DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

TECHNO-ECONOMIC ANALYSIS OF A PARABOLIC AND PANEL TYPE SOLAR COOKER AS A NET ZERO COOKING OPTION IN MALAWI

FAITH MBONONGO BANDA

SUPERVISOR: DR. NICK KELLY

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ABSTRACT

98% of Malawians use solid fuels to cook, commonly charcoal and firewood. These solid fuels are extremely polluting, exposing women and girls who spend most of their time in the kitchen to indoor air pollution, which can lead to respiratory diseases. This necessitates the use of net zero cooking methods such as parabolic solar cookers and solar panel cookers. Solar cookers were proven to be the ideal cooking choice due to the country's high solar radiation for solar energy production. In this study, the parabolic solar cookers and solar panel cookers were designed, and their design parameters considered aspects such as available solar radiation and cooking energy required. Using this information, the sizes of the cooker's components and the capacity for storing energy required during periods of low radiation and nighttime use were determined. The techno-economic computation for parabolic and panel type solar cooker were done in Microsoft excel and PVsyst respectively. The efficiency rates of parabolic and panel solar cookers were found to be 74% and 75%, respectively. The cost of a parabolic solar cooker was £172, while a panel solar cooker cost £866. The outcomes of the technical-economic evaluation were used in the TOPSIS multi-decision tool to compare these two technologies against conventional fuel sources. In comparing the technical, economic, and environmental aspects with traditional fuels like charcoal and firewood, the parabolic solar cooker emerged as the most favourable cooking choice based on the given criteria and their respective weights. Following this were the panel solar cooker, firewood, and charcoal. To verify the findings, a sensitivity analysis was conducted by adjusting the criteria weights to check the consistency of the results. The results of the sensitivity analysis demonstrated that the conclusions obtained remained consistent and robust.

Acknowledgments

I'd like to thank God Almighty for providing me with strength throughout my time at the University of Strathclyde. I'd also like to thank my supervisor, Dr. Kelly, for his tireless efforts and assistance throughout the project research. I'd also like to thank my family and friends for their financial and mental support during my studies.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbol	Description	Units
Q	Energy required to cook	kWh
I	Average solar radiation	kWh/m2/day
T	Time taken to cook a meal	Seconds
n_r	Efficiency of the reflective	%
F	Focal length	m
D	Diameter	m
H	Thermal efficiency cooker	%
M	Mass of cooking fluid	kg
Cp	Specific heat of cooking	(kJ/kg.K)
ΔT	Difference between the maximum and ambient air temperature.	^0c
A	Aperture area	m^2
LR	Thermal losses	%
N	Number of days for storage	Days
P	Density of the storage	Kg
Pt	% of time LPG is used	%
Ml	Monthly mass of LPG consumed.	Kg
Cl	Cost of LPG per kg	£/kg
E	Energy demand	kWh
V	System voltage	V

1. INTRODUCTION

This section gives an overview of the study's the background and explains the motivations for its conduct. It explores into the research's main purpose and explains its specific goals and objectives.

1.1 The current cooking technologies in Malawi

The National Statistical Office of Malawi conducted a survey in 2021 to assess the country's cooking fuel preferences [1]. The survey found that most households (98.8%) used solid fuels as their primary cooking energy source, such as firewood and charcoal. Within this group, 79.1% used firewood, 18.5% used charcoal, and only 1.2% used electricity as their cooking fuel [1]. Studies have been conducted to examine the factors that influence individual's cooking energy choices. According to Tchereni [2], Firewood was more commonly used in low-income households with larger families while higher income household were associated with an increased likelihood of choosing to charcoal as an energy source [2]. Maonga and Gebremariam [3] found out that as household labour increased, the likelihood of selecting firewood decreased, leading to a higher usage of electricity and charcoal. Moreover, individuals with higher levels of education were more likely to choose electricity and charcoal. Additionally, regions with greater electricity installation had a higher probability of using electricity and a lower probability of using charcoal[3].

However, since majority of the households use solid fuels, people are exposed to indoor air pollution that cause blood pressure and respiratory diseases. The level of particulate matter 2.5 (PM2.5) ranges from 97 to 1163 microgram/m3 for firewood and charcoal [4]. Mabonga et.al [4] highlighted that women who use firewood and charcoal for cooking experience respiratory difficulties, coughing, and eye discomfort, although these symptoms are slightly reduced when cooking outdoors [4]. Rylance et. al[5] investigated the connection between respiratory disorders and air pollution in Malawi and discovered that exposure to air pollution has resulted in an increase in respiratory diseases. People who used cleaner burning solid fuel cookstoves had lower levels of PM2.5 exposure. However, even though PM2.5 levels were lowered, there was no effect on lung disease reduction [5]. This emphasizes the pressing need to embrace clean, dependable, efficient, and economically viable cooking technologies to accomplish net zero cooking in the nation.

1.2 Opportunities for net zero cooking technologies

Malawi possesses a range of renewable energy sources, including hydro, solar, geothermal, biomass, and wind, which can be harnessed to fulfil the energy needs of its communities[6]. To attain Sustainable Development Goal 7, the country has formulated energy policies that actively support the utilization of renewable energy [7].

The nation possesses significant hydroelectric power capacity and currently depends on this source to produce 441.95MW of electricity. This electricity supply is then distributed to approximately 15% of the population, comprising those connected to the power grid, who utilize it for both lighting and cooking purposes [8]. Hydropower can be used to generate more electricity which can be used for cooking; however, the construction of large-scale power stations typically requires several years and huge investment [8]. Therefore, it is essential to explore alternative power development plans and utilize other renewable energy resources to generate electricity for cooking and lighting.

The country has no wind energy potential as the wind speeds at a height of 50 meters ranges from 3m/s to 5m/s throughout the year [9]. The cut off wind speed for large scale turbines for electricity production is 4m/s thus no turbine can generate sufficient electricity at wind speeds below 4m/s.[10].

The country does not have a widespread network for large-scale biogas usage in cooking[6]. Nevertheless, there exists significant potential for biogas production, which offers numerous advantages, as identified by the Malawi Renewable Energy Strategy (MRES) [11]. However, the high costs associated with biogas production pose a challenge, mainly due to the importation of components and the payment of additional taxes.

Lastly, Malawi possesses significant solar thermal and photovoltaic (PV) capacity due to its abundant sunlight. Solar PV systems are widely adopted throughout the country due to their ability to utilize the abundant solar radiation available in all regions, as depicted in figure 2.1. The global solar irradiation levels range from 4.6 to 5.6 kilowatt-hours per square meter (kWh/m2), leading to significant conversion of this energy into electricity and thermal cooking [12]. By promoting the utilization of solar energy technologies, the country can make progress towards universal access to modern and sustainable energy.

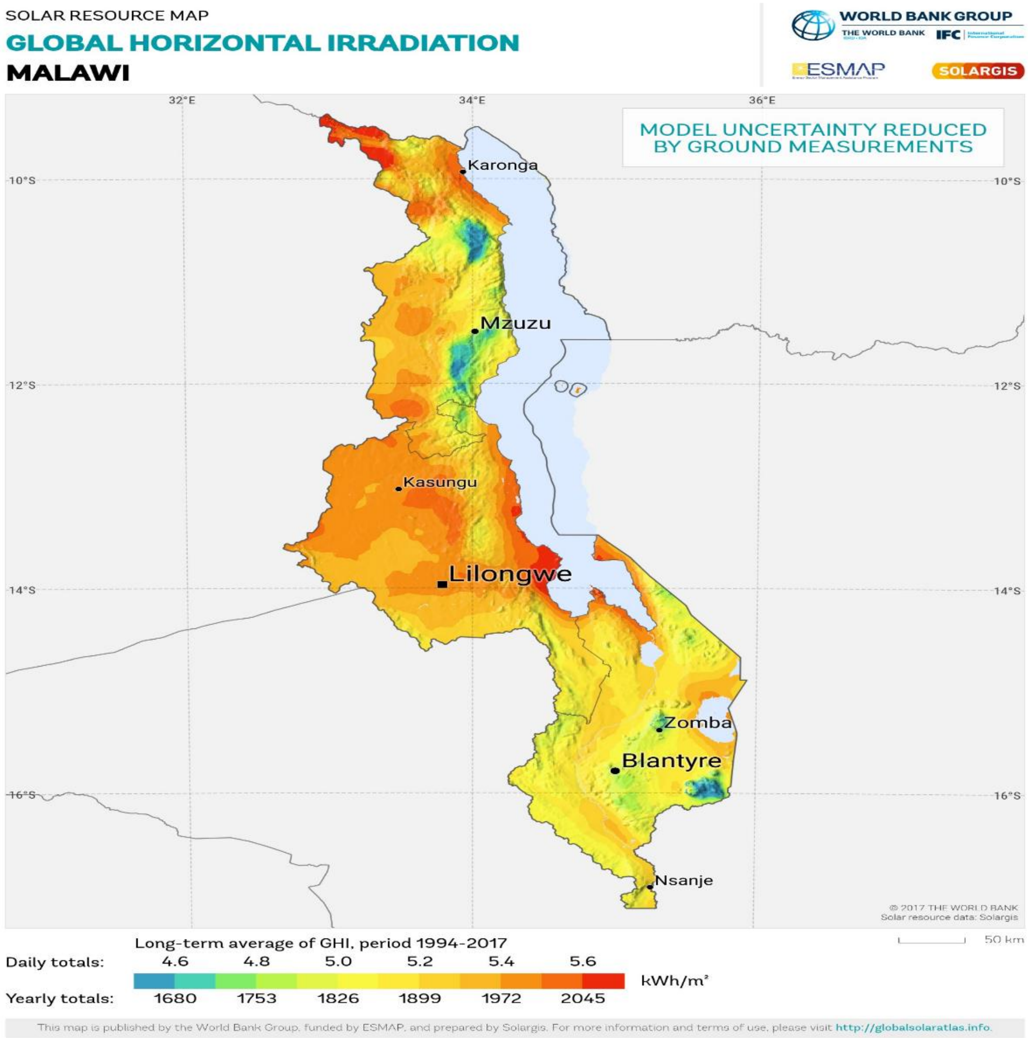

Figure 1-1: Global horizontal irradiation [12]

1.3 Problem Statement

The use of solid fuels in Malawi has given rise to an alarming increase in respiratory diseases caused by indoor air pollution. According to World Health Organisation (WHO) standards, a person should not be exposed to PM2.5 levels greater than 15 micrograms/m3 in a 24-hour period [13]. People in Malawi's rural areas, on the other hand, are exposed to a range of 97 to 1193 microgram/m3 if firewood and charcoal are utilized [4]. This PM2.5 level increases the risk of respiratory disorders including chronic obstructive pulmonary disease [5]. Additionally, deforestation continues to worsen this problem, further compounding the challenges. Particularly affected by these issues are women and girls, who bear a disproportionate burden of collecting firewood for cooking purposes. Therefore, it is crucial to urgently tackle these interconnected challenges and develop sustainable solutions that promote clean energy, reduce indoor air pollution, mitigate deforestation, and alleviate the hardships faced by women and girls in firewood collection. Cooking using solar energy is one of the most promising solutions for achieving net zero cooking and reducing women's burdens. There are various of solar cooker designs, but this study focuses on the technical and economic analysis of parabolic and panel type solar cookers with the goal of determining the optimum cooking alternative between solar cooker and traditional cooking technologies.

1.4 Main Objective

The main objective of this study is to conduct a techno-economic analysis of a parabolic and panel type solar cooker as a net zero cooking option in Malawi.

1.5 Specific Objective

i. To design and size solar cooker components of both parabolic and panel type solar cooker.

ii. To evaluate the performance of both the parabolic and panel type solar cookers throughout the year, as well as their energy storage capacity for operation during low radiation and at night.

iii. To conduct a techno- economic evaluation of the parabolic and panel type solar cooker.

1.6 Justification of the Study

The 2018 national energy policy of Malawi is committed to implementing projects in the energy sector that align with the goal of achieving Sustainable Development Goal 7 (SDG7), which focuses on ensuring access to affordable, reliable, efficient, and modern energy services[7]. As part of this policy, there is a strong emphasis on promoting the use of clean cooking technologies. This prioritization is driven by the understanding that clean cooking not only improves living standards for both men and women but also addresses the significant time burden women face in collecting firewood [7]. Moreover, the adoption of energy-efficient technologies further contributes to the reduction of carbon emissions. By prioritizing clean cooking energy, Malawi aims to make significant progress in increasing access to affordable and reliable energy services while simultaneously improving the quality of life for its population and reducing the environmental impact of unclean cooking fuels [14].

1.7 Significance of the study

This research focuses on investigating the various options for achieving net zero cooking in Malawi, with a specific emphasis on utilizing solar energy resources. It aims to overcome the country's limitations in adopting solar cooking technologies by designing and analysing

Parabolic and panel type solar cooker. By conducting this study, valuable insights will be gained, benefiting scholars in their understanding of solar cooker design and operation. The primary beneficiaries of this project are the Malawian population without access to electricity but who can afford to utilize solar cookers for their cooking needs. The positive outcomes of this research will lead to an improved quality of life for both rural and urban dwellers, while also enhancing the affordability and availability of energy services. Furthermore, the implementation of this renewable energy system will contribute to the reduction of greenhouse gas emissions, promoting a more sustainable and environmentally friendly approach to cooking in Malawi.

1.8 Chapter Summary

Solid fuel is used as the primary energy source for cooking in households, exposing people to indoor air pollution. Nonetheless, the country has the potential to achieve a net zero cooking using renewable energy sources. Solar resources can be utilized because of the abundance of sunlight, allowing for significant solar thermal and photovoltaic PV capacity. This research aimed to design and determined the optimal sizes for both parabolic and solar-type solar cookers. Subsequently, a comprehensive technical-economic analysis was conducted to compare these solar cookers with conventional cooking methods.

2. LITERATURE REVIEW.

This section reviews the existing literature on the historical and present advancements in solar cooker designs. It also discusses the most recent approaches used in the technical-economic analysis of solar cookers.

2.1 Historical development and prospects of solar cooking

Horace-Benedict de Saussure is known for creating the world's first solar energy collector, known as the solar hot box, in 1767 [15]. This initial design consisted of a rectangular wooden box insulated with black cork. Over the following decades, Saussure's invention underwent further improvements, leading to the development of new designs[15]. Additionally, notable contributions in the field of solar energy were made by Frederick William Herschel and Samuel Pierpont Langley[16]. At present, numerous organizations are actively promoting solar thermal cooking technologies. One such organization, Solar Cookers International (SCI), has played a crucial role by serving as a central hub connecting solar cooking researchers, manufacturers, and distributors [17]. The primary objective is to raise global awareness about this innovative product. Currently, more than 4 million solar cookers have been distributed worldwide, positively impacting the lives of 14.3 million individuals and contributing to improved human health [17]. Additionally, the utilization of solar cookers leads to an annual reduction of 5.8 million metric tons of carbon dioxide emissions, thereby mitigating the release of greenhouse gases responsible for global warming [17] Figure 2.1 illustrates the distribution of solar cooking across different regions.

Figure 2-1:Map of solar cooking [17]

The International Solar Energy Society (ISES), recognized as a prominent advocate for renewable energy worldwide, is dedicated to facilitating the growth of renewable energy adoption by offering tools for capacity building [18]. ISES is highly regarded for its support of the solar industry and actively gathers solar data to make it accessible to the public. Additionally, the organization organizes webinars and conferences specifically centred around solar thermal and photovoltaic (PV) technologies [19]. With a diverse membership and global partnerships, ISES collaborates closely with the IEA Solar Heating and Cooling Programme to encourage the widespread implementation of solar thermal solutions, leading to an increasing number of countries embracing this technology [19].

As an approach to reaching net-zero carbon emissions by 2050, the International Energy Agency (IEA) has established a goal to implement 400 million solar thermal technologies by 2030[20]. This objective is a crucial component of the technology and innovation pathways aimed at achieving zero-carbon status by 2030 [20]. The IEA acknowledges that, to meet this target, a minimum of 290 million new solar thermal systems must be installed within this decade. Furthermore, the IEA Solar Heating and Cooling Programme (IEA SHC) indicates that out of these 290 million systems, approximately 170 million will employ standard technologies, while around 120 million will utilize emerging technologies [21]. These installations are projected to be completed by the year 2030.

Figure 2.2 below illustrates the past deployment of solar thermal technologies from 2002 to 2020, the projected deployment based on current trends from 2020 to 2030, as well as the target set by the IEA for achieving net zero by 2030 (IEA, 2023).

