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SUSTAINABLE DEVELOPMENT

Title: Design of a DC Solar Powered Electric Cooker for off-Grid Dwellers

Case study: Nyamata Sector/ Bugesera District

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October, 2022 Kigali-Rwanda

DECLARATION

I declare that this Dissertation is entirely original where specifically acknowledged, and it has been passed through the anti-plagiarism system and found to be compliant and this is the approved final version of the thesis.

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This thesis has been submitted for examination with my approval as a university advisor.

Date of Submission: **October 2022**

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I want to extend my gratitude and appreciation to Dr. JMV Bikorimana for all of his help and encouragement during this study, my special gratitude to my family and who has been on my side in everything. Additionally, I want to thank my colleagues for their endless support and encouragement during this entire masters program.

DEDICATION

I dedicate this dissertation:

To my family and friends.

To my supervisor JVM Bikorimana, PhD.

To my department of Renewable Energy Engineering (REE).

To the African Center of Excellence in Energy studies for sustainable development (ACE-ESD).

To all University of Rwanda authorities.

To Africa Energy Services Group, Electrocook and ARC power

To all those who contributed to carrying out my research.

ABSTRACT

This thesis aimed to design a solar powered electric Cooker, in response to heavy reliance on traditional biomass cookstoves that is exposing to toxic smoke and environmental degradation from traditional cooking practices. During this study, different literatures were reviewed; data were collected in Nyamata sector with ARC Power mini-grid clients, data collection was to assess the cooking dairies/behaviour that helped to define the cooking load profile of households. Findings have shown that the average time for cooking with AC electric pressure cooker is 53 min for breakfast, 1h30min for lunch and 1h49min for supper. Additionally, findings revealed that the use of EPC over wood and charcoal reduces the price of fuel and cooking time by two. For the case of a DC solar powered electric cooker, a hot plate, the time for cooking will be the same. However, referring to the structure of any type of a pressure cooker, electric or traditional, the cooking time can be reduced by factor of two or four. Therefore, the designed DC solar powered cooker can be applied to a DC EPC and the cooking time will be reduced by factor of two of four. The designed cooker has the ability to control the power referring to the change of the input voltage from a PV system for its supply. This is done by controlling the gate signal for the MOSFET using PID. This study was limited to the electrical design of DC solar powered electric cooker; therefore, it recommends to do further studies on its housing, mass and heat transfer specifically for DC Electric pressure cooker to increase that could improve its efficiency.

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ABBREVIATIONS

AC: Alternative Current

BRD: Development Bank of Rwanda

CAPEX: Capital Expenditure

DC: Direct Current

DG: Distributed Generations

EDPRS: Economic Development and Poverty Reduction Strategy of Rwanda

EPC: Electric Pressure cooker

HAP: Household Air Pollution

HIV: Human Immunodeficiency Virus

HVS: High Voltage Section

ICS: Improved Cook Stoves

LPG: Liquefied petroleum gas

LVS: Low Voltage Section

MININFRA: The Ministry of Infrastructure

MPPT: Maximum Power Point Tracking

MtCO_{2e}: Metric tons of carbon dioxide equivalent

NST1: National Strategy for Transformation

OPEX: Operation Expenses

PID: Proportional-Integral-Derivative

PV: Solar photovoltaic

SHS: Solar Home System

WHO: World Health Organization

WRI CAIT: World Resources Institute Climate Analysis Indicators Tool

BLDC: Brushless Direct Current Motor

CHAPTER 1: INTRODUCTION

1.1 Background

Rwanda's access to electricity is rapidly growing over the last years, thanks to targeted government intervention. The government of Rwanda aims to ensure universal electricity access by 2024. As of August 2022, 74% of Rwandan households have access to electricity. Where 50.7% are connected to the national grid and 23.2% using off-grid solutions (mainly solar). The Government of Rwanda made a clear policy choice to diversify the sources of power from the conventional dominating grid to allow even off-grid connections during the development of the EDPRS II. In order to lower the cost of access to electricity while easing restrictions on historical government subsidies, households far from the planned national grid coverage have been encouraged to use alternative, less expensive connections like mini-grids and solar photovoltaics (PVs). [1]

The total generating capacity of Rwanda with percentages of share of renewable energy sources in the generating capacity of Rwanda, according to annual report for Rwanda Energy Group, of the Year 2020-2021[2]. Hydropower and thermal power continue to dominate with the highest shares of the installed generation capacity of 107.328 MW equivalent to 39.80% and 58.8MW equivalent to 21.30% respectively, while solar power contributes the least (4.4%) as per the table and graph below:

Table 1 : Installed capacity by technology[2]

