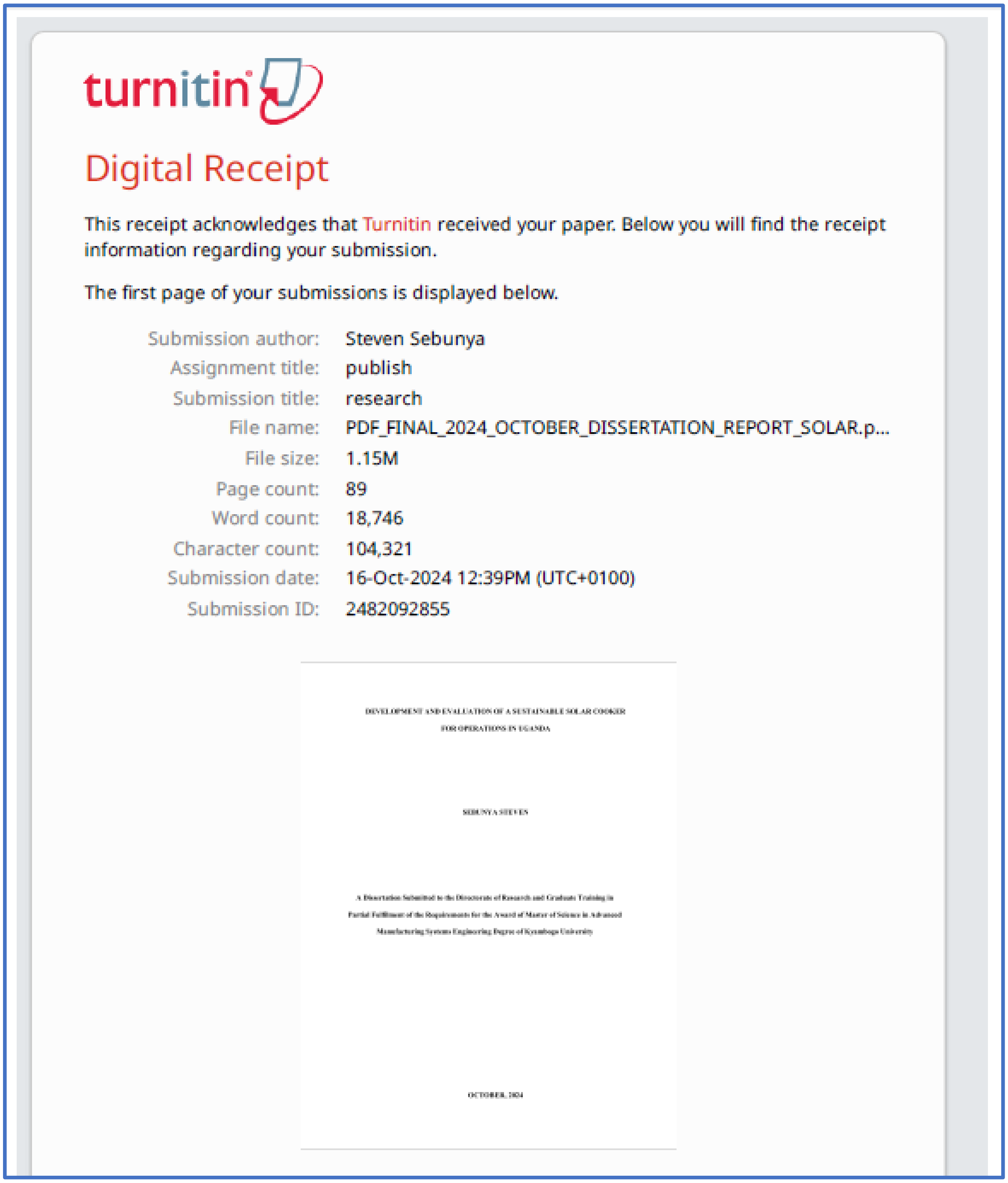
APPENDICES

Appendix A: Plagiarism Report



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DEVELOPMENT