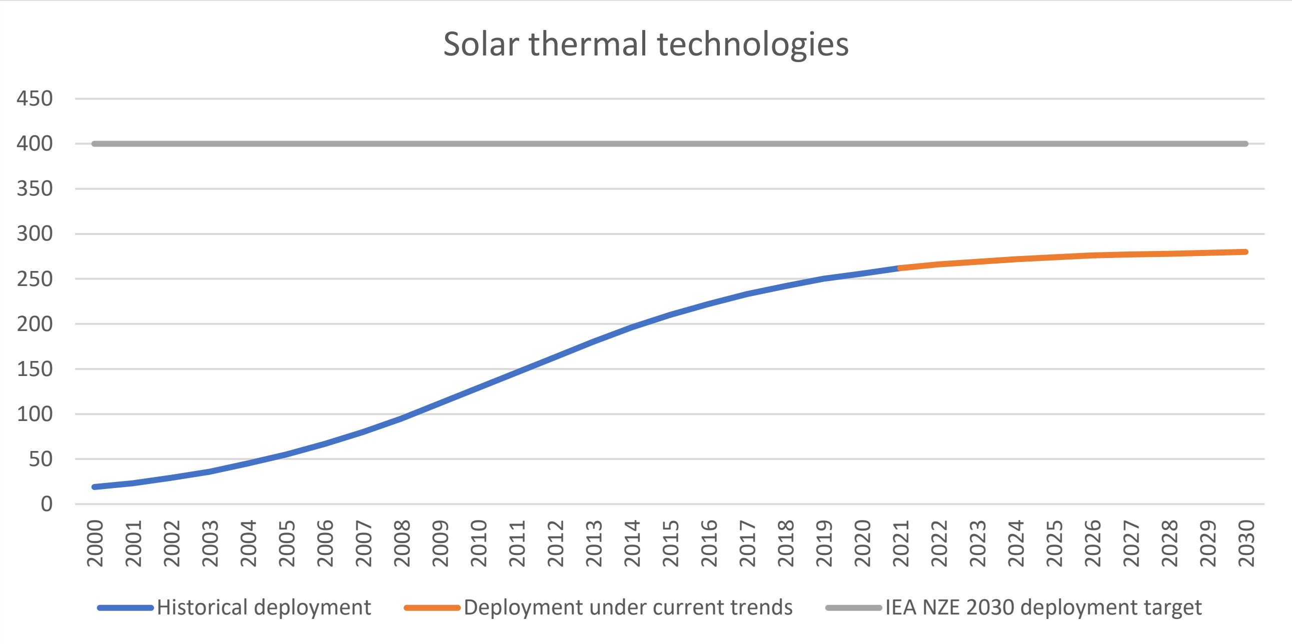

Figure 2-2:Solar thermal technologies trends

2.2 Solar cooker designs

Solar cookers come in three main classifications: box type, parabolic type, and panel type as shown in figure 2.8. Researchers have devoted their efforts to enhancing the performance of these cookers [22]. They have made a wide range of modifications to achieve greater efficiency and effectiveness. These modifications have focused on different aspects of the solar cookers. One area of improvement has the integration of innovative heat storage materials in the cookers [23], [24] The thermal storage classified as latent and sensible heat as shown in figure2.8. Latent thermal storage materials are capable of absorbing and releasing significant heat energy during phase transitions, like from solid to liquid or liquid to gas [25]. In contrast, sensible heat storage involves capturing and storing heat in a material without any change in its state [26], [27]. In this solar cooker design, a thermal storage unit is integrated, typically consisting of well-insulated materials with high thermal mass, such as stones, bricks, or ceramics[27]. The stored thermal energy can then be gradually released, maintaining a consistent cooking temperature over an extended period [25].

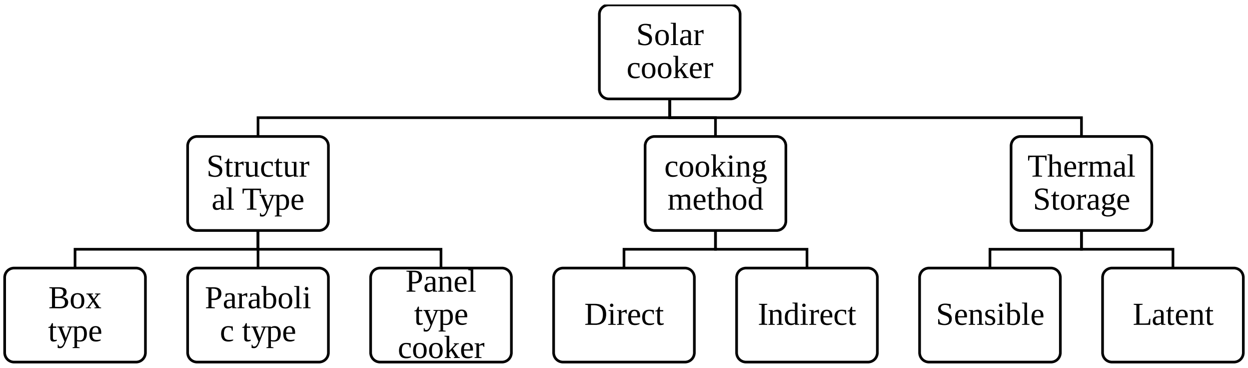

Figure 2-3: Classification of solar cookers [22]

Although modifications have been made, the performance of the solar depends on solar radiation. There is a direct correlation between the solar radiation received and the temperature of the cooker. Joyee et.al [28] found that on cloudy days, the solar cooker temperature decreased leading to longer cooking times. Likewise, Rulazi [23] designed and tested the performance of a parabolic solar cooker between 7:00 am to 6:00 pm., covering a range of averaged solar radiation varying from 10 W/m2 to 1060 W/m2 [23]. The cooker achieved low temperatures in the morning because of low levels of irradiation and achieved higher temperatures at noon when solar radiation was maximum.

The box-type solar cooker was an early model in solar cooking technology [15]. The design of the side walls in a box-type solar cooker is crucial as the cooker's efficiency relies on proper reflection [29]. The side walls enhance the thermal response of the solar cooker and must be fixed at an angle. Hemish (2020) designed a box solar cooker with optimal design angles and the cooker was able to achieve the temperature of 76 ^{o} C whereas the conventional cooker only reached 65^{o} C. Over time, various new designs have been introduced to the market, improving upon the conventional box-type solar cooker. These upgraded designs have demonstrated a higher level of performance compared to the older version [29]. In this view, Milikias et.al [27] evaluated a solar box cooker and found that the improved design achieved a first figure of merit of 0.1349, while the conventional cooker only managed a figure of merit of 0.115 [27]. Saxena [30] assessed a mixture of sand and granular carbon as thermal energy storage using a solar box cooker, finding it capable of maintaining high temperatures and storing energy for extended periods, making it a cost-effective heat storage option for solar cookers [30]. Coccia et al.[31], experimented to verify the performance of a solar box cooker with salt-based thermal storage. The study demonstrated that thermal storage improved thermal stabilization when solar radiation was unavailable. The solar cooker could still achieve high temperatures even in the absence of direct sunlight, confirming the effectiveness of the proposed design [31].

Figure 2-4: Solar box cooker source: India Mart (2023

Another type of solar cooker design is the parabolic dish, which functions by concentrating sunlight onto a central focal point. This arrangement allows for efficient heat collection and distribution, making it an attractive option for solar cooking [32]. Mohammed [33] successfully developed and built a solar thermal cooker using a parabolic dish design capable of cooking 12 kilograms of dry rice each day, making it suitable for a medium-sized family. The study yielded promising results, with the solar cooker effectively cooking 3 kilograms of rice in just 90 minutes [33]. Ahmed et al [24] conducted a performance analysis of a parabolic solar cooker using different reflective materials, including stainless steel, aluminium foil, and Mylar tape. Various weather conditions were tested to evaluate the energy absorption capabilities of these materials. Both stainless steel and aluminium foil exhibit similar reflective capabilities, with temperatures of 77 degrees and 73.1 degrees, respectively, as found in this study. These results align with Silviyanti & Santoso's study comparing the two reflective materials [34]. However, Mylar tape outperformed both, reaching the highest temperature of

93.7 degrees. Nonetheless, Mylar tape has certain limitations, such as its limited availability and higher cost when compared to aluminium foil and stainless steel. Kumar stressed that aluminium foil is not only the optimal choice for designing a parabolic solar cooker due to its high reflectivity rate and cost effective but also a suitable option for construction because of its lightweight nature and energy efficiency [32]. Wollele et.al [35] designed a parabolic solar cooker with rocks as thermal energy storage, utilizing engine oil as a heat transfer fluid. The rocks absorbed heat during the day and gradually released it at night during discharging [35] . Yadav et. al [26]investigated the performance of phase change materials combined with various sensible heat storage materials for evening cooking using a parabolic cooker. The study found that sand and stone pebbles were better at storing heat compared to iron grits and balls [26]

Figure 2-5: Parabolic dish solar cooker source: India Mart(2023

Kalolo et al [36] undertook a project to design and build both a parabolic and box-type solar cooker using locally available resources. The primary objective was to determine the thermal efficiency achievable with the prevailing weather conditions in Malawi throughout the winter months [36]. Through this project, the parabolic solar cooker attained a temperature of 146 degrees, while the box type cooker reached a temperature of 96 degrees [36].

Lastly, the panel type solar cooker design incorporates three essential components: a solar panel, an electric cooker, and a battery [22]. The solar panel plays a pivotal role in the process of converting sunlight into electricity. Subsequently, this generated electricity powers the electric cooker, allowing for efficient cooking [22]. An advantageous feature of the panel type solar cooker is its ability to store excess electricity. During times of ample sunlight or high solar radiation, any surplus electricity not immediately required for cooking is stored in a battery. This stored energy can then be utilized later when solar radiation is insufficient, such as during nighttime or on cloudy days [37].

This study, however, concentrated on the investigation of parabolic and panel type solar cookers due to their practical use in Malawian rural households. Because most meals cooked in communities demand regular stirring, a solar box cooker that functions as a solar oven cannot be used for such meals. Table 2.1 summarises recent studies on the performance of parabolic and panel-type solar cookers.

Table 2.1: Recent studies on performance of Parabolic and Panel type solar cooker.

Author	**Year**	**Location**	**Description / design**	**Results**
Gupta et al[38]	2021	India	Development of panel type solar cooer with storage.	When compared to box type solar cookers, panel type reached a comparatively low temperature. However, it proved to be a feasible cooking choice.
Komolafe et al [39]	2022	Nigeria	Parabolic solar cooker with sensible heat storage with Arduino based tracking device.	The maximum temperatures for water, cooker and sensible heat storage were 73.5ºc, 76ºc, and 59ºc respectively.
Kalolo et al. [35], [36]	2022	Malawi	Design and performance evaluation of a parabolic and box type solar cooker.	Thermal performance results showed that the parabolic solar cooker and the box type achieved the temperature of 146ºc and 76ºc respectively.
Wollele et al [35].	2022	Ethiopia	Parabolic solar cooker with thermal energy storage (TES).	The cooker was able to cook 1 kg of rice in 45 minutes using TES providing a power of 421W and temperature 355K.
Kumar [32]	2022	India	A solar cooker with a parabolic reflector.	The cooker achieved the maximum temperature of 110ºc.

Lentgwe et al [40]	2021		Comprehensive review of parabolic solar cookers with TES.	Parabolic dish solar cooker with TES is common. However, there are less experimental studies on TES and techno-economic aspects of the technology.
Tibebu et al[41]	2021	Ethiopia	Comparison of parabolic cooker with conventional fuels	The energy output and input are 0.182kW/m2 and 1.69kW/m2 respectively. The cooker boiled water faster than other fuels.
Atmane et al.[42]	2021	Morocco	Development of Panel type solar cooker	The cooker achieved the thermal efficiency of 86% and achieved remarkable results with improvement in the achieved temperature, time taken and heating speed.

2.3 The Gap identification and Main Contribution of this Study

The performance of the solar cooker is dependent on the location and reflecting material, as addressed in recent studies of the solar cooker design. The available solar energy resource is determined by the location. The recent studies selected the solar cooker design to use based on efficiency, temperature achieved, and the initial figure of merit, which is primarily based on technological study. However, there have been a few studies that compare the techno-economic aspects of solar cookers. In this study, the best solar cooker design was selected based on both technological and economic factors. The major contributions of this study are as follows:

- A Parabolic and Panel type solar cooker was designed to reduce the exposure of indoor air pollution.
- The study provided insights into which solar cooker is ideal for usage in Malawi and solved the problem of selecting the most appropriate cooking technology using TOPSIS, a multicriteria decision tool.
- A sensitivity analysis was carried out to validate the selected solar cooker.

The thesis is structured in the following way. Section 3: Materials and Methods, Section 4: Results and discussion, Section 5: Recommendation and Conclusion.

3. MATERIALS AND METHODS

This section discusses the materials and methods that were taken to carry out the techno-economic analysis of the parabolic solar cooker and Panel type solar cooker.

3.1 Study Location

This research was carried out in Malawi (Lilongwe), a country situated in the southern part of Africa. Figure 3.1 shows the map of Malawi made using ArcGIS. The country is a landlocked country positioned at coordinates 13.2543° S, 34.3015° E, and it lies below the equator. The assessment considered the country's distinct seasons, including the warm wet season from November to April. During this period, Malawi experiences abundant rainfall and cloudy days, with an average precipitation range of 725mm to 2500mm [43]. The winter season follows from May to August, characterized by temperatures between 17ºC and 27ºC. The coldest months, June, and July may experience frost. Finally, the hot dry season occurs between September and October, bringing the highest temperatures ranging from 25ºC to 37ºC [43].

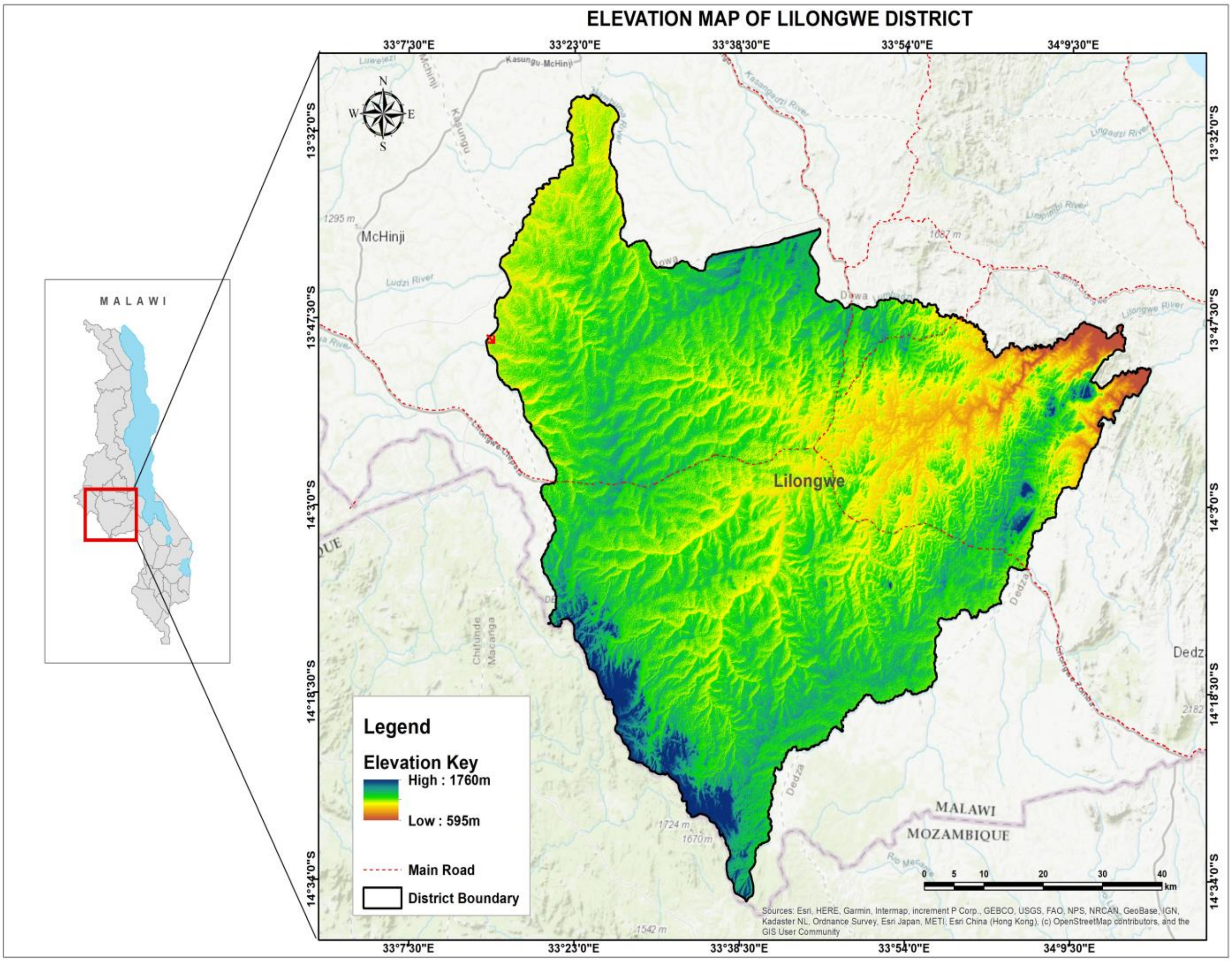

Figure 3-1: Map of Malawi, Lilongwe source: Author

3.2 Overall Methodology Flowchart

The flowchart in Figure 3.2 depicts the methodology used to conduct a techno-economic study of a parabolic and panel type solar cooker. Solar irradiance data and the energy required for cooking were needed to design and size the solar cookers. The design specifications for the parabolic solar cooker were entered into solid works for visual depiction. The design specifications, specifically the aperture area and solar irradiance data, were used for techno-economic computations in Microsoft Excel to determine the amount of solar energy gathered by the cooker, the amount of energy missing for cooking, and to size of the energy storage. Using the same tool initial cost, NPV, and Payback period were calculated. For panel type solar cooker, the number and costs of panels and batteries were entered into PVsyst, yielding the system's solar energy production, Performance ratio, solar percentage, initial cost, NPV, and payback period. To perform the techno-economic study, TOPSIS was used to determine the optimum cooking choice using results from Microsoft Excel, PVsyst, and conventional fuel.