Technology (sources)	Installed capacity (MW)	Percentage(%)
Renewable sources		
Hydropower	107.328	39.8
Solar power	12.05	4.4
Other sources		
Methane gas	29.79	10.8
Thermal power	58.8	21.3
Imports & shared	18.1	6.6
Peat fired pp	50	18.1

Total	276.068	100
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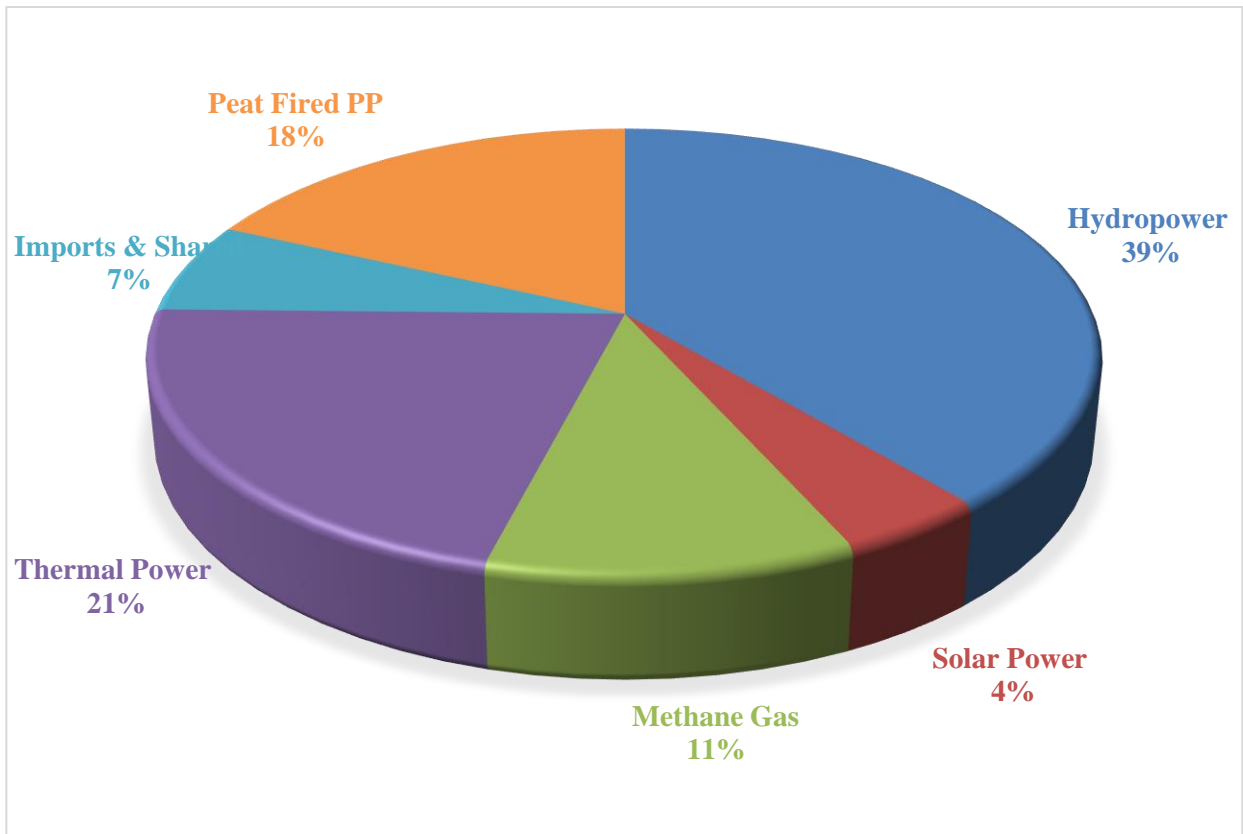


Figure 1: Installed capacity (MW) [2]

Even if most households are connected, Access to clean cooking remain a hindering issue in Rwanda. Rwanda heavily relies on traditional biomass for both domestic and industrial applications. 99% of households still use biomass for cooking. Rwanda ranks among the top 20 countries with the lowest percentage of the population with access to clean fuels and technologies [6]. According to the World Resources Institute Climate Analysis Indicators Tool, Rwanda's overall greenhouse gas emissions in 2018 were 7.82 million metric tons of carbon dioxide equivalent (MtCO₂e). The increasing costs of fossil fuels, degrading forestry resources, the threat of climate change, and the need to increase energy security and access have put alternative energy sources and efficient electric appliances at the forefront. An increase in demand for cooking fuel and industrial processing has exerted immense on forest resources.