AND EVALUATION OF A SUSTAINABLE SOLAR COOKER
FOR OPERATIONS IN UGANDA

SEBUNYA STEVEN

A Dissertation Submitted to the Directorate of Research and Graduate Training in
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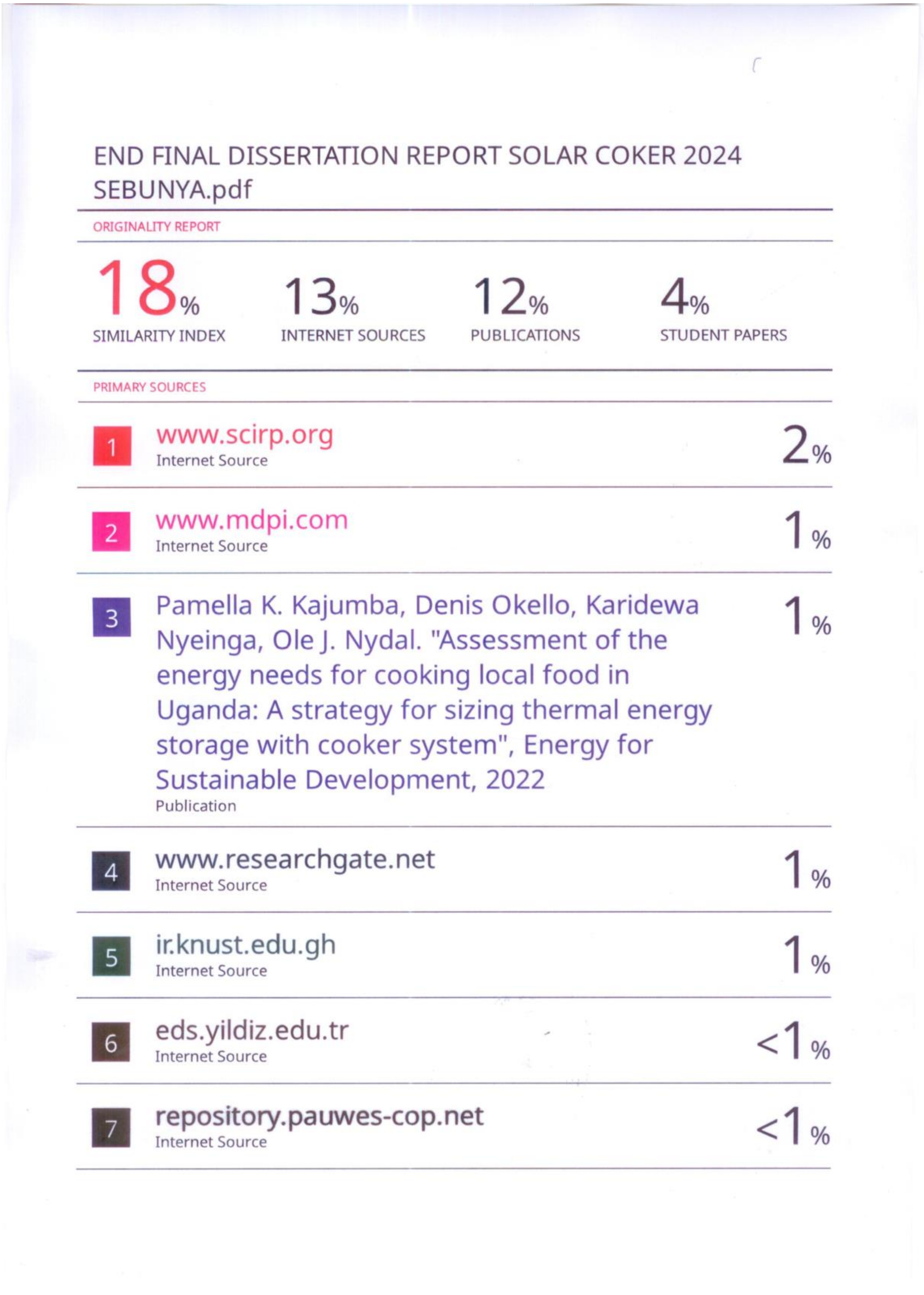