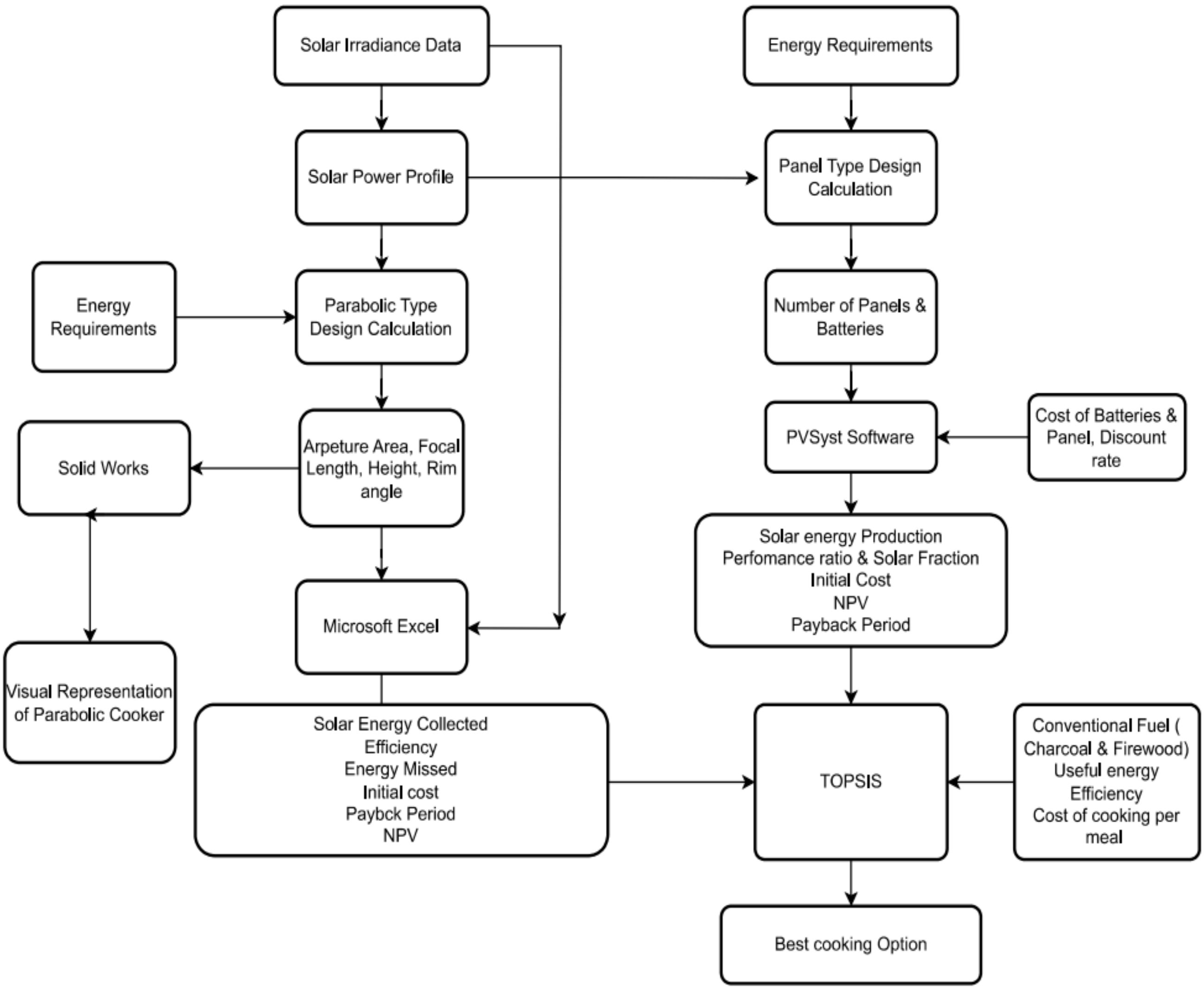

Figure 3-2: Methodology flow chart source: Author

3.3 Solar Resource Assessment and cooking energy demand.

The meteorological data for Lilongwe was obtained from NASA power. The website was chosen for its extensive coverage encompassing a global scope and has solar energy database for 23 years. Figure 3.3 illustrates the solar radiation levels throughout the year, ranging from January to December. The solar radiation falls within the range of 5 to 7 kWh/m2/day, which indicates an ample amount for generating solar energy. In terms of solar radiation frequency, 41.37% of the radiation falls within the range of 6-8kWh/m2/day. As indicated in figure 3.4, the lowest solar radiation of 1 to 3kWh/m2/day has a frequency of 1.24%. Thus, the country has consistently high levels of solar radiation all year, indicating a favourable climate for solar energy utilisation. Singh et al developed a method for calculating the energy necessary to make a meal. It was revealed that the energy necessary to vaporise water, boil food, and lose energy to conventional losses were 1474.1kJ, 842.4kJ, and 1895Kj, respectively. As a result, the energy required per meal is 4212KJ, and making three meals per day requires 12636KJ, or 3.5KWh/day.

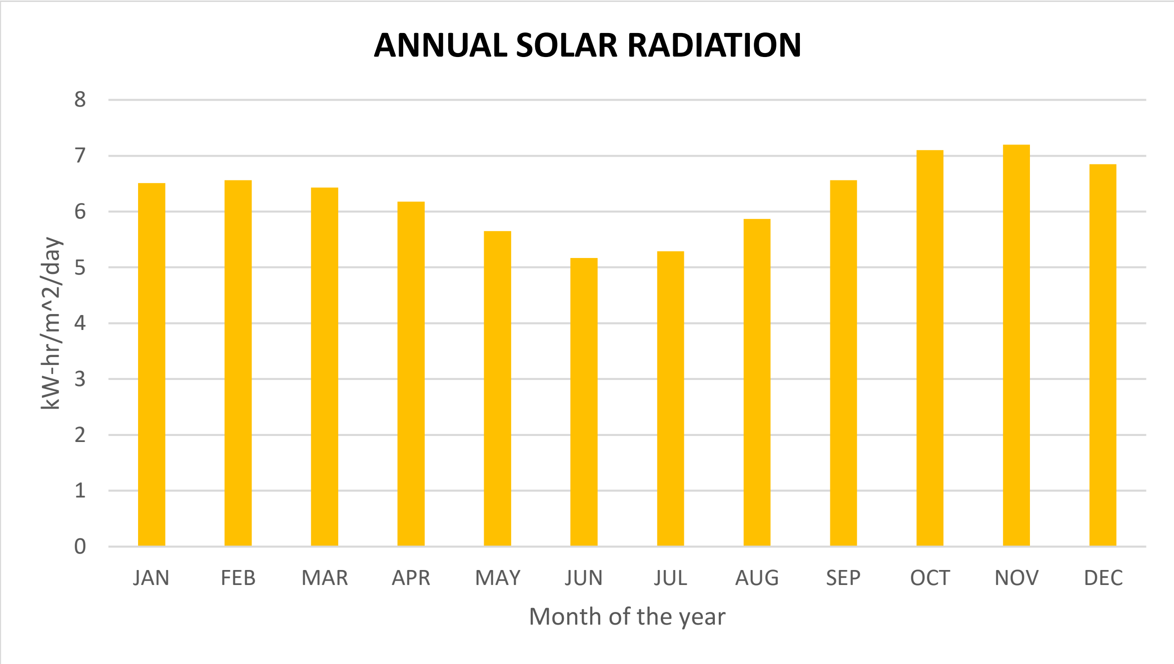

Figure 3-3: Annual solar radiation *source: Author*

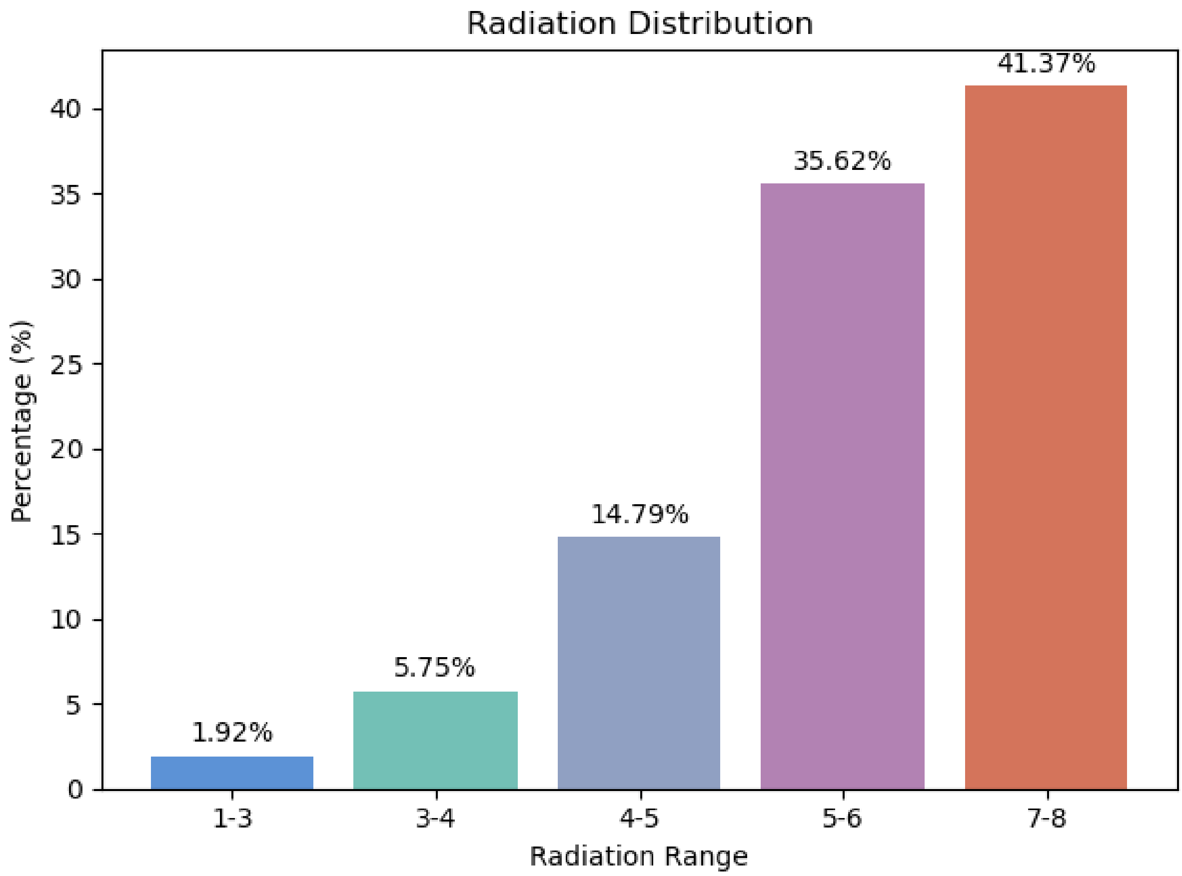

Figure 3-4:Radiation frequency *source: Author*

3.4 Parabolic Solar Cooker System Design.

This study first step was to assess the solar resource and identify the energy required for cooking. Then using parabolic system sizing computations, the design specifications of the solar cooker were found. To determine the performance for the Parabolic solar cooker, the amount of solar energy collected by the parabolic cooker was determined for each day minus the energy required each day. Lastly, the financial computations were done.

3.4.1 The System Parameters of the Parabolic Solar cooker

The Aperture area of was computed by equation (1). The energy required per meal is 4212KJ, therefore preparing three meals per day is 12636KJ, or 3.5KWh/day [44] . Typically, most meals take around 1 hour to cook on average [44]. The average solar radiation in Malawi is approximately 5.6 kWh/m2/day. The efficiency ranges from 30% to 50% [33] .

$$A = \frac{Q}{\cap \times I \times t} \tag{1}$$

Where A: Aperture area

Q: Energy required to cook

I: Average solar radiation

t: Time taken to cook a meal.

n: Efficiency of the reflective material

The diameter of the parabola was computed by:

$$D = \sqrt{\frac{4A}{\pi}} \tag{2}$$

The focal length of a parabolic solar cooker which is the distance from the vertex of the parabolic reflector to its focus point [45]. The depth is 10% of the diameter.

$$f = \frac{D^2}{16 \times depth} \tag{3}$$

Where f: Focal length

D: Diameter

The height of a parabolic solar cooker referred to the vertical distance from the base or focal point of the parabolic reflector to its highest point at the rim. The height was computed by [45]:

$$H = \left(\frac{D^2}{16f}\right) \tag{4}$$

The rim angle of a parabolic solar cooker is the angle formed by the outer edge or rim of the parabolic reflector for a reference line or plane. This angle determines how effectively the sunlight is focused onto the cooking area. A well-designed rim angle ensures that the incoming solar rays are accurately concentrated at the cooker's focal point, where the cooking vessel or container is placed. The rim angle is calculated as[45]:

$$\varphi = tan^{-1}\left(\frac{\frac{8f}{D}}{16\left(\frac{f}{D}\right)^2 - 1}\right) \tag{5}$$

The surface area of a parabolic solar cooker refers to the total area of the parabolic reflector's curved surface. It includes both the interior and exterior surfaces of the reflector. The surface area is given by [45]:

$$A_s = \frac{8\pi}{3} * f^2 * \left[\left\{1 + \left(\frac{D}{4f}\right)^2\right\} - 1\right] \tag{6}$$

The overall thermal efficiency was based on the water boiling test and the maximum time required it will take to reach the maximum required temperature.

$$n_c = \frac{mC_p\Delta T}{IA\Delta t} \tag{7}$$

Where:

η = Thermal efficiency (%)

M= mass of cooking fluid (kg)

Cp= specific heat of cooking fluid (j/kg.K)

ΔT= difference between the maximum and ambient air temperature.

I= average solar intensity (W/m2) during the time interval.

A= is the aperture area (m2) of the cooker.

Δt= time required to achieve the maximum temperature of the cooking fluid (s)

The solar cooker was then modelled using SolidWorks software, bringing it closer to a practical and tangible realization.

3.4.2 Performance of the Parabolic solar cooker

The performance of the parabolic solar cooker was determined by its ability to meet the cooking energy demand in all three seasons, namely the hot dry season, the warm wet season, and the winter season. The amount of solar energy captured is given by equation (8):

$$Solar\ collected = direct\ radiation\ \times Aperture\ Area\ \times Efficiency \tag{8}$$

To measure the ability of the parabolic solar cooker to meet the cooking energy demand was given by equation ((9).

$$Energy\ surplus\ or\ deficit = solar\ energy\ collected - energy\ needed \tag{9}$$

The volume of the storage to meet the energy deficit during periods of low radiation or at night was computed by equation (10). The number of days of storage were determined using the performance of the solar based on solar radiation.

$$V = \frac{Q\ (1 + LR\ \times N)}{\rho\ C_p\ \Delta T} \tag{10}$$

Where V: Volume of storage required.

Q: Energy Required to cook

LR: Thermal losses

Cp: Specific heat capacity of the storage material

N: Number of days for storage

P: Density of the storage material

The parabolic cooker used granite rocks as a sensible heat storage material for energy storage. Table 3.1 shows the thermal properties of granite rocks.

Table 3.1: Thermal and Physical properties of granite

Thermal and Physical properties	
Phase at STP	Solid
Density	2750kg/m3
Ultimate tensile strength	4.8MPa
Brinell Hardness	6 Mohs
Melting point	1260°C
Thermal conductivity	3.2W/mk
Heat capacity	790 J/g.K
Price	£0.031/kg

3.4.3 Financial Analysis of the Parabolic solar cooker

Amazon and Alibaba Express were used to obtain the cost of the cooker. The cost of energy storage used the volume of storage required multiply by the cost of the storage material per volume. The total cost of a Parabolic solar cooker is given by equation (11).

$$Total\ cost = cost\ of\ the\ cooker + cost\ of\ energy\ storage \tag{11}$$

The payback period for the solar cooker was determined by dividing the total cost of the cooker by the monthly savings achieved through its usage instead of LPG. The money saved was calculated based on the cost savings from using the solar cooker in place of LPG. Given the parameters below the monthly saving was £130.15 as shown in equation (12).

$$Savings(S) = Pt\ \times Ml\ \times Cl \tag{12}$$

Where Pt: percentage of time LPG is used (25% of the day)

Ml: monthly mass of LPG consumed (274kg/day)

Cl: cost of LPG per kg (£1.90/kg)

Thus, the payback period was given by equation (13)

$$Payback\ Period\ (PP) = \frac{Total\ cost\ of\ solar\ cooker}{Savings} \tag{13}$$

Net Present Value (NPV) assessed the profitability of the solar cooker. NPV was computed by equation (14) where S_Y is the saving per year, $C_{o\,\&m}$ is the cost of operation and maintenance, C_{sv} is the salvage value of the solar cooker, and C_C is the capital cost.

$$NPV = S_Y - C_{o\,\&m}\left[\frac{(1+d)^n - 1}{d\,(1+d)^n}\right] + \frac{C_{sv}}{(1+d)^n} - C_C \tag{14}$$

To determine the cost of preparing meals using the panel type solar cooker, the total annual cost, encompassing both the capital investment and maintenance expenses associated with owning a solar cooker, was divided by the total number of meals cooked in a year as shown in the equation (15).

$$cost\ of\ cooking = \frac{capital\ cost + maintenance\ cost}{Number\ of\ meals\ per\ year} \tag{15}$$

3.5 Design of a Panel type solar cooker

This study first step was to assess the solar resource and identify the energy required for cooking. Then using panel type design computations, the PV array characteristics of the solar cooker were found. To determine the performance and financial viability for the panel type solar cooker PVsyst software was used.