According to the most recent data on the national energy balance, biomass (mainly wood fuel) makes up roughly 83% of all energy consumed, with petroleum coming in second at 9.7%, electricity

coming in at 1.3%, and other sources coming in at less than 5%. Over 90% of energy needs are met by biomass in rural regions. The majority of Rwandans reside in rural regions where traditional biomass, particularly wood fuel, has continued to be the primary source of energy for cooking[3].

The type of stove has a significant impact on the amount of fuel required and on the health of the users. According to the latest estimates by World Health Organization (WHO) as reported in the Biomass Energy Strategy, Household Air Pollution (HAP) from traditional Cookstoves leads to over Globally, TB alone causes 4.3 million deaths annually, more than HIV, malaria, and malaria combined. Children make up a sizable share of these fatalities. Severe respiratory ailments, perinatal mortality, low birth weight, cancer, eye conditions including blindness, and cardiovascular problems are all caused by carbon monoxide and particles from fires. The increasing practice of cooking with agricultural residues in areas where wood is scarce leads to even higher exposure to harmful smoke. A significant proportion of households still resort to utilizing three-stone cookstoves (the simplest cookstove, made by placing a pot on three stones, which are positioned around a fire) or other traditional cooking stoves: these are normally fuelled by firewood. The average household uses around 1.8 tons of firewood each year to satisfy its cooking needs with low-efficiency cookstoves[4].

The Ministry of Infrastructure (MININFRA) recently approved an ambitious new Biomass Energy Strategy (2019-2030) and an amendment to its Targets set forth in the National Determined Contribution include halving by 2024 the proportion of families using firewood for cooking from the baseline figure of 79.9 percent in 2017 and phase-out of the use of charcoal in urban areas.. In May 2020, the Government updated its Nationally Determined Contributions under the Paris Agreements which includes promoting the use of efficient cookstoves as a mitigation measure, since cooking accounts for 14 percent of the GHG emissions from the energy sector [5].

1.2 Statement of the Problem

The heavy reliance on traditional biomass cookstoves yet daily exposure to toxic smoke from traditional cooking practices is known to cause health complications and deaths. Rwanda experienced 9,040 premature deaths due to indoor air pollution and another 2,960 deaths due to ambient air pollution [6]. Culturally, women cook for their families hence bear the brunt of these health issues and complications. Women and girls collect biomass, cook and perform household activities including igniting traditional fuels during the rainy season which is very time-consuming.

This reduces their total working hours and constrains their productivity which in turn undermines efforts in gender equality and with it, local economic development.

The drawbacks associated with the use of wood fuel and charcoal extend well beyond first order effects, with studies showing that declining availability of wood fuel leads to changes in cooking and eating patterns that negatively affect the nutritional status of households[7]. The low transmission/distribution power grid coverage also prevents the dissemination on large-scale of electricity-based solutions that could be the cheapest one if adequate planning strategies were adopted. However, even when electricity is available, it is used preferentially for other purposes and does not equate to moving up the cooking energy and technology ladder, as noticed in Rwanda [8] and other countries like Bangladesh[9]. Solar energy could potentially be the main source of energy in African countries due to the high annual irradiance available, combined with the number of sunshine hours throughout the year [10]. Despite the availability of solar energy source, its exploration on use for different purposes such as electricity generation, heating and cooling or cooking is still low. Yet solar technologies have several advantages compared to other renewable energy technologies, for example: lower investment and operation costs (CAPEX and OPEX); the modular feature allows system growing as needs change compared to Liquefied Petroleum Gas (LPG) which is being mostly affected by the absorption of economic shocks especially on the fuel owing to the global escalated prices of commodities where the Ukraine/Russia war has been a catalyst to the situation. As of now, different researchers are diving more on how the utilization of solar can be maximized however, the intermittence of solar and integration of DC appliances on solar PV system remain a critical challenge.

1.3. Objectives

This study aimed to design a Solar Powered Electric Cooker for off-Grid Dwellers in order to give a clean alternative cooking solution for Rwanda's rural communities.

1.4. The Specific Objective

The specific objectives of the study were as follows;

- i) To conduct a feasibility study of a solar DC electric cooker.
 - ✓ Conduct solar resource assessment
 - ✓ Load profile assessment

- ✓ Off-grid market assessment for solar cooking
- ii) Model, Design, and simulate a solar DC electric cooker
- iii) Prototype a solar DC electric cooker

1.5. Research questions

To achieve successfully the objectives of the present research, the following research questions will be based on:

- i) What are characteristics of solar resources in Rwanda?
- ii) How long and how much fuel do they use to cook?
- iii) How is the solar cooking market being likely to behave?
- iv) What can be the appropriate solar DC cooking model and design in Rwanda?
- v) What does it require to prototype a solar DC cooker?