Manufacturing Systems Engineering Degree of Kyambogo University

OCTOBER, 2024



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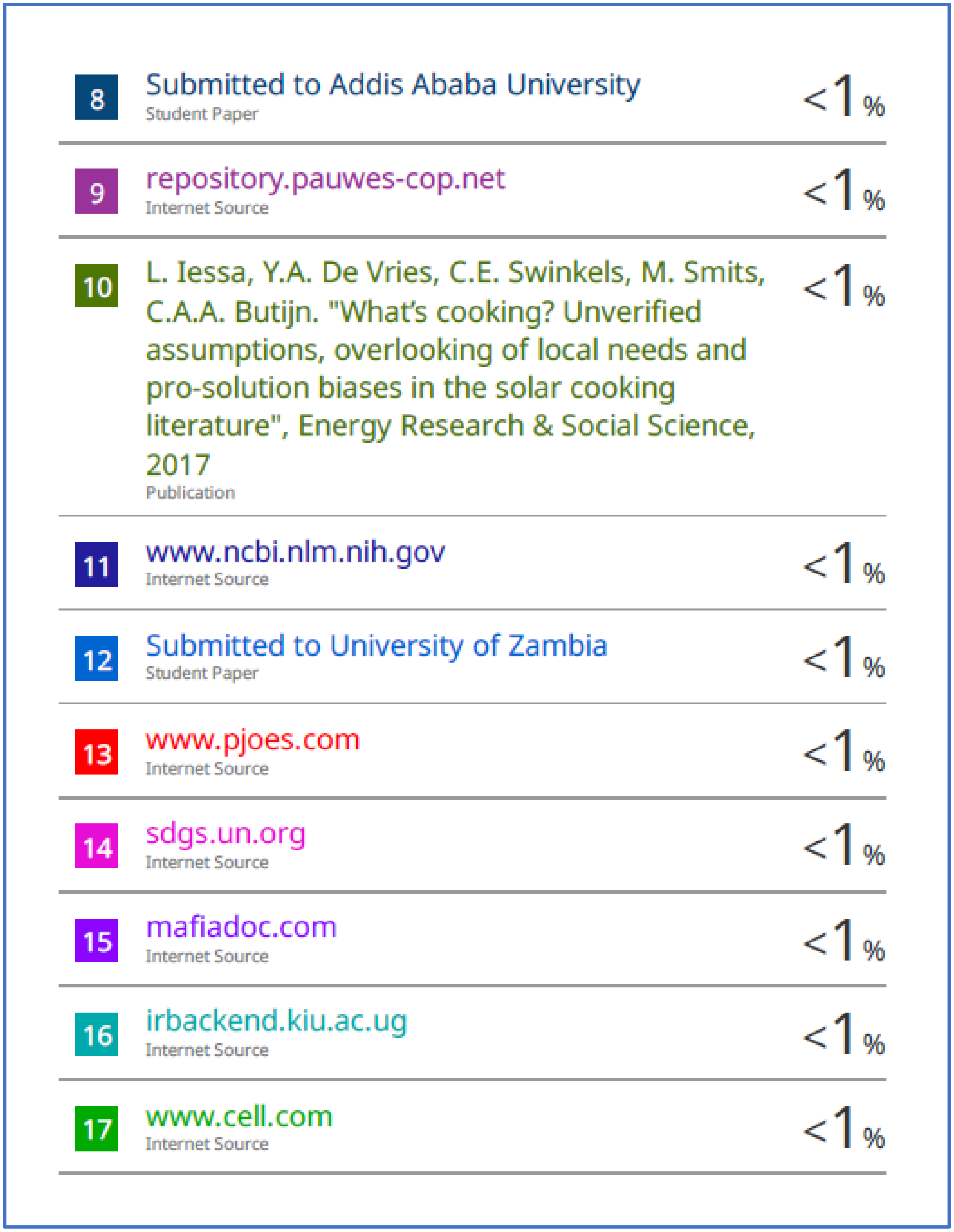

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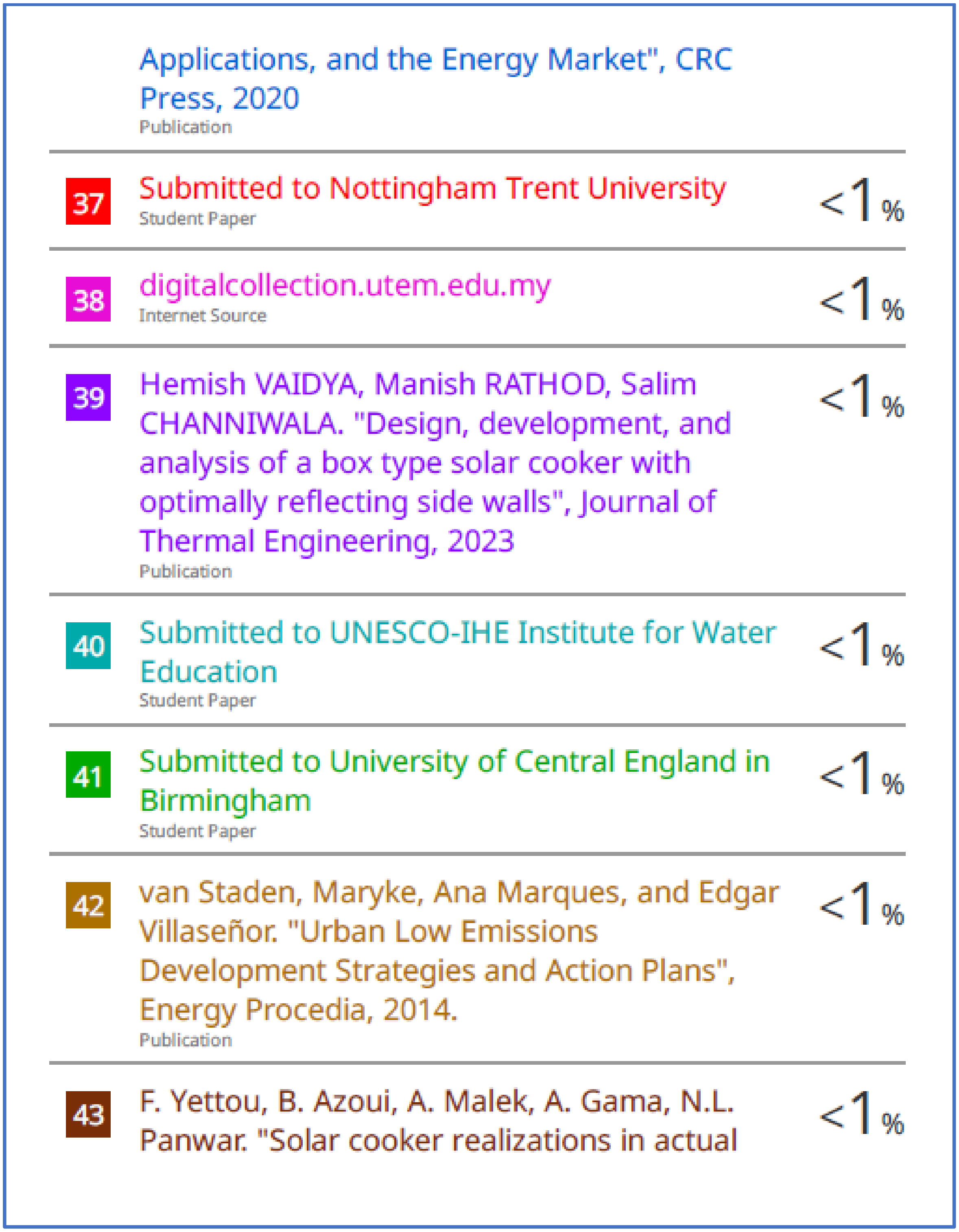