3.5.1 System Components of the Panel Type Solar cooker

3.5.1.1 Calculating number of solar panels

The number of solar panels required for meet the energy demand of 3.5kWh/day was computed using the following equations. The design process involved finding the system design charge current which depended on the system voltage of 12V.

$$System\ design\ charge\ current\ (Ah) = \frac{Energy\ demand\ for\ cookin(Wh)}{system\ voltage\ (V)} \tag{16}$$

The charge current is computed by equation (17).

$$Charge\ current\ (A) = \frac{System\ design\ charge\ current\ (Ah)}{solar\ insolation\ hours\ in\ Malawi\ (h)} \tag{17}$$

The actual number of panels required is computed by equation (18).

$$Number\ of\ panel = \frac{Charge\ current\ (A)}{rated\ current\ output\ of\ available\ modules\ (A)} \tag{18}$$

3.5.1.2 Calculating number of batteries

The number of batteries were calculated using the equation (19) and (20).

$$\begin{aligned} &Battery\ Charge\ current\ required \\ &\quad = design\ charge\ current\ \times days\ of\ autonomy \end{aligned} \tag{19}$$

$$No.of\ Batteries = \frac{Charge\ Current\ required}{Battery\ capacity} \tag{20}$$

3.5.2 Financial Analysis of the Panel type solar cooker

PVsyst performed a financial analysis of the project. The system costs, maintenance expenses, and any subsidies or incentives available were inputted to determine the system's financial viability. To determine the cost of preparing meals using the panel type solar cooker, the total annual cost, encompassing both the capital investment and maintenance expenses associated with owning a solar cooker, was divided by the total number of meals cooked in a year as shown in the equation (12).

3.6 Comparison of techno-economic analysis of solar cookers and conventional cooking fuels using TOPSIS

To conduct a comprehensive comparison of the solar cookers and domestic cooking technologies the results obtained from the performance and financial analysis of the solar cooker were used.

3.6.1 TOPSIS Algorithm

The first step was creating a matrix consisting of M alternatives and N criteria as shown in equation (21). Where I = 1….m and j =1…. n where as a_{ij} is a measure of performance of the ith for the jth criterion. In this case the M alternatives included Parabolic solar cooker, Panel type solar cooker, Charcoal and Firewood. The criteria and weights are shown in figure 3.5.

$$a_{ij} = M \times N \tag{21}$$

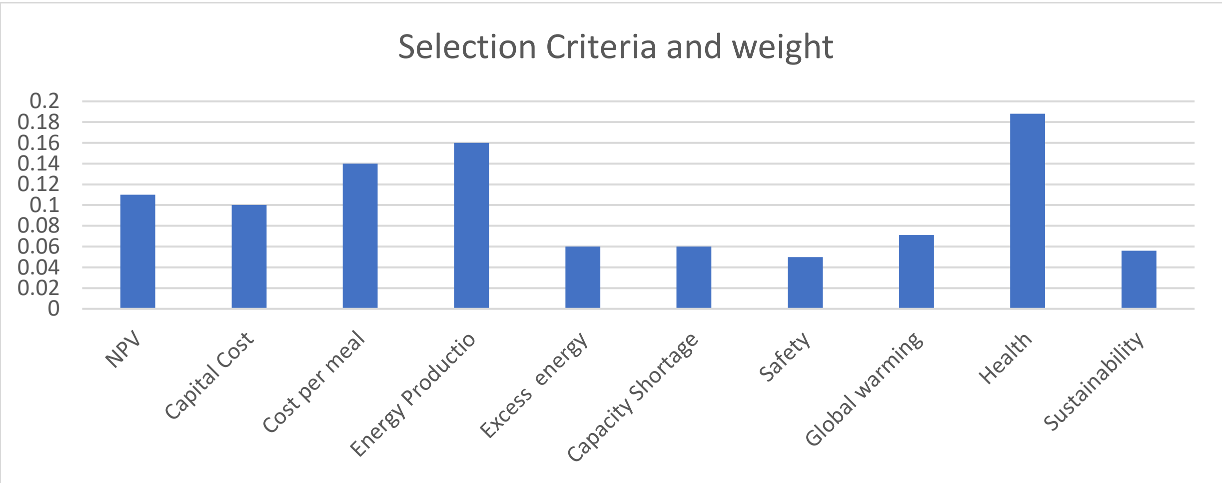

Figure 3-5: Selection criteria and weight

The Matrix was then normalized using equation (22). Each metric j for each cooking fuel i is normalized to be in between 0 and 1.

$$\alpha_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m}(a_{ij}\ )^2}} \tag{22}$$

The next step was to calculated the weighted normalized decision matrix using equation (23). The criterias had weights that added up to 1. The weights were derived from Chisale et.a.l [8]and Patel et al [46] .

$$X_{ij} = \alpha_{ij} \times w_j \tag{23}$$

The next step was to determine the ideal and non ideal value for each criterion using equation (24). The aim was to find the find the maximum and minimum for each criterion among the cooking fuels. The lowest value of the criterion was non ideal and the highest value was the ideal.

$$\begin{aligned} X_j^b &= Max_{i=1}^{m} Xij \\ X_j^w &= Min_{i=1}^{m} Xij \end{aligned} \tag{24}$$

Where X_j^b was the ideal value of the criterion and X_j^w is the non-ideal value of the criterion. The upper subscripts b and w represent best and worst value respectively.

The Euclidean distance between the cooking alternative and the ideal/ non ideal value of the criterion was calculated using equation (25). This is the distance between the value of each criterion for the cooking alternative and the ideal/ non ideal value of the criteria among the cooking alternative.

$$d_i^b = \sqrt{\sum_{j=1}^{N} (X_{ij} - X_j^b)^2} \ or \ d_i^w = \sqrt{\sum_{j=1}^{N} (X_{ij} - X_j^w)^2} \tag{25}$$

Each cooking alternative then had an ideal Euclidian distance (d_i^b) and non-ideal Euclidean distance (d_i^w). And a sum of the ideal Euclidian distance and non-ideal Euclidean distance was found. For each cooking alternative the similarity to the non-ideal solution was calculated using equation (26). The higher the value of the similarity, the higher the ranking order. This means that the cooking alternative with a high similarity has the best performance.

$$S_i = \frac{d_i^w}{d_i^w + d_i^b} \tag{26}$$

Finally, the cooking alternatives were ranked according to the score from TOPSIS analysis. The best cooking option is the one with higher score in its criterions.

3.7 Chapter Summary

This chapter highlighted the methodology employed to conduct a techno-economic analysis of the parabolic and panel type solar cooker. It described the design stages for parabolic and panel-type solar cookers. The performance of the solar cooker and the economics associated were determined using the design specification of the parabolic solar cooker and PV array characteristics. Using the techno-economic results, TOPSIS multi-criteria tool was used to determine the optimal cooking option. The results of the analysis are discussed in the following chapter.

4. RESULTS AND DISCUSSION

This chapter discusses the findings of the study. It highlights the design specifications of the parabolic solar cooker and the PV array characteristics of the panel type solar cooker. It further discusses the performance of the solar cooker in different months of the year as well as the costs and financial metrics associated with each solar cooker.

4.1 Parabolic Solar cooker design and financial analysis

4.1.1 Design specifications

Table 4.1 presents the design specifications for the parabolic cooker calculated using equation (1) to (8). Detailed calculations are shown in appendix A, section 7.1. The table below provides essential information about the parabolic cooker's dimensions, including the aperture area, diameter, focal length, height, radius, rim angle, and surface area.

Table 4.1: Parabolic cooker design specification

Parameter	Size
Aperture area	1.78 m^2
Diameter	1.505 m
Focal length	0.94 m
Height	0.1506 m
Radius	0.752 m
Rim angle	43.6^0
Surface area of the Parabola	1.18m^2
Efficiency	74%

4.1.2 Visual presentation of the parabolic solar cooker

By utilizing Solid Works, a powerful computer-aided design (CAD) software, the parabolic solar cooker was visualized and constructed virtually. This allowed for precise modelling of the cooker's shape, dimensions, and focal properties. Figure 4.1 shows the side view of the parabolic cooker and figure 4.2 shows the back view of the parabolic cooker.

Figure 4-1: Side view of the parabolic solar cooker

Figure 4-2: Back view of a parabolic solar cooker

4.1.3 Performance of the parabolic solar cooker based on daily solar radiation.

This section highlights the performance of the parabolic solar cooker throughout the year by examining the solar energy collected in the peak month of each season in the location. The performance of the other months is shown in appendix 7.1A.

4.1.3.1 Performance of the parabolic solar cooker in hot dry season

During hot dry season which peaks in October, the all-sky radiation which encompasses both direct sunlight and diffuse radiation scattered by clouds ranges between 4 and 8 kWh/m2/day as shown in figure 4.3. In contrast, clear sky radiation ranges from 7 to 8 kWh/m2/day. This is the solar energy received solely on days with unobstructed sunlight.

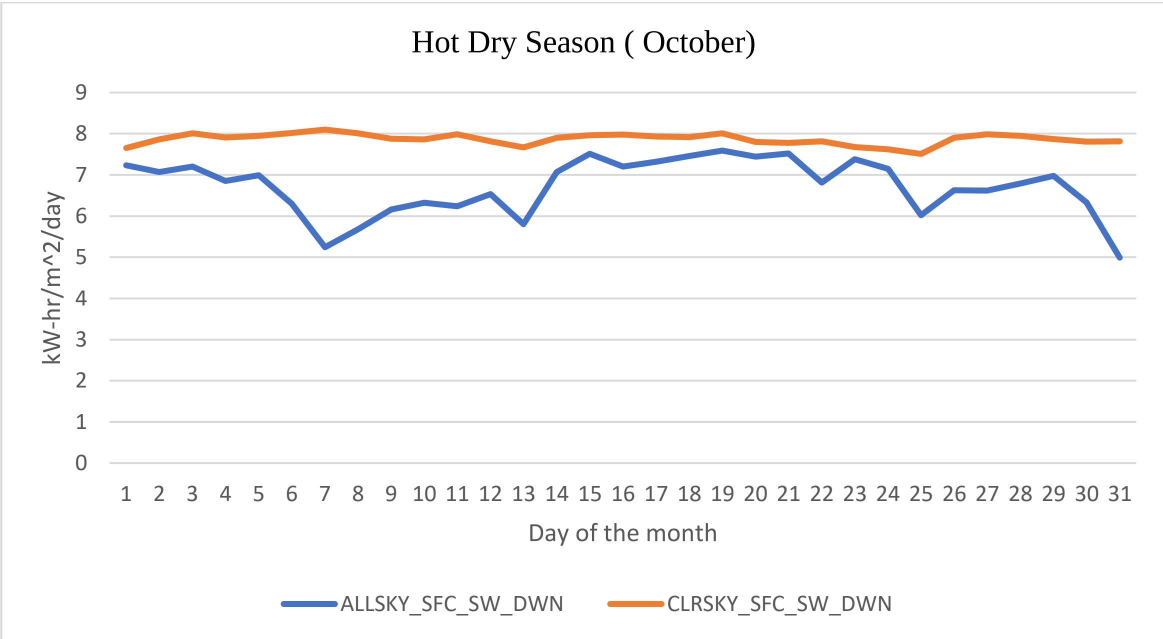

Figure 4-3: Solar radiation in October

Figure 4.4 displays the performance of the cooker in October. The energy required to cook is 3.5 kWh/day, which is needed for cooking three meals in a day. Meanwhile, the solar collected represents the energy available from the solar cooker which is found by multiplying solar radiation by aperture area and cooker efficiency. Solar collected fluctuates throughout each day due to variations in solar radiation daily. When the solar collected is positioned above the energy required to cook line on a particular day, it indicates that there is sufficient and surplus energy available for cooking purposes. Conversely, if the solar collected falls below the energy required to cook, it signifies a lack of solar radiation energy, rendering it insufficient for cooking. For the month of October, the solar collected is over the energy required for cooking thus there is no day when the parabolic solar cooker is failing to meet the energy required for cooking.

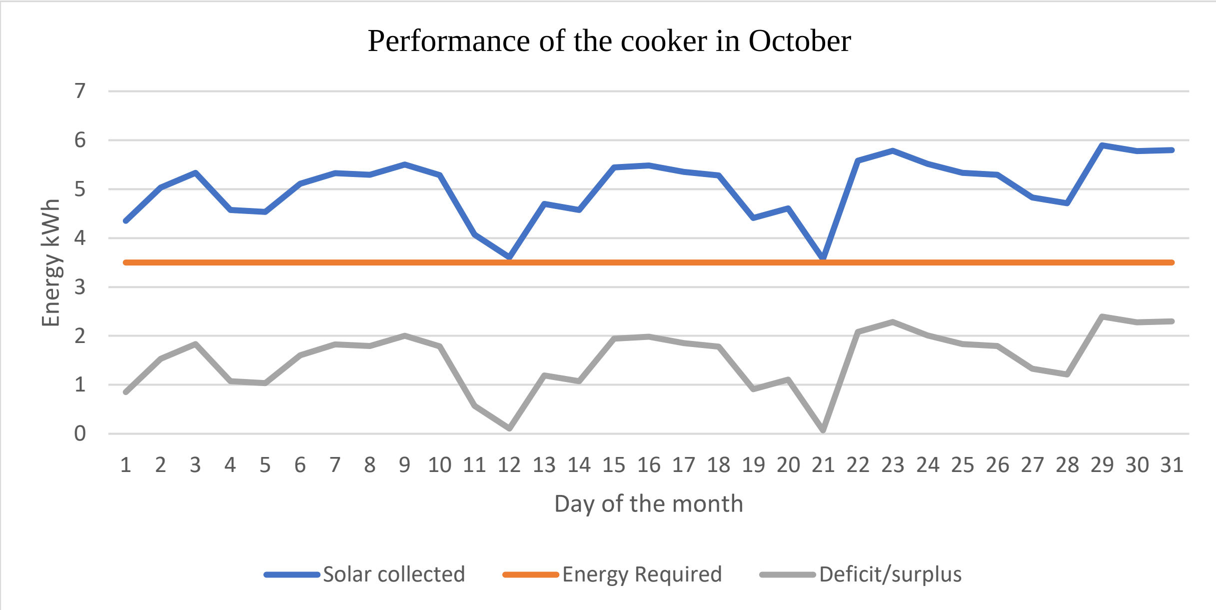

Figure 4-4: Performance of the cooker in October

4.1.3.2 Performance of the parabolic solar cooker in warm wet season

During the warm wet season which peaks in January, all sky solar radiation varies between 2.5 and 6.7 kWh/m2/day as shown in figure 4.5. Due to increased precipitation during this period, there is significant fluctuation in solar radiation throughout the day. Despite the rainfall, the clear sky solar radiation remains relatively high, ranging from 6 to 8 kWh/m2/day.

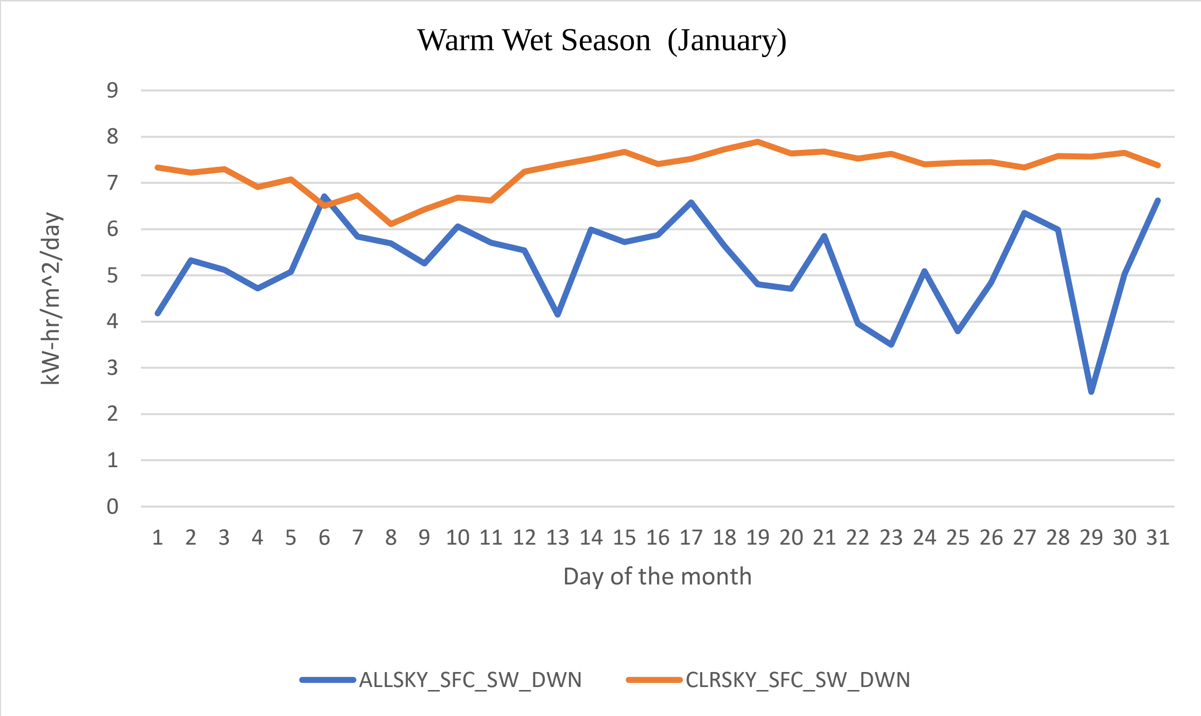

Figure 4-5: Solar radiation in January

Warm wet season is characterized by frequent cloudy days due to precipitation, leading to a significant number of days with inadequate solar radiation. During this period the clouds are prevalent, and sunlight is limited. Thus, the solar parabolic cooker may experience difficulties in harnessing sufficient energy to meet the energy demand. As a result, there are instances during the month when the cooker may not reach its maximum potential due to insufficient solar radiation as shown in figure 4.6. During these days when there is insufficient energy supply, a storage system is needed to meet the energy demand. By incorporating storage, any excess energy generated on days with high solar radiation can be stored and subsequently used during periods of low solar radiation, ensuring a consistent energy supply for cooking.