1.6. Scope of the study

The research focused on how to provide a clean cooking alternative solution for off-grid people by designing a solar-powered electric cooker. In reality, the research focused on the technological development of a solar DC electric cooker that is both economical and environmentally friendly

1.7. Outcome of the Study

The purpose of this study was to produce a research report that emphasizes clean cooking solutions by including the technical development of a DC solar powered electric cooker

1.8. Significance of the Study

Energy Sector Strategic Plan and other strategic documents clearly target to boost the use of clean energy for both domestic and industrial uses. Rwanda heavily relies on traditional biomass for both domestic and industrial applications. An increase in demand for cooking fuel and industrial processing has exerted immense on forest resources and the country aims to reach a potential net reduction in wood use to 5,770,000 tonnes by 2030 through a number of measures, including developing a modern and efficient clean cooking methodologies like introducing and encouraging the use of electricity in domestic cooking activities.

In addition, the Second Economic Development and Poverty Reduction Strategy (EDPRS II) targeted a reduction of biomass uses from 94% in 2009 to 50% in 2020 in national energy consumption. National Strategy for Transformation (NST1) targets to halve the number of households depending on firewood as a source of energy for cooking from 83.3% (2014) to 42% by 2024. This will be achieved by focusing on promoting the use of alternative sources of energy such as biogas, biomass pellets /briquettes, and the use of improved cooking stoves and electric cooking appliances. Furthermore, the targets to attain universal access to electricity have also been set. It's anticipated that 52 percent of households will be connected to the grid and 48 percent connected by off-grid electricity by 2024.

Adoption of electric clean cooking will reduce the emissions that contribute to climate change and deforestation which is rampant in rural Africa. This is especially important considering that Africa's population is growing and developing hence the bulk of Africa's carbon emissions might be released in the future. The project will assist in stemming the quantity of these emissions and reduce deforestation thus sustaining forests that act as carbon sinks.

1.9. Thesis organization

This thesis report is broken into five chapters:

Chapter one: covers a broad overview of the project, as well as the Rwandan government's cooking technology aim for 2024 and the history of electric solar cookers.

Chapter two: provides a broad overview of electric solar cookers and their evolution, as well as assessments of prior related successful initiatives. The research technique

Chapter three: provides the methodology of used in data collection and design of the DC solar Powered cooker

Chapter four: Illustrate more on the Design of a DC solar powered electrical cooker

Chapter five: Shows the DC powered electric cooker simulations and results.

CHAPTER 2: LITTERATURE REVIEW

2.0.Introduction

This chapter gives a picture of the clean cooking sector in Rwanda especially e-cooking, it also provides some narratives on works done by other researchers related with DC appliances and its integration on the PV systems. Additionally, it dives much ore on the electric cookers and its functionalities.

2.1.Clean Cooking Sector in Rwanda

Rwanda's population is estimated at 13,670,000 million, with the country occupying a land area of 26,338 Km². The country is also the most densely populated in Eastern Africa, with a population density of 554 people/per Km², making Rwanda the second highest population density in Africa (after Mauritius which has a population density of 630 people/km² The majority of the population lives in rural areas, with only 35.3% of the population living in urban areas, estimated at 4,828,000 million with median age standing at 24.7 years according to demographic statistic.

The population growth rate is estimated at 2.1% which coupled with the high population density, increases the risk of competition for land and unsustainable exploitation of environmental resources and ecological services which can lead to environmental degradation. The risk to the environment can be further aggravated as the vast majority of households in Rwanda, majority cook on wood fuels (wood/charcoal), which is a leading cause of deforestation with access to clean cooking was reported at 2.4% in 2020%. 99% of households still use biomass for domestic cooking duties[11].

The lack of modern energy cooking services also has serious health effects due to IAP (Indoor Air Pollution) and gender impacts as women and girls are the ones mostly tasked with cooking thus impacted strongly by IAP and drudgery from fetching fuelwood from long distance. In Rwanda, there is still a huge reliance on traditional fuels for cooking. In rural areas, firewood accounts for 93% of the fuel used for cooking. Even in urban areas, firewood represents 26.3% of cooking fuel, with charcoal being the most common (65% of the total cooking fuel used). With firewood and charcoal as the prevalent cooking fuels, the use of traditional cooking technologies is also common in Rwanda. Traditional stoves are the most commonly used 53% by HHs, followed by charcoal or open fire stoves with 16% [12] . As a result, access to clean cooking acts as a significant bottleneck when it comes to improving the health and well-being of Rwandan HHs. The government of Rwanda (GoR), through its Rwanda Energy Policy, recognises both the environmental and health threats