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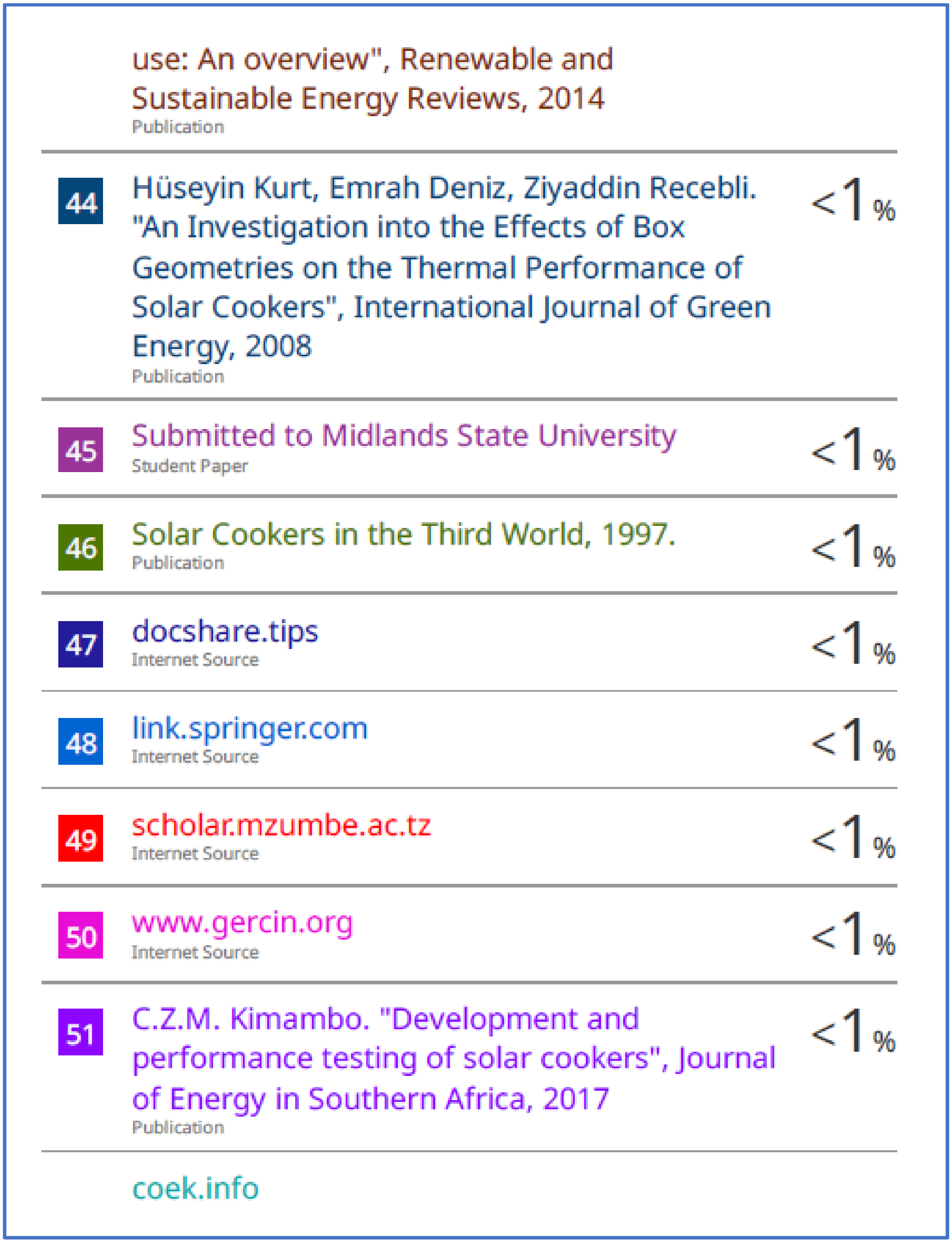

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