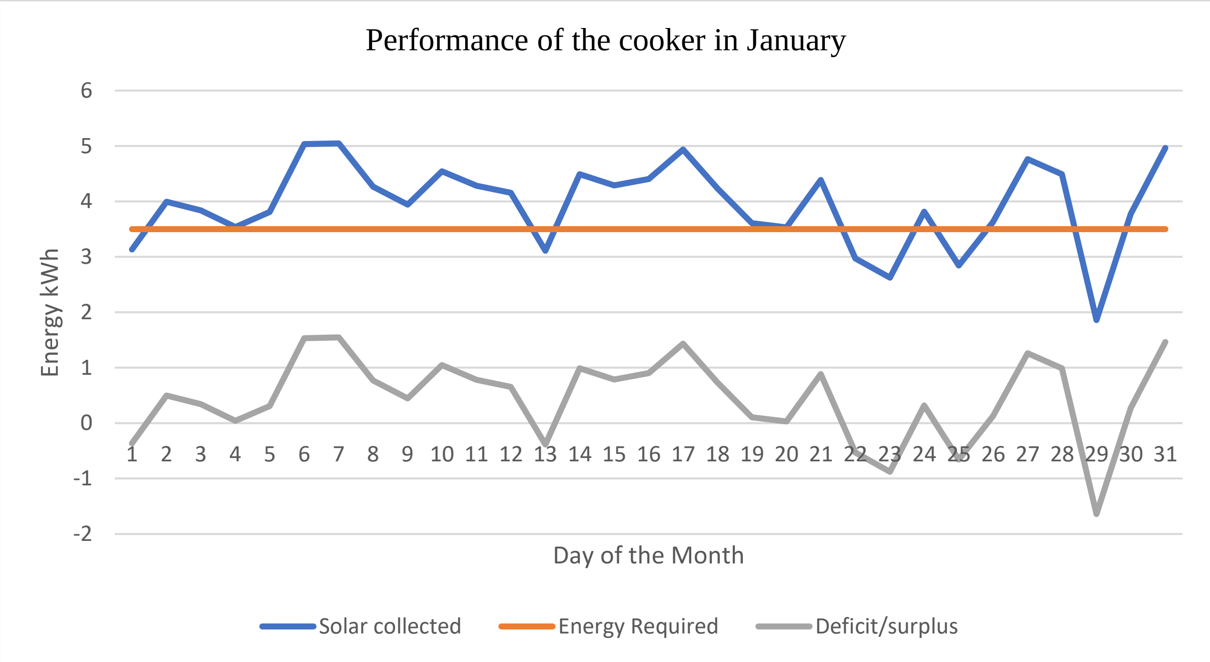

Figure 4-6: Performance of the cooker in January

4.1.3.3 Performance of the parabolic solar cooker in winter season

During the winter season which peaks in June, there is a decrease in solar radiation. All sky solar radiation levels range from 3 to 5.5 kWh/m2/day as shown in figure 4.7. This measurement represents the total solar radiation received during both clear and cloudy days. It is noticeable that the values are lower compared to those in the hot dry season and warm wet season. The clear sky radiation during winter ranges from 5 to 6 kWh/m2/day.

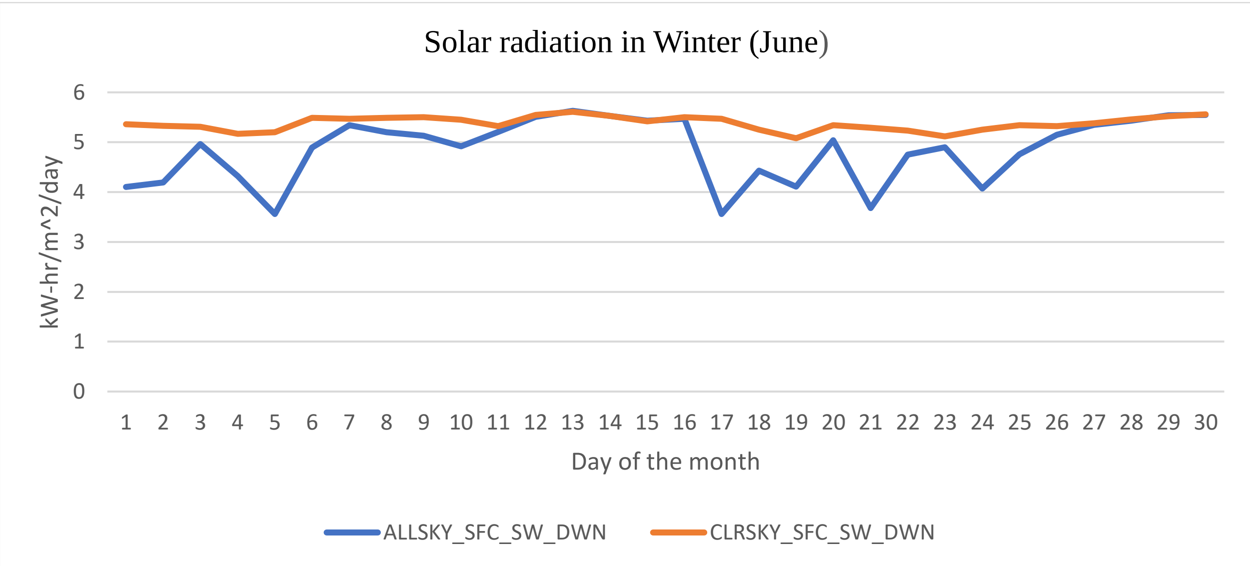

Figure 4-7: solar radiation in June

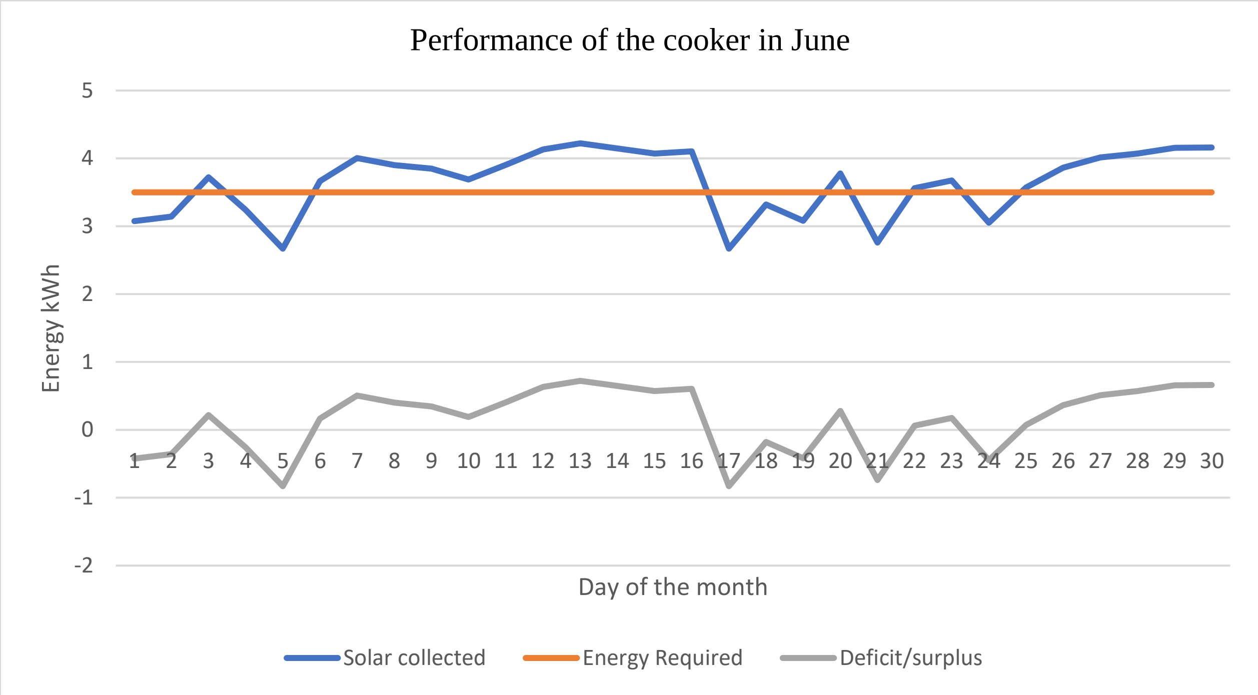

Figure 4-8: Performance of the cooker in June

Similarly, in the winter season peaking in June, there was also an energy deficit, likely due to reduced solar radiation. The solar cooker is only able to collect 4kWh in most of the days thus missing some of energy required for cooking. To ensure a continuous energy supply for the 3-day period from 17th to 19th June approximate energy storage needed is calculated below.

$$E = \frac{(Q + LR) \times N}{n} = \frac{(3.5 + 0.35) \times 3}{0.74} = 15.6kWh$$

Where N is the number of days with insufficient radiation, LR is the energy loss, and n is the efficiency of the solar cooker. The volume of the granite stone required to store the energy for 3 days was found using the calculation below. The density and specific heat capacity of granite is from table 3.1.

$$V = \frac{E}{\rho C_P \Delta T} = \frac{15.6 \times 3.6 \times 10^6}{2750 \times 10^3 \times 790 \times (250 - 180)} = 0.369m^3$$

Thus, the mass of granite required for storage is $0.369m^3$ x 2750 which is 1014.75kg.

4.1.4 Financial analysis of the parabolic cooker

The financial analysis was calculated from equation (11) to (15). The parabolic cooker's total capital comprises the cost of the cooker as well as the cost of energy storage. When acquired from big online markets such as Alibaba and Amazon, the parabolic solar cooker cost roughly £140. The total cost of 1014.75kg of granite is £32, the cost of granite was £0.031/kg as shown in table 3.1. Thus, the total cost of the parabolic cooker was £172 as shown in table 4.2 The reflecting material was the most significant component, accounting approximately 50% of the entire cost. The remaining cost was split among support structure, insulation and miscellaneous.

Table 4.2: Cost of the parabolic solar cooker

Cost of the parabolic solar cooker	
Parabolic Solar cooker	£140
Granite energy storage	£32
Total cost	£172

Table 4.3 shows the payback period and Net present Value. The payback period of the solar cooker was calculated by dividing its total cost (£172) by the monthly savings it provided compared to using LPG, which amounted to £130.2 as stated in equation (10). As a result of this calculation, the payback period was determined to be 1.32 years. The calculated net present value from equation (14) amounted to £1076.04. This value was obtained by considering an annual savings of £1560, which was derived by multiplying the monthly saving of £130.2 by 12 months in a year. The calculations were made using a discount rate of 10%, and the analysis considered a 5-year lifespan for the solar cooker, with a salvage value equivalent to 30% of the total initial capital cost.

Table 4.3: Financial analysis results

Financial analysis results	
Payback period	1.32 years
Net present value	£1076.04

The total cost cooker divided by the number of meals in a year yielded the cost of cooking a meal using a parabolic solar cooker. Because an energy storage system is included into the design, the cooker can make three meals every day for 365 days. The entire cost is £172, thus the cost per meal is £0.157, which is extremely affordable.

4.2 Panel Solar cooker design and financial analysis

4.2.1 PV Array characteristics

The PV characteristics, as shown in table 4.4, provide information about the PV module and battery configuration used in the system. The number of PV modules and batteries used were calculated from equation (16) to (20). Detailed calculations are shown in appendix 7.2A.

A unit with a nominal power of 400Wp was chosen from the PVsyst database for the PV module selection. To meet the energy demand, two units were required, resulting in a total nominal power of 800Wp. In terms of battery selection, a lead-acid gel battery from the PVsyst database was used. A total of 4 batteries with individual capacities of 296Ah were deemed essential, resulting in a notional capacity of 1184 Ah. The entire PV system, comprising the PV modules and batteries, will occupy an area of approximately 4m^2.

Table 4.4: PV array characteristics

User's needs	Daily energy demand	3.50kWh
	Average Power	146W
Battery set characteristics	Battery Properties	12V 296Ah Pb sealed
	Number of batteries	4
	Stored energy (80% DOD)	11.4kWh
	Battery pack voltage	24V
	Battery connection	2 in series, 2 in parallel
PV array	Panel properties	400W si-mono 72 cells panel
	Number of modules	2
	Panel connection	2 Strings of 1 module
	Nominal power	800Wp
	Area	4m^2

4.2.2 Performance of a panel type solar cooker.

The reference incidence energy in the collector plane used in PVsyst falls within the range of 5 to 7 kWh/m2/day, which indicates an ample amount for generating solar energy. It is worth noting that the country experiences consistently high levels of solar radiation throughout the year, indicating a favourable environment for the panel type solar cooker. Figure 4.9 illustrates the solar radiation levels and reference incident energy throughout the year, ranging from January to December. The energy output of the PV array varies, corresponding to changes in solar radiation throughout different months. The reference incident energy is highest in October and lowest in January.

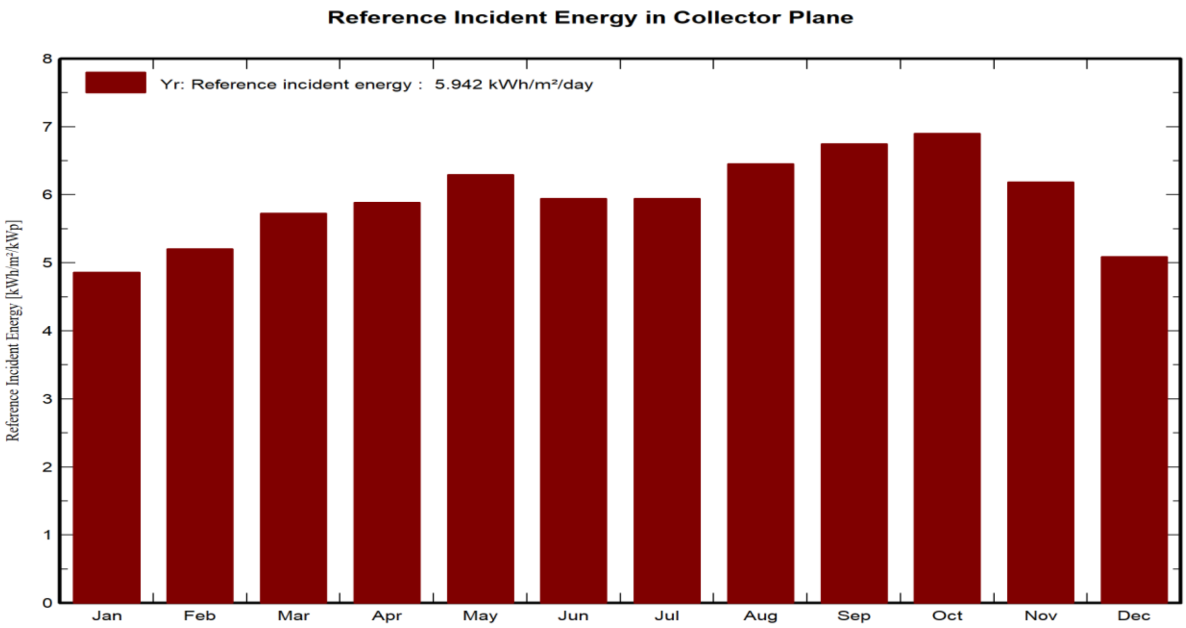

Figure 4-9: Reference Incident Energy in Collector Plane

The daily input/output diagram in Figure 4.10 shows the relationship between the amount of solar radiation received and the power generated by the PV array during the day. This figure vividly depicts how changes in solar radiation affect the array's power generation. Increased power generation occurs when the PV array receives more solar energy. In contrast, as solar radiation falls, so does the amount of power generated by the array.