presented by the overexploitation of biomass – in particular, firewood and charcoal. HH air pollution (HAP) from solid fuel use is the fourth-leading risk factor for morbidity and mortality in Rwanda, and respiratory infection is the leading cause of loss of life [13]. It is estimated that annually, more than 7,383 premature deaths in Rwanda are attributable to HAP, with total welfare losses of U\$ 674 million per year [14]. On average, 76% of HHs spend at least seven hours per week acquiring fuel, either by collecting or purchasing it and preparing the fuel for their stoves, with a disproportionate burden on HHs using firewood. Additionally, the burden of tasks associated to cooking and fuel collecting falls disproportionately on women and girls. The outcome is women and children are more susceptible to HAP and associated adverse health effects, and chores relating to cooking take a considerable amount of their time, which otherwise could be used for other productive activities such as education or employment [15]. Exploiting other available renewable sources of energy at local levels through appropriate designs of energy technologies seems like the more sustainable solution. Solar energy is one of the more sustainable substitutes. The sun is an abundant, clean and safe source of energy. DC solar cookers with appropriate designs are therefore a potential substitute for exploiting solar energy.

2.1.1. The Clean Cooking Growth Path in Rwanda

Rwanda faces a double challenge in improving access to modern energy cooking solutions: a high percentage of households that still use highly polluting three-stone and traditional stoves and a very low percentage of households that use clean fuels. The ultimate objective should be to provide all households access to cooking solutions that are clean, efficient, convenient, affordable, safe, and available (Tiers 4 and 5), but in the interim e-cooking could be one of immediate solution to move households in off grid areas .Given the low adaptation on clean stoves in rural areas, rural households in particular, should be targeted. Health-related consumer awareness campaigns would be critical for promoting clean cooking technologies. Given the important health benefits that clean cooking technologies deliver, ways to expand their small share, particularly in more affluent developed countries, should be explored. A strategy to do so should be accompanied by a strategy to minimize the parallel use of biomass stoves. Potential adaptation constraints should be analyzed and removed accordingly, particularly for off grid households. clean cooking technologies adaptation incentives could be an effective way to increase households' ability to go for clean cooking technologies.

2.1.2. Advantages of adopting and using clean cooking technologies

Using clean cooking technology will support the move by the Government of Rwanda to Save the Country's existing forest resource. The use of clean cooking technologies will reduce the country's annual disease burden attributable to HAP. Access to modern energy makes a significant difference to health and well-being. Women and girls especially those in rural areas are predominantly responsible for the bulk of household work. Clean cooking technologies reduce the amount of time women and girls spend collecting fuel, giving them the opportunity to pursue education, training and economic activities. High-efficiency clean cooking technologies lead to even larger benefits in time and energy savings, hence also contributing to emissions reductions. Affordable, efficient, improved and renewable energy technology not only increases energy security and reduces greenhouse gas emissions but can also provide new economic and educational opportunities for women, men and children. Access to affordable modern energy services can reduce both the time and effort spent in reproductive and productive labour

2.1.3. E-Cooking in Rwanda

According to the Rwandan government's Biomass Energy Strategy, electricity is an alternative source of energy for cooking, particularly for the hospitality sector and high-income segments of the population. Progress in electricity generation and electricity access in recent years has meant that Rwanda experiences significant surpluses of energy during off-peak hours, while power supply and demand become more closely matched in peak evening hours. This, in addition to the challenge of low electricity demand across the country, indicates that using electricity for cooking through "smart" electricity tariffs around meal hours might help to absorb the excess baseload electricity in the daytime, and help reduce the dependence on biomass at the same time. The inclusion of e-Cooking appliances within the recent clean cooking results-based-finance window by the Development Bank of Rwanda (BRD) has been seen as a positive development. All around Kigali city, there are several shops selling e-Cooking appliances. However, there is a lack of aftersales service and little awareness of their benefits, which has hampered their adoption. Encouragingly, there is growing interest from different development partners in Rwanda, which would reduce considerably most of the barriers to adoption of e-Cooking. Solar energy as major source for Prosumers in Rwanda

2.2.DC household appliances

In late the 1880s, the war between two rivals in favour of AC and DC power was won by the AC because of the lack of technologies in DC system. Carbon emissions coexist with the generation of AC by traditional dominant fossil fuels that seriously not only balancing out the earth environment but may also be a cause of the extinction of earth species. In DC distribution system with DC sources and DC appliances, 47% energy saving is observed by Gholase and Fernandes. 22% system efficiency is improved by Anand and Fernandes. That Stand-alone DC distribution systems are flexible enough to integrate with other distributed generations. Most appliances work internally on DC power; they take AC as input and after conversion process bring the required DC voltage level. 33% energy saving is estimated by replacing standard technology with the DC internal efficient appliances and a further 14% by operating DC internals on direct DC.