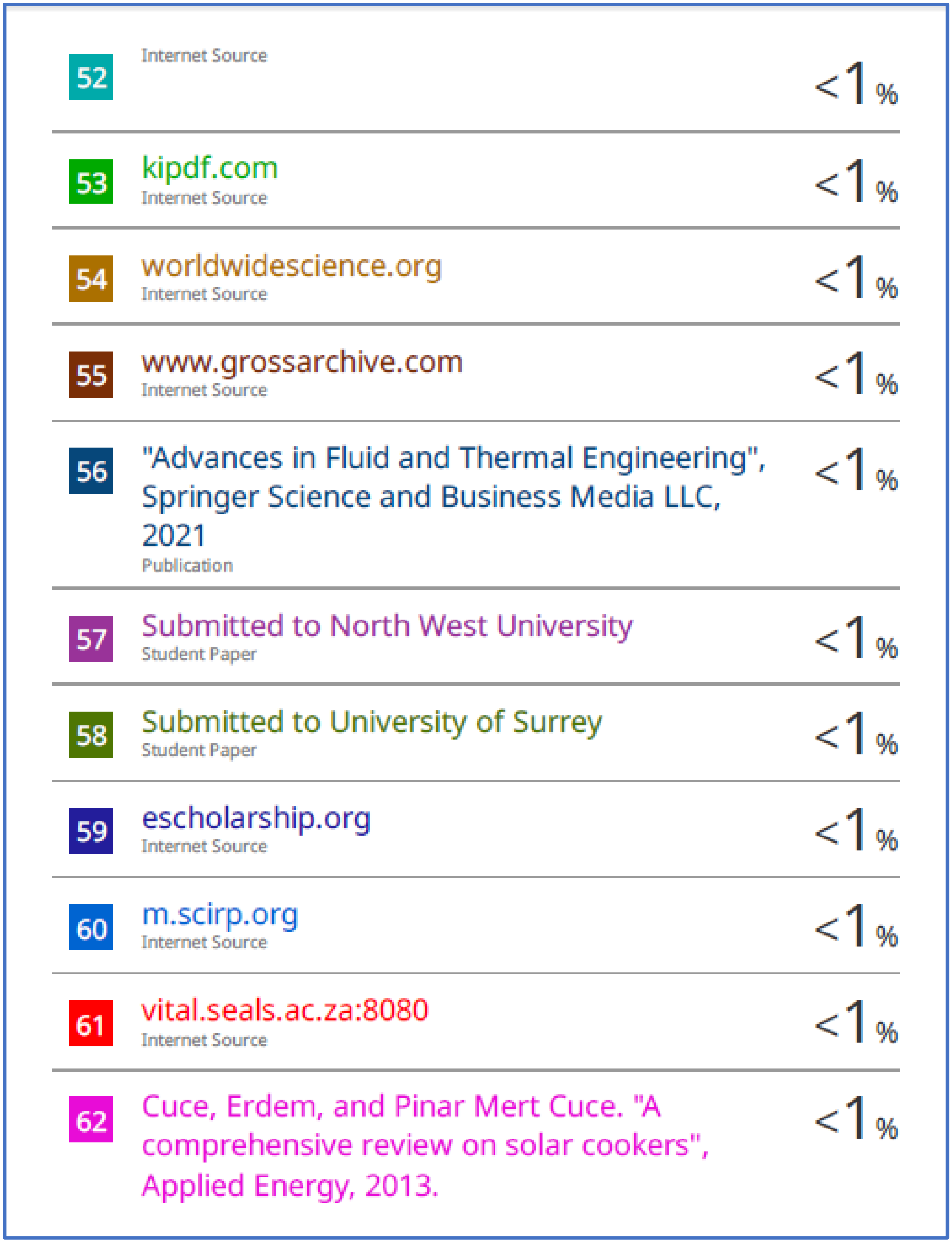

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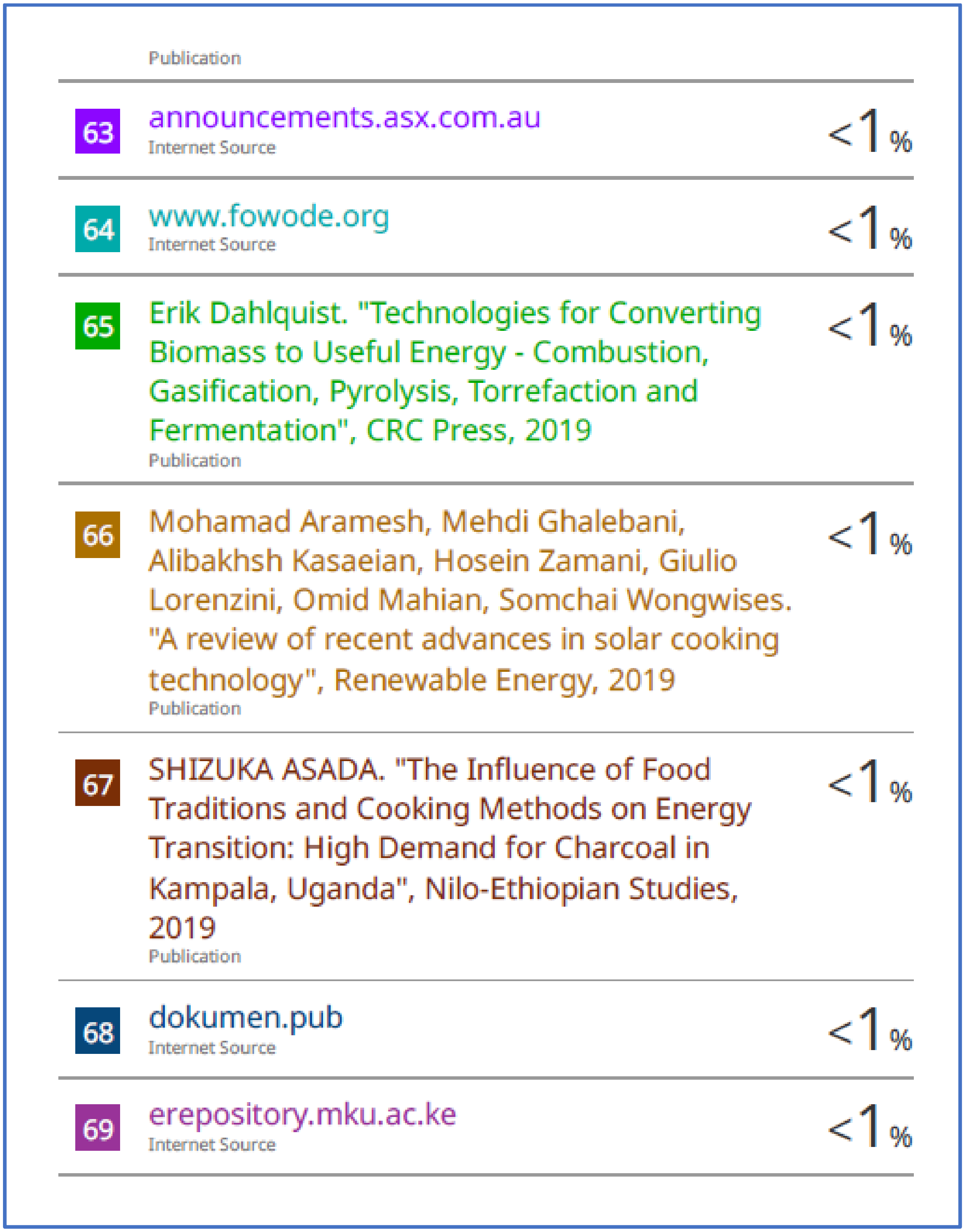