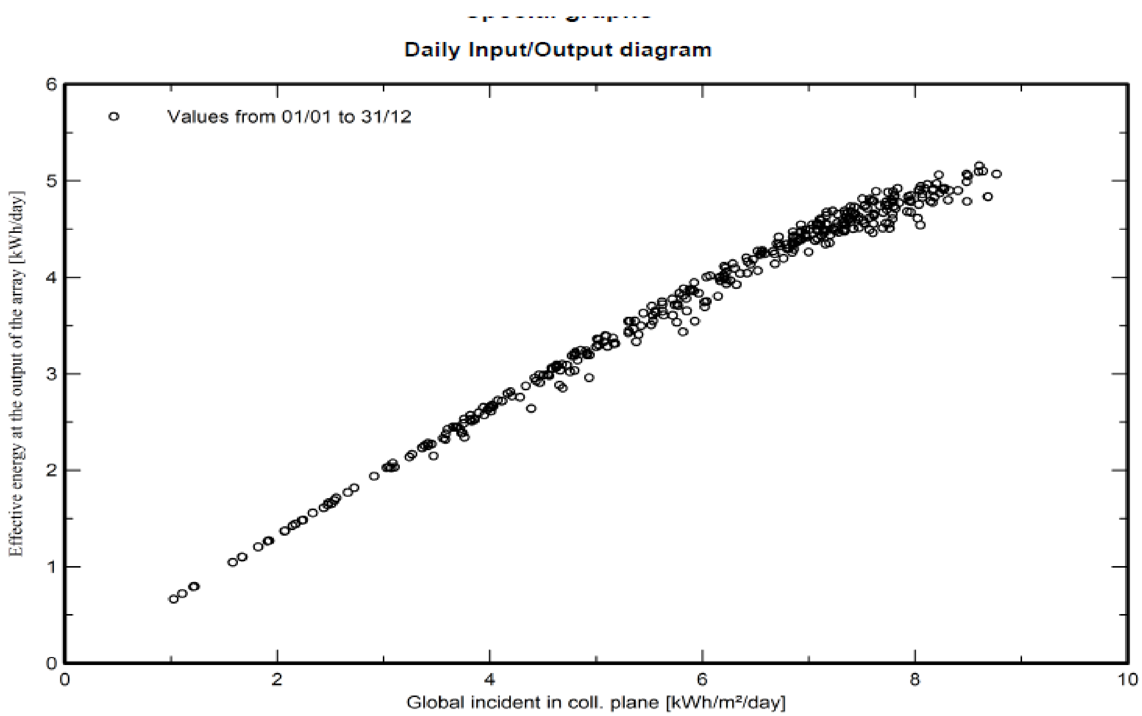

Figure 4-10: Daily input/ output diagram

Figure 4.11 shows normalized energy production per installed kWp. The energy produced is approximately 5.5kWh/kWp/day however the energy supplied to the user is approximately 3.9kWh/kWp/day. The remaining energy is lost through system losses and collection loss which accounts for 0.73 and 1.26kWh/kWp/day respectively. The panel type solar cooker is able to provide 3.5kWh which is the energy required for cooking as on average 3.9kWh/kWp/day is supplied to the user

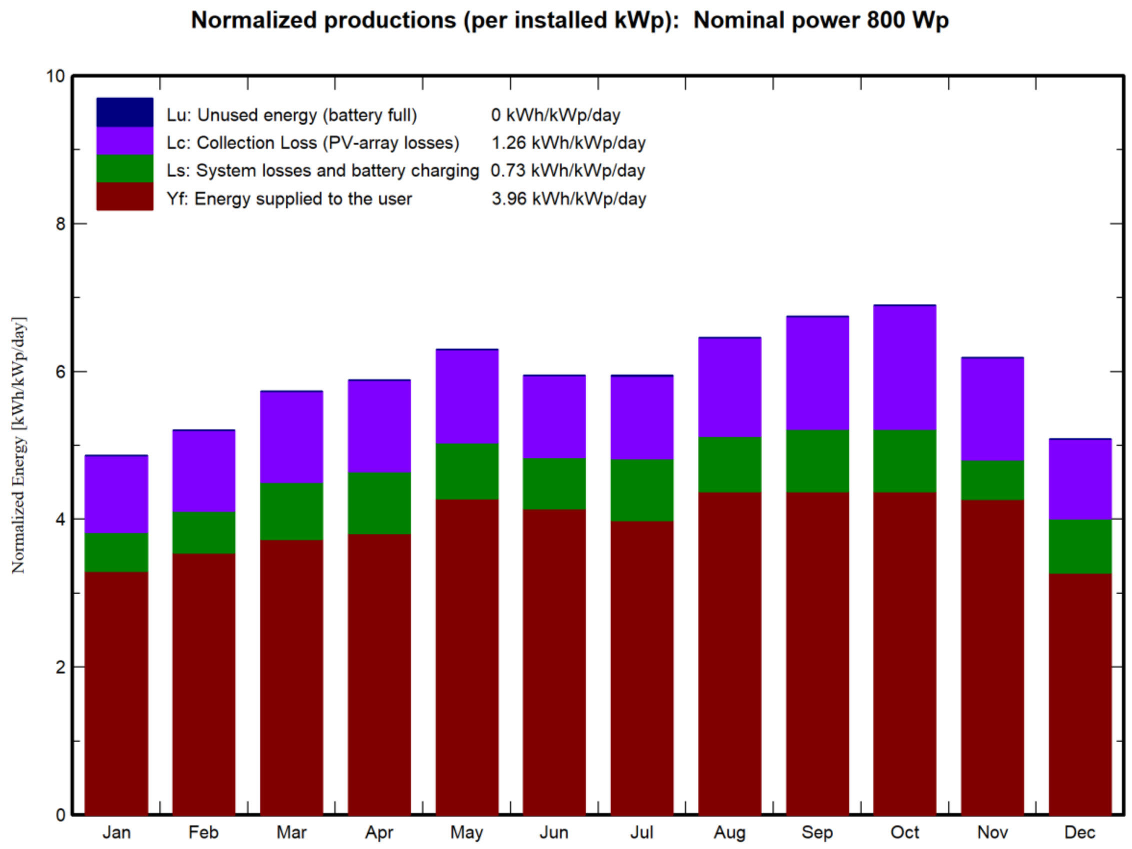

Figure 4-11: Nominalized production per installed kWp

The solar fraction and performance ratio are depicted in Figure 4.12. The performance ratio evaluates a photovoltaic (PV) system's overall efficiency and performance. It is determined by dividing actual energy output by expected energy output under standard test conditions (STC). PR considered both PV array and battery losses. A greater performance ratio indicates improved system performance and efficiency, whereas a lower performance ratio indicates lower-than-expected energy output. A well-designed and adequately maintained PV system should have a performance ratio of 0.75 to 0.85. The PR for the panel type solar cooker was 0.755. The solar fraction of the cooker was 0.97, which remained rather stable throughout the year. This demonstrates that the solar cooker can meet the energy need for cooking throughout the year.

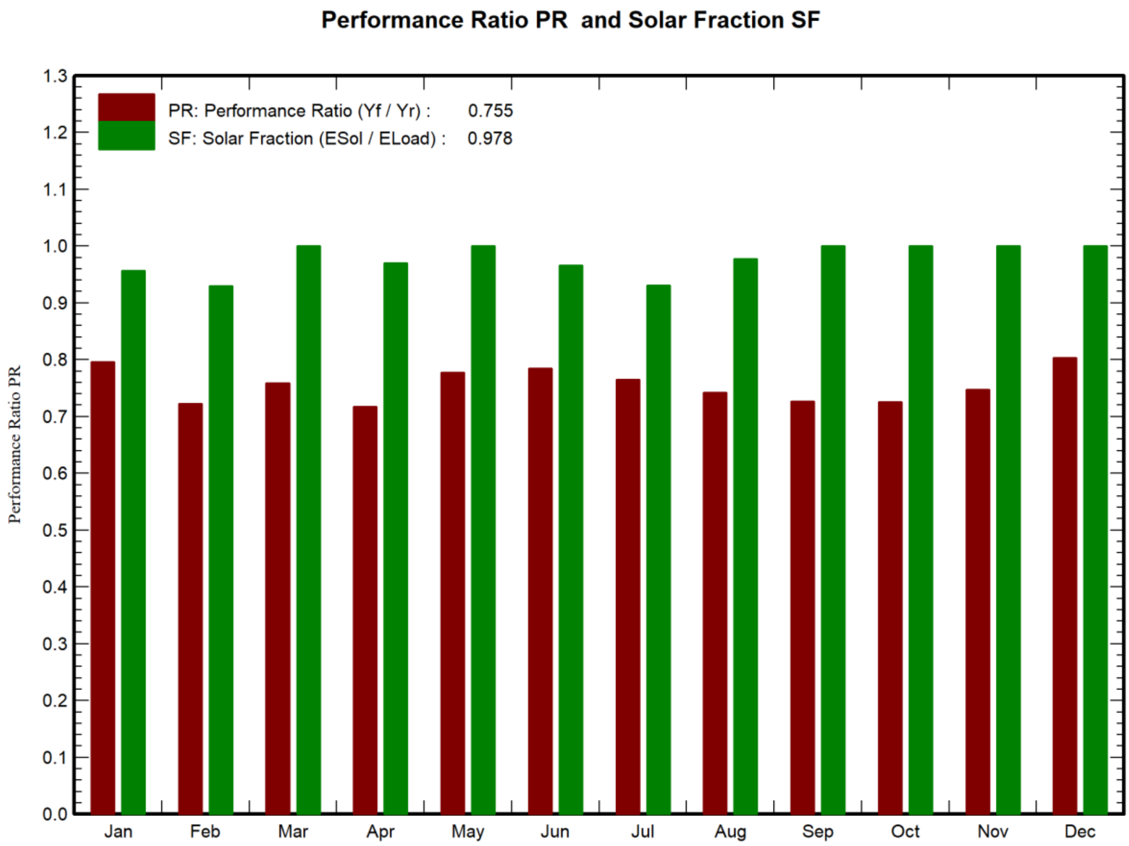

Figure 4-12: Performance Ratio and Solar Fraction

4.2.3 Financial Analysis of the Panel type solar cooker.

The cost breakdown for the project includes the PV modules at £310, the PV module support at £20 and battery costs at £134. The cooker needed to consider a total investment of £866. The annual operating cost of the panel type solar cooker is £50.

Table 4.5: Cost of the system

Cost of the system			
Item	Quantity units	Cost (£)	Total (£)
PV modules	2	155	310
Support for modules	2	10	20
Batteries	4	134	536
Total Depreciable asset			866
Operating cost	-	50	50

Table 4.4 below provides a comprehensive financial analysis of the project over a 20-year period. The analysis considers a 10% inflation rate and a yearly discount rate of 10%. Based on this, the payback period for the initial investment is estimated to be 2.5 years. This indicates that within a span of 2.5 years, the project is expected to generate enough revenue to cover its total investment cost. Moreover, the financial evaluation reveals a net present value (NPV) of £2346.4. NPV indicates the project's profitability by considering the present value of expected cash flows and expenses over the 20-year period, accounting for the discount rate. A positive NPV value signifies that the project is financially viable and expected to yield positive returns. Furthermore, the internal rate of return (IRR) for the project is calculated to be 49.29%. IRR represents the annualized percentage return that the project is expected to generate over its lifetime. A high IRR percentage, such as 49.29%, signifies a highly attractive investment opportunity, indicating strong potential for substantial returns on investment.

Considering the results of the financial analysis, including the short payback period, positive NPV, and high IRR, it is evident that this project is a viable option for cooking in the country. The figures suggest that the investment in this solar cooking project is likely to be financially rewarding over the long term, making it an attractive and feasible choice for implementation.

Table 4.6: Financial analysis results

Financial Analysis results	
Net Present Value	£2346.4
Payback Period	2.5 years
IRR	49.29%

Figure 4.13 depicts the total cash flow throughout the length of the project. There is a negative cash flow in the first year, indicating that the project requires an initial expenditure. However, beginning in 2026, the cash flow becomes positive, indicating that the project is beginning to generate revenue and recoup its initial expenditure. As the project proceeds, the positive cash flow grows progressively over time, eventually reaching an amazing £6000 by 2043. This upward trend in cumulative cash flow illustrates the project's ability to not only recoup its initial investment but also produce substantial financial advantages over time.

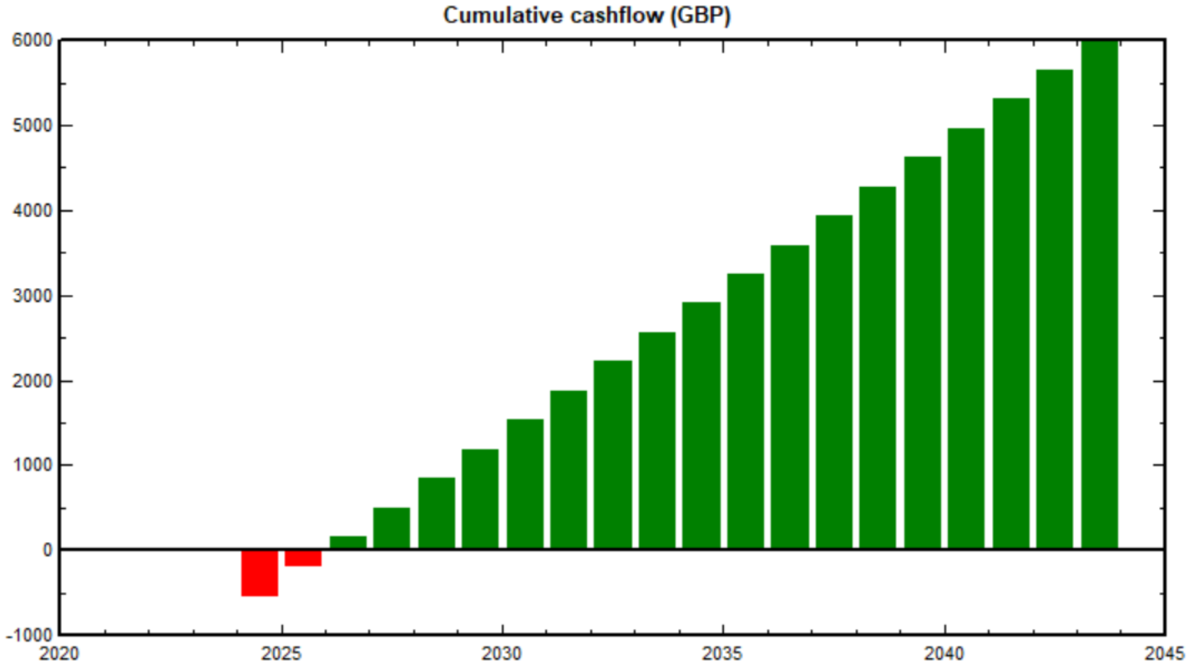

Figure 4-13: Cash savings

The cost of producing a meal using the panel type solar cooker, which consists of panels and batteries, was determined by dividing the total cost of the panel type cooker, which is £866, by the number of meals prepared per year, which is 1095, yielding a cost of £0.79 per meal.

4.3 Comparison of techno-economic analysis of solar cookers and conventional cooking fuels using TOPSIS

Table 4.7 displays a matrix of the technical, economic, and environmental analysis results that were used as selection criteria. The technical and economic results were based on the methodology's analysis, while the environmental results were based on existing literature. For Excess energy (EE), Energy Shortage backup (ES), Safety (S), Global warming reduction (GWR), Health (H), and Sustainability (SUS), a scale as shown in table 4.8 was used.

Table 4.7: Technical, Economic & Environmental results

	Economic results			Technical Results				Environmental Results		
	NPV (£)	Initial Cost (£)	Cost £ /meal	Eff %	EE	ES	S	GWR	H	SUS
Parabolic Solar Cooker	1076	172	0.157	0.74	5	5	5	5	5	5
Panel Solar Cooker	2346	866	0.79	0.75	5	5	5	5	5	5
Charcoal	0	365	0.325	0.25	1	1	3	2	2	2

Firewood	0	0	0	0.1	1	1	1	1	1	1

Table 4.8: Measuring Scale

Measuring Scale	
1	Low
2	Below Average
3	Average
4	Good
5	Excellent

Table 4.9 displays the normalised weighted matrix, which was derived by multiplying the normalised matrix by the weight of the criteria. The weights of the criteria is shown in figure 3.5. The maximum and minimum values for each criterion among the cooking alternatives are X_j^b and X_j^w respectively. The distance between the value of each criterion for the cooking alternative and the best/worst value of the criteria among the cooking alternatives was calculated using these values. A total of the Euclidean distances for the best / worst value of the criterion was determined for each possibility. Table 4.10 displays the ranking of the cooking alternatives as well as their ratings in respect to the worst alternative value for each cooking option.

Table 4.9: Normalized Weighted Matrix

	NPV (£)	Cost	Cost £/m	Eff	EE	ES	S	GWR	H	SUS
Parabolic	0.0462	0.02	0.0252	0.11	0.04	0.0414	0.0325	0.0469	0.12596	0.0375
Panel	0.1001	0.09	0.1274	0.11	0.04	0.0414	0.0325	0.0469	0.12596	0.0375
Charcoal	0	0.04	0.0518	0.04	0.01	0.0084	0.0195	0.0189	0.05076	0.0151
Firewood	0	0	0	0.01	0.01	0.0084	0.0065	0.0098	0.02632	0.0078
X_j^b	0.1001	0	0	0.11	0.04	0.0414	0.0325	0.0469	0.12596	0.0375
X_j^w	0	0.09	0.1274	0.01	0.01	0.0084	0.0065	0.0098	0.02632	0.0078

Table 4.10: Cooking alternatives ranking.

	X_j^b	X_j^w	$X_j^b + X_j^w$	$X_j^w / (X_j^b + X_j^w)$	Ranking
Parabolic Solar	0.062184	0.204447	0.266631	0.76678	1
Panel Solar Cooker	0.156562	0.184971	0.341533	0.541589	2
Charcoal	0.169859	0.099569	0.269428	0.369558	4
Firewood	0.184971	0.156562	0.341533	0.458411	3

According to the TOPSIS analysis, the parabolic solar cooker emerged as the most favourable cooking option, outperforming the panel type solar cooker, firewood, and charcoal in terms of benefits and suitability for cooking. This implies that in the country under consideration, the parabolic solar cooker is the optimal choice, providing significant advantages over the other alternatives.

4.4 Results verification using sensitivity analysis.

The sensitivity analysis assessed the quality and robustness of the decision to cook with a parabolic solar cooker. The study was carried out to determine whether the parabolic solar cooker is the best cooking option that can be chosen even when the weights of the criteria are changed. The first scenario weight shown in figure 3.5 were compared to two other possibilities scenario in this case. In the second scenario, the economic, technical, and environmental weights were 35%, 35%, and 30%, respectively. The economic study weighed 40%, the technical study 35%, and the environmental study 25% in the third scenario. Table 4.11 shows changed weights for both scenarios. To find the weight of each criterion, the percentage of the economic, technical and environment category was divided by number of criteria in that category. For example, to find the weight of the environment category for scenario 2, 30% was divided by 3.