These DC internal appliances take AC as input followed by AC/DC converter. This conversion process creates heat losses both in working mode and standby mode. If these appliances are fed with solar PV power, transformer and rectifier would be terminated from the circuit that saves a considerable amount of energy [16]. The absence of skin effect in DC system reduces the material cost of the wiring as the whole cross section carries the current. The overall cost of the system is greatly reduced as the equipment for the power factor improvement, AC/DC and DC/AC conversion and reactive power compensation is not required in DC distribution system. Enhanced energy savings and improved reliability by DC distribution system is recommended by Vagelis Soo and Jung have studied the efficiency of the DC distribution system by using multiple DGs (Distributed Generations) while Kamran et. al. [17] has studied MPPT based DC-DC buck-boost converter for multiple DGs. With the advancement in semiconductor materials and devices DC can directly be generated by using solar PV cell. Solar PV cell generates clean and green renewable energy. Historically, this energy is either stored in batteries or delivered to the AC grid through inverters that brings major conversion losses[18].

2.2.1. Air Conditioner

For the compressor, swing, and blower fans in conventional air conditioners, either 1-0 induction motor or a universal motor is used. Additionally, they have some AC-DC conversion for low voltage applications and are fed with 220V AC as shown in figure 2.

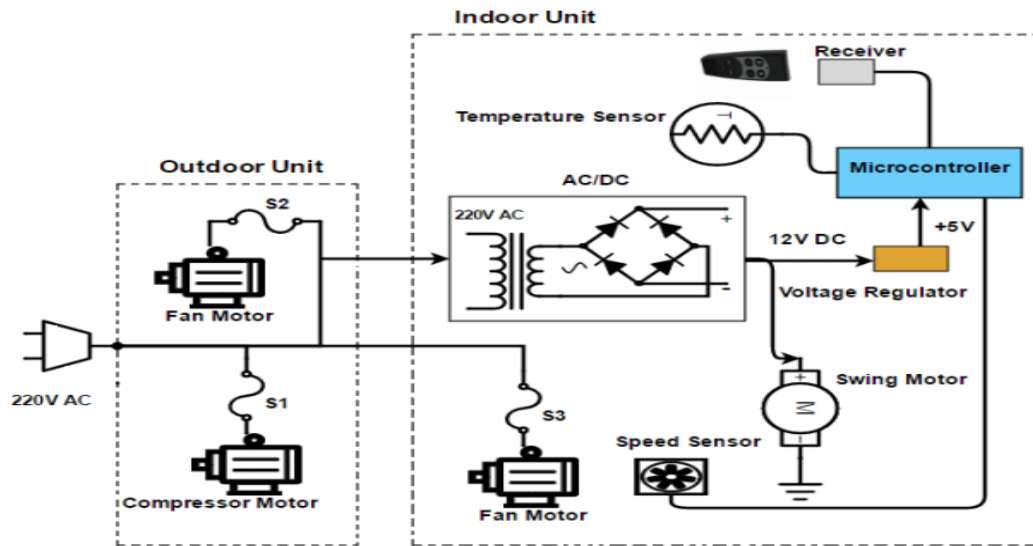


Figure 2: Current air conditioner circuit

A microwave oven is divided into two portions, each of which has its own independent circuitry and power source. HVS (High Voltage Section) and LVS (Low Voltage Section). The magnetron in the HVS is powered by a voltage doubler after a high voltage transformer. Turntable motor, magnetron fan motor (1- θ induction motor), and switching device are all included in LVS. The AC-powered microwave oven's turntable and magnetron fan motor get 220V from the input AC source. A 21V turntable AC motor is powered by a 220V step-down converter in some modified versions, which lowers production costs and energy consumption. [19]. In a DC microwave oven, the input AC is transformed into DC using a transformer and rectifier, and the output DC voltage is then reversed into AC, boosted by a transformer, and then again converted into DC to power the magnetron fan motor, light, and switching device. The BLDC turntable motor, BLDC magnetron fan motor, DC light, and a switching device in the proposed DC microwave oven's low voltage component are directly driven by a DC distribution line. It is supplied to the magnetron and amplified in HVS via a flyback converter. This method greatly reduces mechanical losses, noise, and conversion losses while achieving a high efficiency.