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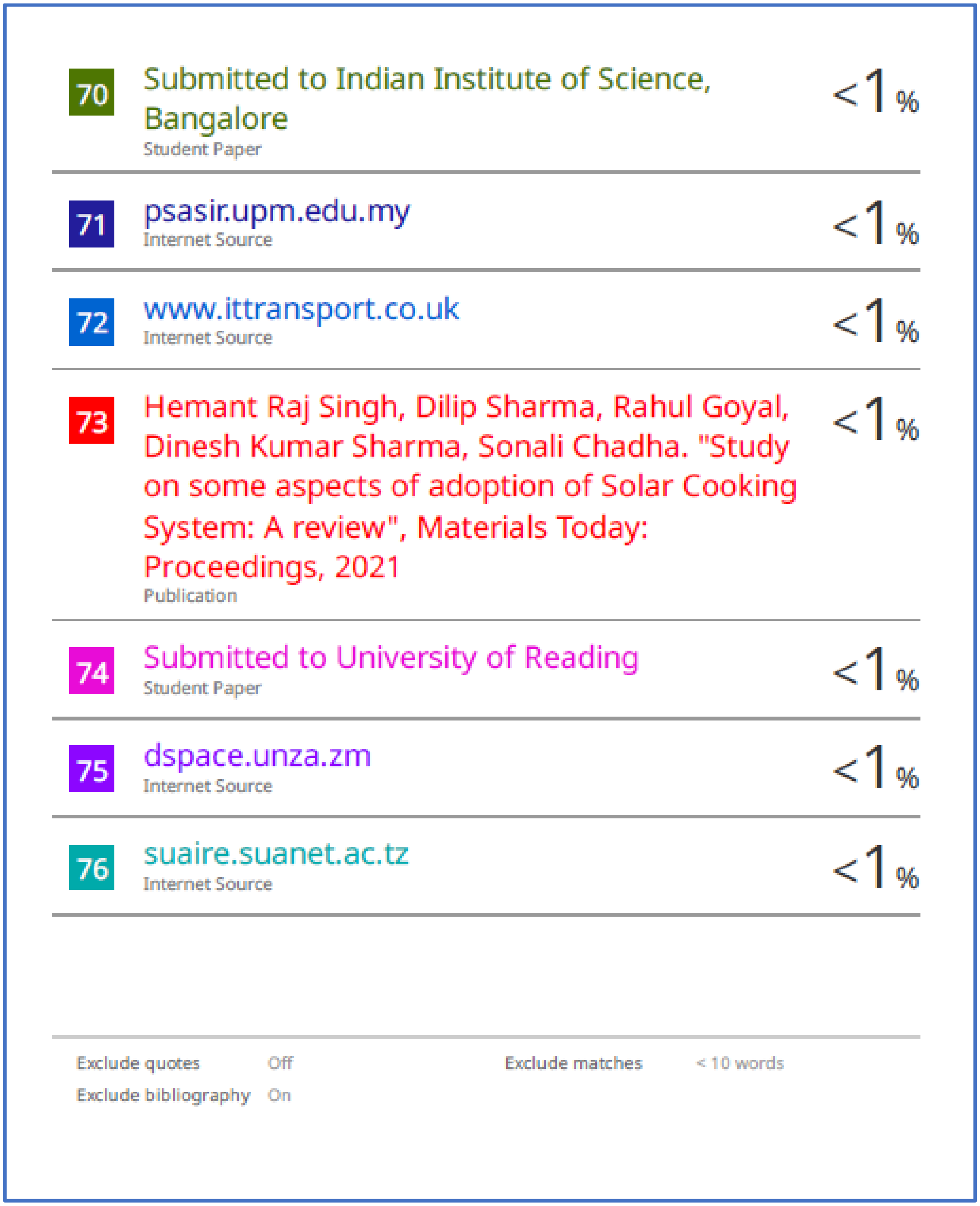

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