Table 4.11: Weights for scenario 2 and 3

	Economic			Technical				Environmental		
	NPV (£)	Cost (£)	Cost £/ m	Eff	EE	ES	S	GWR	H	SUS
Scenario 2	0.116	0.116	0.116	0.087	0.087	0.087	0.087	0.1	0.1	0.1
Scenario 3	0.083	0.083	0.083	0.0625	0.0625	0.0625	0.0625	0.16	0.16	0.16

The sensitivity analysis findings acquired using the same TOPSIS analysis method demonstrated that even when the weight of the criterion was adjusted, the results produced remained consistent and robust. Even when the weights were altered, the parabolic solar cooker was the best choice. Detailed calculations are shown in appendix 7.3. Figure 4.14 shows the results from the sensitivity analysis.

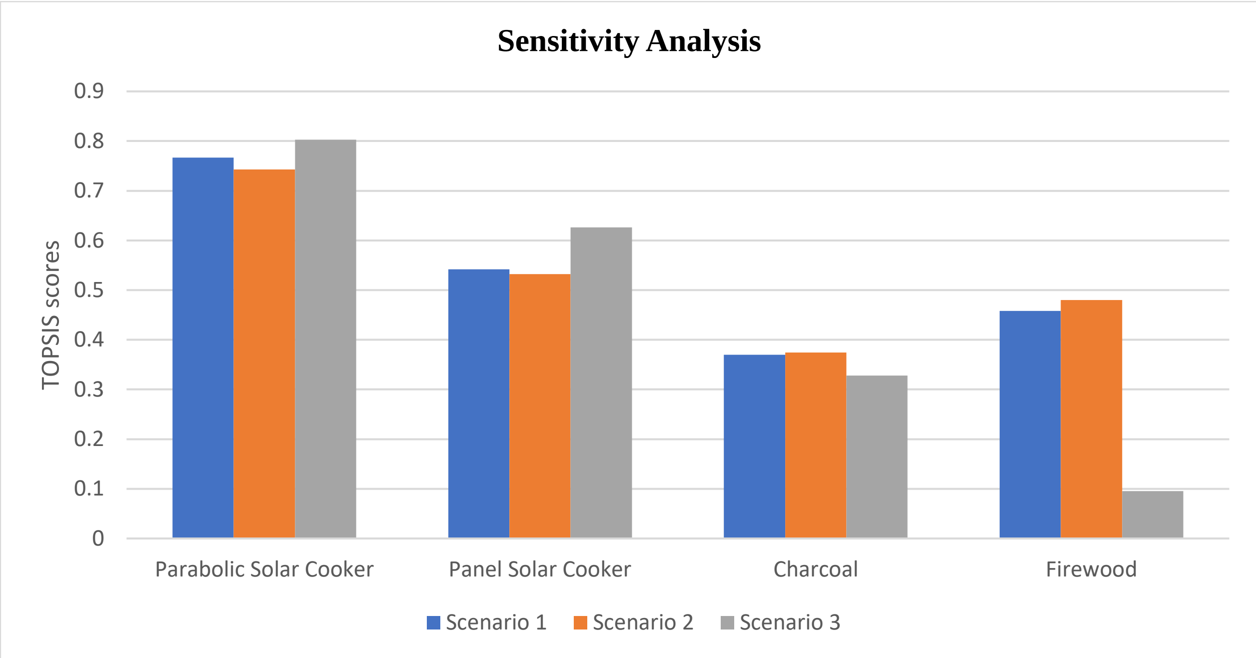

Figure 4-14:Sensitivity Analysis results

4.5 Limitations of the study

The goal of performance a technic-economic analysis of parabolic solar cooker and panel type solar cooker was met, and the optimum cooking choice was chosen. This outcome marks a significant step towards sustainable energy utilization in the country as a net zero cooking option has been chosen. However, it is important to acknowledge that the study faced one limitation, which was related to the determination of the weights assigned to the technical, economic, and environmental criteria used in the TOPSIS analysis. The weights were determined using available literature. This necessitated the use of sensitivity analysis to determine whether the parabolic solar cooker is indeed exceptional.

To address this limitation and enhance the accuracy of the results without the use of sensitivity analysis, a comprehensive survey can be conducted within the communities. By engaging with the people who would be directly impacted by the choice of cooking technology, valuable insights were gained. The survey sought to understand their specific cooking needs, preferences, and priorities. Participants are asked to provide feedback on which criteria they deemed most crucial in the context of their daily cooking practices. By incorporating the community's perspectives, the study can obtain more precise and relevant weights for the criteria.

4.6 Chapter summary

This chapter focused on the performance and financial analysis of both parabolic and panel solar cookers. According to the study, the parabolic and panel types of solar cookers have efficiency rates of 74% and 75%, respectively. The prices of a parabolic and a panel type solar cooker are £172 and £866, respectively. When the technical, economic, and environmental outcomes were compared to traditional fuels such as charcoal and firewood. The parabolic solar cooker was proven to be the best cooking choice for Malawians. A sensitivity analysis was performed to verify that the parabolic solar cooker is the best option, even when various criteria weights were used.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The utilization of unclean solid fuels has led to an increase in indoor air pollution in Malawi. As a result, there is a growing demand for clean cooking technologies. To address this issue, a study was undertaken to perform a techno-economic evaluation of two solar cookers - the parabolic and panel type - as net-zero cooking alternatives. Due to the country's high solar radiation for solar energy production, solar cooker was discovered to be the best cooking alternative. These two cooking options were designed, and the results of their technical-economic analysis were employed in TOPSIS to compare the two technologies with traditional fuels. The performance and financial analysis of both parabolic and panel solar cookers was assessed. According to the study, the parabolic and panel types of solar cookers have efficiency rates of 74% and 75%, respectively. The prices of a parabolic and a panel type solar cooker are £172 and £866, respectively. When the technical, economic, and environmental outcomes were compared to traditional fuels such as charcoal and firewood. The parabolic solar cooker emerged as the best cooking option based on the criteria and weight, followed by the panel type solar cooker, firewood, and charcoal. Sensitivity analysis was performed to validate the findings. To see if the same findings could be obtained, the weights of the criteria were adjusted. The sensitivity analysis results reveal that the obtained results remained consistent and robust.

5.2 Recommendation

The government should encourage the use of parabolic solar cookers by investing in technological innovation since they improve community livelihoods and environment. Grants should be given to communities so that more people can utilise the parabolic solar cooker. The government and organisation should accelerate the transition to sustainable cooking practices, encourage and promote the widespread adoption of parabolic solar cookers among households and communities. Awareness campaigns and incentives can be implemented to raise awareness and make the technology more accessible.

The government should introduce favourable policies and regulations to support the deployment of solar cookers, such as tax incentives, subsidies, or mandates for solar cooking technologies in specific regions. Finally, this study should be promoted among many institutions to secure funding for the next phase of research and possibly improve the performance of the parabolic solar cooker by researching the best reflective materials to use as well as the best angle orientation to harness more energy.

5.3 Future work

The research concentrated on the technical-economic analysis of both the parabolic and panel type cookers. Although the panel type shown potential performance due to high solar radiation throughout the year, the cost of installation was expensive. In the future, researchers can investigate the use of new materials such as nanomaterials to lower production costs and improve the efficiency of the panel type solar cooker.

Furthermore, more research on solar cookers and smart control systems is needed. To maximise the energy collected from the sun, the solar cooker may incorporate a smart control system as well as solar tracking. The smart control system can regulate the flow of energy from the parabolic and panel type cookers to energy storage, as well as how it is transmitted back to the solar cooker for use during low solar radiation and at night.

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7. APPENDIX

7.1 Appendix A: Parabolic solar cooker design calculation and performance analysis

Table 7.1 shows the design calculation of the parabolic cooker that were used to find the design specification of the parabolic solar cooker.

Parameter	Calculation	Size
$Arperture\ area = \frac{Q}{\cap \times I \times t}$	$A = \frac{3.5kWh}{0.35 \times\ 5.6\ \text{kWh/m2/day} \times 1}$	1.78m
$Diameter = \sqrt{\frac{4A}{\pi}}$	$D = \sqrt{\frac{4\ (1.78)}{\pi}}$	1.505m
$focal\ length = \frac{D^2}{16 \times depth}$	$f = \frac{(1.505)^2}{16 \times 0.1505}$	0.94m
$Height = \left(\frac{D^2}{16f}\right)$	$= \left(\frac{(1.505)^2}{16(0.94)}\right)$	0.1506m
$Rim\ angle$ $= tan^{-1}\left(\frac{\frac{8f}{D}}{16\left(\frac{f}{D}\right)^2 - 1}\right)$	$= tan^{-1}\left(\frac{\frac{8(0.94)}{1.505}}{16\left(\frac{f}{1.505}\right)^2 - 1}\right)$	= 43.6
Energy to store E = $\frac{(Q+LR) \times N}{n}$	E = $\frac{(3.5+0.35) \times 3}{0.74}$	15.6kWh
$V = \frac{Q\ (1 + LR\ \times N)}{\rho\ C_p\ \Delta T}$	$V = \frac{15.6 \times 3600000}{2750 \times 790 \times (250 - 180)}$	0.369m3

Section 4.1.2 highlighted the parabolic solar cooker's performance during peak months in each season. It displays the number of days the parabolic cooker can satisfy the energy demand and the number of days the parabolic cooker cannot meet the need. The data below indicate how the parabolic solar cooker performed in the remaining months of the year.