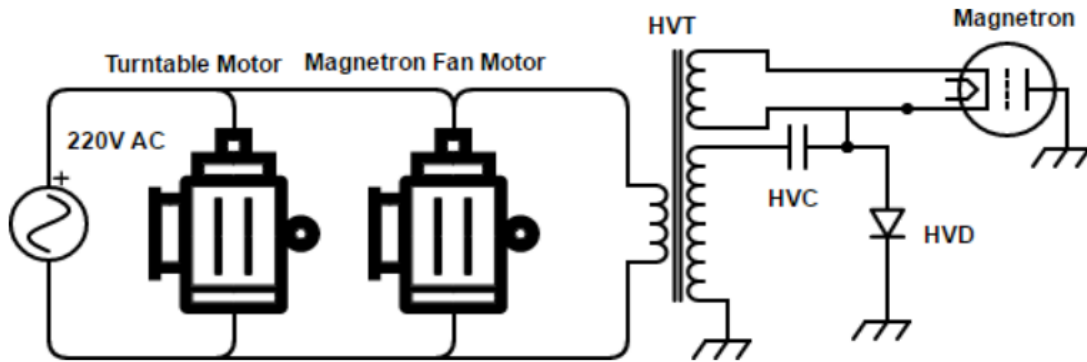


Figure 3: AC microwave oven

2.2.2. DC Fans

The 1- ϕ induction motors used in modern ceiling, table, and bracket fans are hefty, inefficient, and only have a 50% efficiency. After being transformed and rectified from the commercially available 220V AC, fans with DC motors use DC electricity. These DC motors are inefficient because of friction losses and brush maintenance costs. With BLDC motors that directly draw DC from the anticipated DC distribution line, DC fans will become more and more common in the future. Fans using BLDC motors consume 50% less power, which can be further decreased by enhancing the blades' aerodynamics. With a 75W BLDC fan, Desroches and Garbesi calculated an efficiency of 90%, while with a 75W AC induction motor, they estimated an efficiency of 75%. These fans would operate with little conversion losses and be extremely efficient.

2.2.3. Cloth Washer

Most textile washers on the market today use one-phase induction motors. To get a DC lowlevel voltage to power the control circuit, they employ a transformer and the rectification process. Some versions from Fisher and Paykel employ BLDC motors but also include rectifiers. The operation of the BLDC motor and control circuit of the washing machine and dryer is proposed utilizing DC input from a DC distribution line as opposed to AC power, followed by a transformer and rectifier.

2.2.4. Water Pump

Currently, 220V AC is used to power a 1- ϕ induction motor used in residential water pumps. An inverter is used in solar DC water pumps for flood irrigation to power a single induction motor. By swapping out the induction motor for a BLDC motor that runs on 48V from the DC distribution line, this water pump may be upgraded to one that is more efficient. For drip irrigation systems, there are

certain 12V BLDC pumps with modest flow rates available on the market. An MPPT-based DC-DC buck-boost converter has been suggested by Rajan to power a BLDC water pump from solar PV.

2.2.5. Refrigerator

Modern refrigerators feature a compressor powered by an induction motor. For mobile freezers and car/truck air conditioners, Zhejiang Boyard offers 12 and 24V BLDC compressors on the market. They are suitable for use in household refrigerators, and a 48V BLDC compressor is also offered for demanding applications. These freezers may be powered at 48V using the planned DC distribution line. The BLDC fan motor also takes the place of the universal motor formerly utilized for the condenser fan. Most conversion stages are eliminated when AC motors are replaced with BLDC motors, increasing system efficiency.

2.3. Research on Solar Cooking systems

Solar cooking solutions consisted of using solar cookers. Those are devices that harness solar radiation, converting it into heat that is used to cook food. This type of device can overcome the aforementioned drawbacks and is an environmentally friendly solution. The marginal cost of using such solution is zero as they use only the Sun's energy. Solar cookers use solar radiation by reflecting it to a focal area where a pot or pan is located and/or by trapping the radiation to retain heat. The most common solar cooker types are: box, parabolic, and panel cookers. This type of cooker requires protection from strong winds and access to direct sunlight[20]. People's attitudes about solar cooking are influenced by a variety of factors, including access to materials, availability of traditional cooking fuels, climate, culinary choices, cultural considerations, and technological capabilities.

Jean Marie Vianney Bikorimana [21] studied on Direct DC use of PV for cooking and sanitary. The research explored various types of cooking and found that the cooking mechanism gets costly. In truth, the cost of photovoltaic panels has not decreased significantly. In fact, the research offered a simple electronic circuit that may be used to cook straight from a photovoltaic system. The circuit which is made up of seeks to make it easier for a user of a cooking plate to select a duty ratio. The duty ratio is controlled to keep the array voltage above a certain level. When less power is available, it should function at a minimum level to prevent operating too far away from the maximum power point.