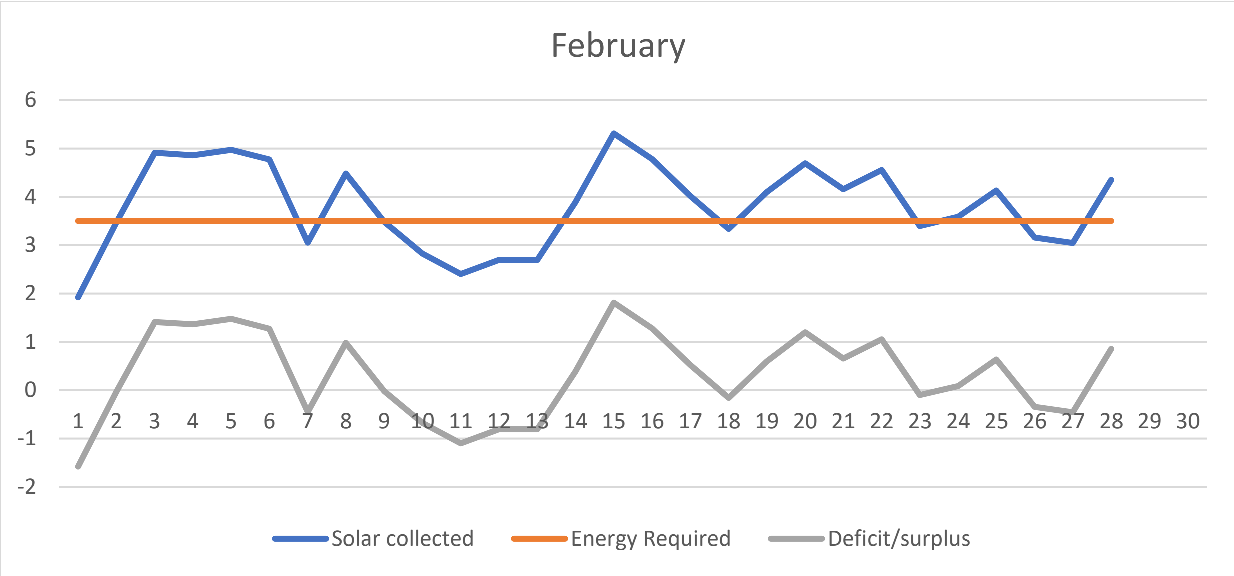

Figure 7-1A: Performance of the cooker in February

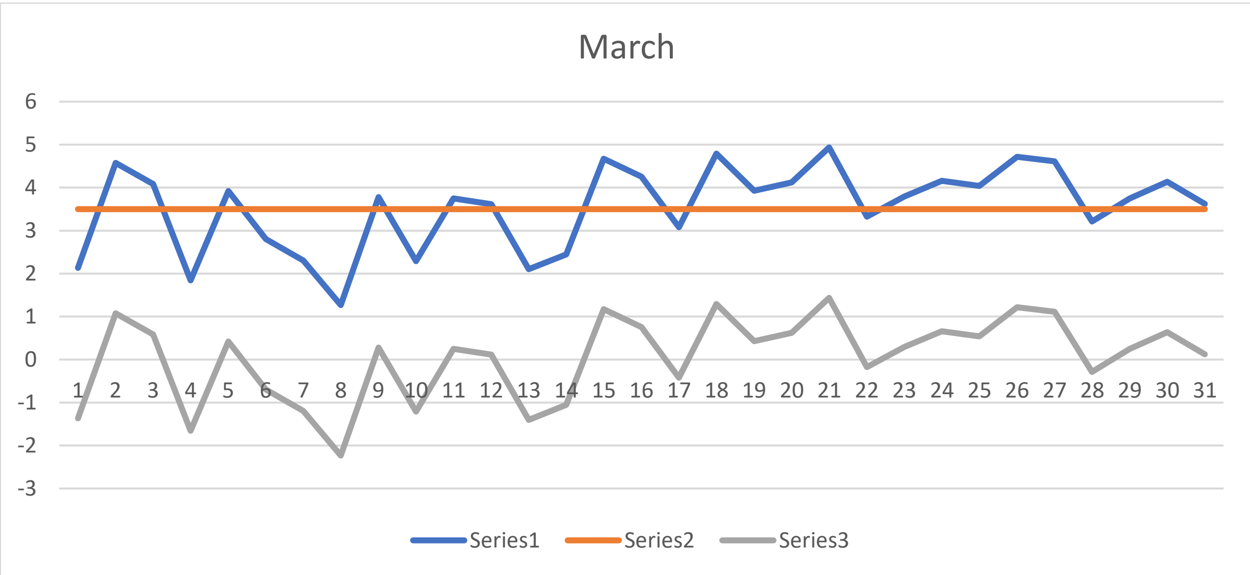

Figure 7-2A: Performance of the cooker in March

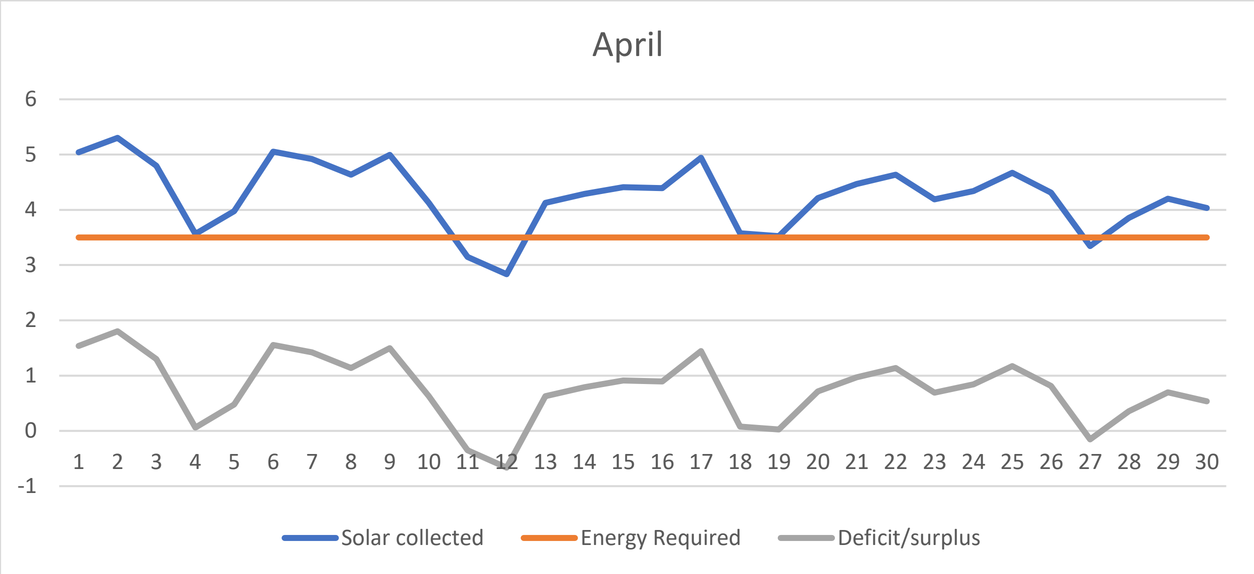

Figure 7-3A: Performance of the cooker in April

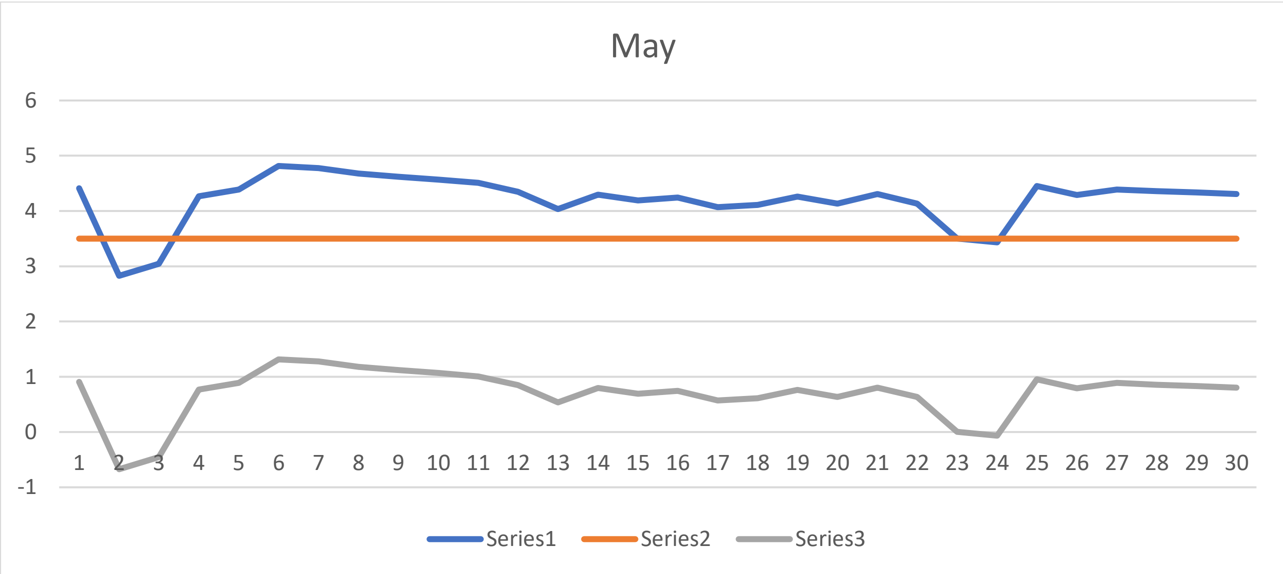

Figure 7-4A: Performance of the cooker in May

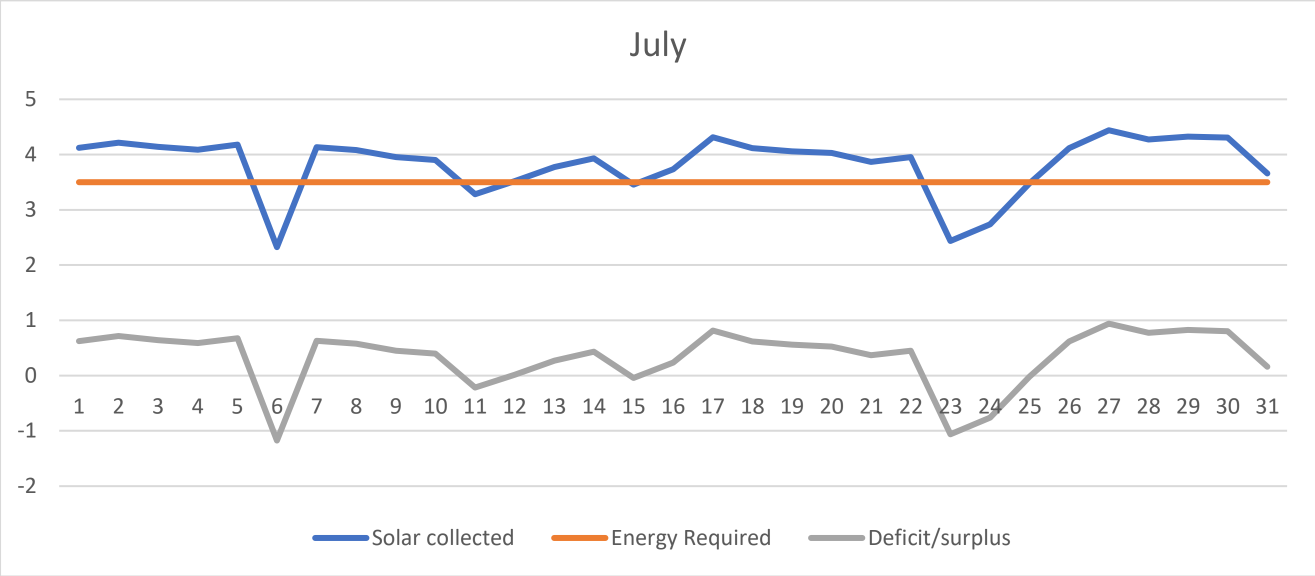

Figure 7-5A: Performance of the cooker in July

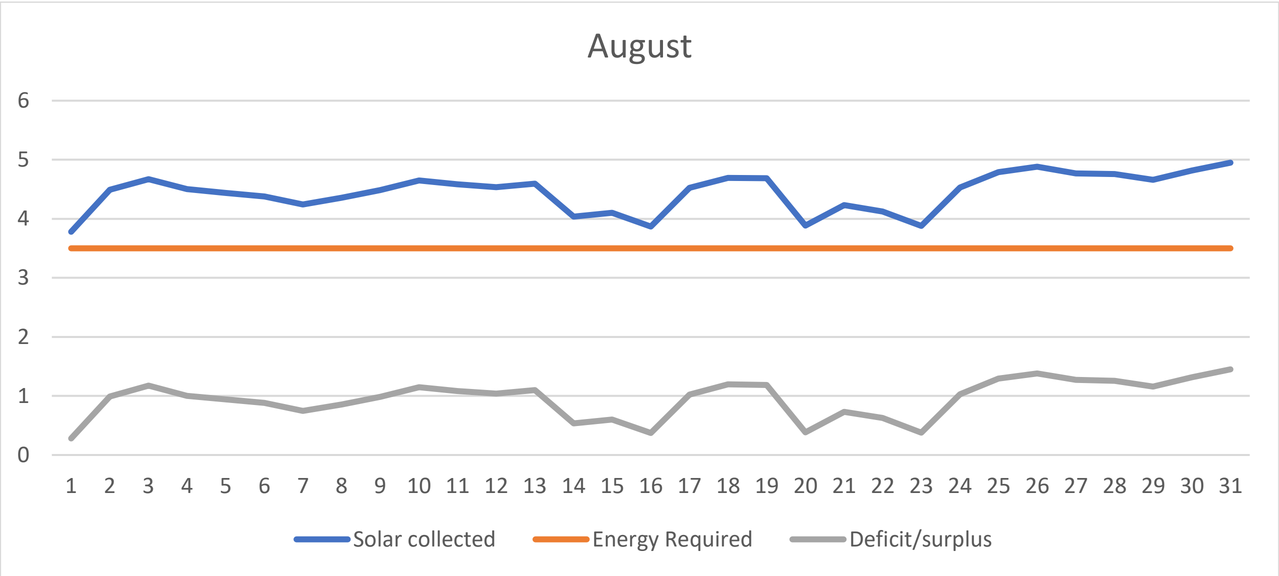

Figure 7-6A: Performance of the cooker in August

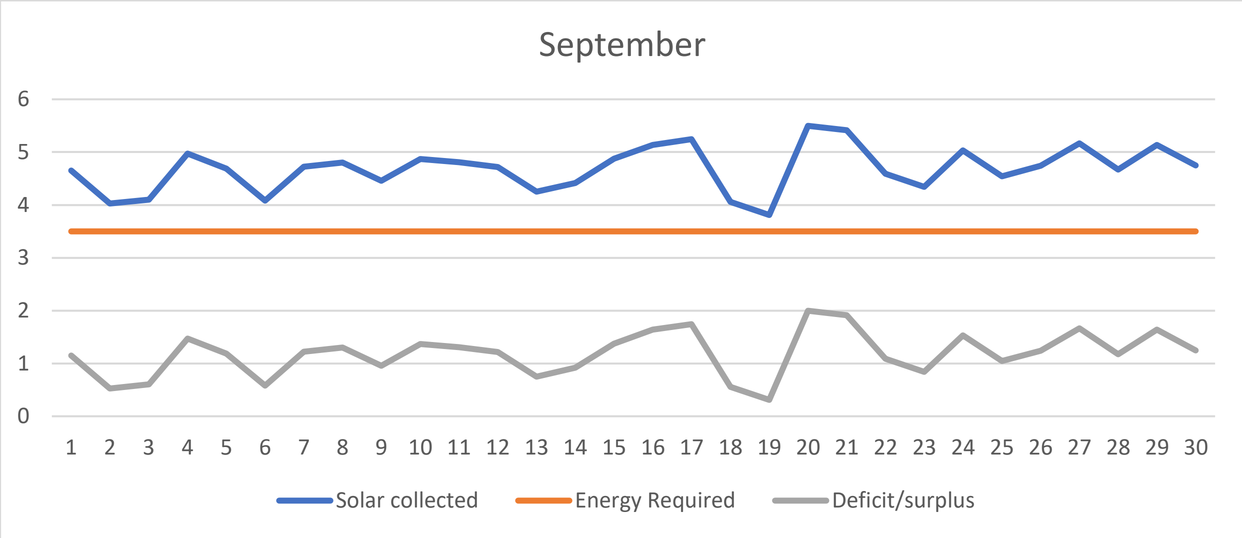

Figure 7-7A: Performance of the cooker in September

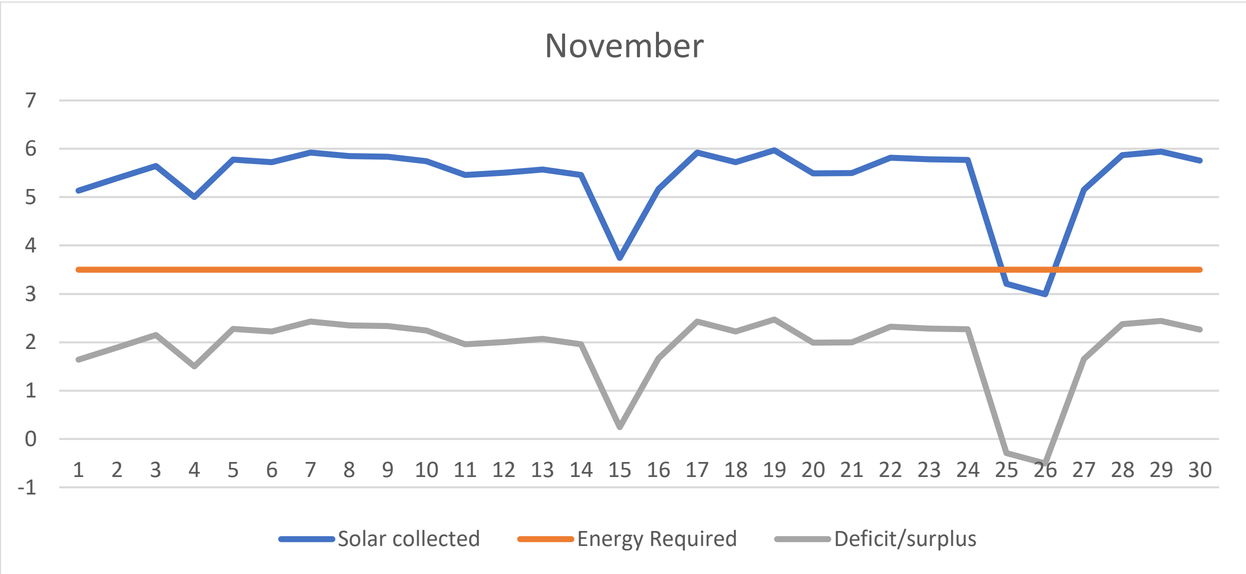

Figure 7-8A: Performance of the cooker in November

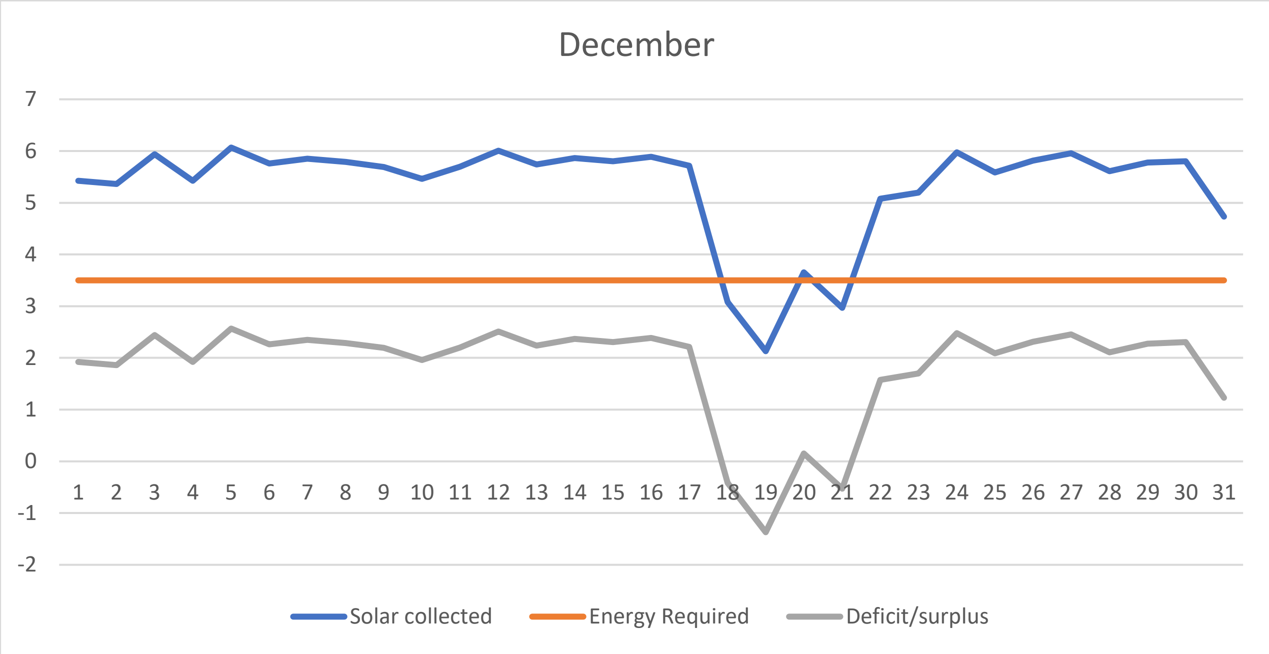

Figure 7-9A: Performance of the cooker in December

7.2 Panel type solar cooker design.

The design calculation for the panel type solar cooker is shown in Table 7.1. It outlines the steps taken to determine the number of solar panels and batteries to be used in the system.

Table 7.1A: Panel type solar cooker parameters.

Daily Energy demand (Wh)	3500	
Energy demand	3500	
System Voltage (V)	12	
Average insolation per day (h)	4	
System design charge current = Total daily energy demand/ system voltage		
	291.67	
Charge current = System design charge current/ Average insolation per day		
	72.917	
Rated output current of available modules (A)	(A)	42
No. of modules = Charge current/ rated output current		1.7361
		2 panels
Days of autonomy	4	
Battery Charge current required = System design current* Days of autonomy		

	1166.7
Available batteries (12V) Pb sealed	296 Ah
Depth of Discharge	80%
Available Charge current in battery	296

Number of Batteries = Charge current required / Available charge current in battery

3.9414

4

Batteries

7.3 Technic-economic analysis using TOPSIS.

TOPSIS was used to determine the best cooking technology to be adopted. However, sensitivity analysis was carried out to determine if the selected choice is indeed outstanding. Thus TOPSIS selection process was done again if changed weights. Table 7.2 and Table 7.3 shows the normalized weighted matrix with the ideal and non-ideal values for each scenario case.

Table 7.2A: Normalized weighted Matrix for Scenario 1

	NPV (£)	Cost (£)	Cost £/m	Eff	EE	ES	S	GWR	H	SUS
Parabolic	0.04872	0.02088	0.02088	0.05916	0.06	0.06	0.0566	0.067	0.067	0.067
Panel	0.10556	0.10556	0.10556	0.06003	0.06	0.06	0.0566	0.067	0.067	0.067
Charcoal	0	0.04408	0.04292	0.02001	0.0122	0.012	0.0339	0.027	0.027	0.027
Firewood	0	0	0	0.008004	0.0122	0.012	0.0113	0.014	0.014	0.014
Ideal value	0.10556	0	0	0.06003	0.06	0.06	0.0566	0.067	0.067	0.067
Non ideal value	0	0.10556	0.10556	0.008004	0.0122	0.012	0.0113	0.014	0.014	0.014

Table 7.3A:Normalized decision matrix for Scenario 2

	NPV (£)	Cost (£)	cost £/m	Eff	EE	ES	S	GWR	H	SUS
Parabolic	0.03486	0.01494	0.01494	0.0425	0.043125	0.043125	0.040625	0.1072	0.1072	0.1072
Panel	0.07553	0.07553	0.07553	0.043125	0.043125	0.043125	0.040625	0.1072	0.1072	0.1072
Charcoal	0	0.03154	0.03071	0.014375	0.00875	0.00875	0.024375	0.0432	0.0432	0.0432
Firewood	0	0	0	0.00575	0.00875	0.00875	0.008125	0.0224	0.0224	0.0224
Ideal	0.07553	0	0	0.043125	0.043125	0.043125	0.040625	0.1072	0.1072	0.1072
Non Ideal	0	0.07553	0.07553	0.00575	0.00875	0.00875	0.008125	0.0224	0.0224	0.0224

The ideal and non-ideal value of the criteria's were used to calculate the similarity to the worst alternative as shown below.

Table 7.4A: TOPSIS score for Scenario 1

	X_j^b	X_j^w	$X_j^b + X_j^w$	$X_j^w / (X_j^b + X_j^w)$	Ranking
Parabolic Solar Cooker	0.064150968	0.18543161	0.249582578	0.742967	1
Panel Solar Cooker	0.149327871	0.170007414	0.319335285	0.532379	2
Charcoal	0.157545037	0.094161396	0.251706433	0.374092	4
Firewood	0.161851929	0.149284384	0.311136313	0.479804	3

Table 7.5A: TOPSIS score for scenario 2

	X_j^b	X_j^w	$X_j^b + X_j^w$	$X_j^w / (X_j^b + X_j^w)$	Ranking
Parabolic Solar Cooker	0.045834995	0.18681737	0.232652364	0.802989	1
Panel Solar Cooker	0.10681555	0.179148884	0.285964435	0.626473	2
Charcoal	0.152920119	0.074701577	0.227621696	0.328183	3
Firewood	0.001030046	0.10681555	0.107845596	0.009551	4