Atmane Ilias et al (2020) [22] studied on the feasibility of a photovoltaic (PV) heating plate. On a sunny day, the heating of the water and cooking at temperatures over 200°C were investigated using thermal resistance. To size the heating elements of the heating plate and to assemble the PV panels, knowledge of the electrical characteristics of the PV panels is required. They looked examined the electrical characteristics of a PV panel on a day when the solar radiation intensity was around 730 W/m² and the ambient temperature was around 250°C. They took measurements by heating one liter of water to evaluate thermal yields below 100 degrees Celsius and 0.3 liters of oil to estimate cooking temperatures above 100 degrees Celsius. The Funk model is used to calculate the power P₀ and the thermal efficiency of the plate based on the rise in water temperature at time intervals of -10min. The cooker system generates 730 W/m² of illumination and 230 W of peak PV panel power, with a resistance heating temperature of 500 °C after 30 seconds, a water and oil heating temperature variation of 10 °C/min, bake temperatures of 200 °C, and thermal efficiency of over 70%. When these findings are compared to the most recent study on standard box-type solar ovens, several very intriguing conclusions emerge A temperature increase of 75%, a 164 percent increase in frying temperatures, and a 16% increase in thermal efficiency

Robert Van Buskirk et al [23], the study showed the marginal levelized cost of energy (MLCOE) of cooking with wood and cooking with cutting-edge solar electric technology were compared. The two primary off-grid solar technologies investigated are high-cycle-life lithium titanate (LTO) batteries and direct-use DC solar (DDS) electricity for kitchen applications. The MLCOE is stated in USD/kWh for the energy used to cook meals. DDS power, which is directly generated from a solar panel with little or no intermediary electricity storage and negligible electricity conversion and control expenses, achieves a low median MLCOE of USD 0.125/kWh. DDS solar panels' fluctuating voltage and current output are controlled by a specially designed DDS cooker. LTO battery-regulated energy has a median MLCOE of USD 0.24/kWh under electric pressure, which decreases to USD 0.16/kWh. The MLCOE distributions for cooking using wood, DDS, and LTO electricity are quite comparable. The MLCOE cost model offers precise recommendations for modifying input costs, component longevity, and system performance in order to increase solar MLCOE even more in contrast to wood MLCOE. The study, however, could not demonstrate the technological viability of electric cooking.

Octavio Lo´pez-Martí´nez et al (2017) [24], studied how rural residents in Mexico and Yucatan prepare meals with the goal of eliminating open-flame cooking in households and encouraging the

use of improved cookstoves. The campaign against conventional cooking methods, such as utilizing wood or other biomass as a fuel, was motivated by health concerns, resource waste, and greenhouse gas emissions. Improved Cook Stoves were classified as technical systems made up of subsystems (fuel input opening, combustion chamber, chimney, and base). They see ICS as a collection of subsystems that are used by a community of people to meet their cooking needs, with energy, goods, and byproducts flowing in and out. They emphasize the importance of environmental (resources), psychological (unique to each cook), and sociocultural (of each household and community) systems in ICS adoption efforts. They did two workshops with each group throughout ICS design, experimented with building materials, and came up with two proposed ICS designs. They provided ICS features in the first workshop, outlining how to use each section to ensure that everyone understood the fundamental concepts and was aware of linguistic disparities. Second, they presented photographs of several ICS utilized in other parts of Mexico and Central America, discussing the benefits and drawbacks of each model as well as components that may be employed in Yaxcaba. Finally, they created a mock-up to allow each participant to offer thoughts on how to improve and adapt it to their own living conditions. The ICS design stage took two months. They came up with a cup with a series of advantages in their everyday activities' evaluation after two months of continuous usage, especially in sociocultural, environmental, and comfort difficulties. ICS benefits include increased cooking capacity for all of the meals they regularly prepare, reduced wood use, improved interior temperature comfort, less smoke within the home, and increased safety and accident prevention. In a nutshell, the project's experiences and outcomes led to the creation of an illustrated manual for ICS building, which has since been disseminated to Yaxcaba residents, municipal governments, and regional NGOs. Friends and neighbors applauded the effective construction of ICS models, which are still used every day for food preparation and water heating. However, the study was generalizing all the cases, it didn't go in details of each type of improved cook stoves.

Simon Batchelor et al (2018) [25] Millions of lives have already been impacted by the rapid expansion of solar photovoltaics (PV) in Africa, but it has yet to affect cooking, which is the main source of energy for low-income people. With declining PV prices globally, recent advancements in battery technology, and growing charcoal/fuelwood costs in areas with significant deforestation, solar electric cooking might be a game-changing solution (PV-eCook). While early research concentrated on cooking-sized solar household systems (cooking equipment, battery storage, charge controller, and PV array), it has subsequently been demonstrated that battery-supported electric

cooking (eCook) can enhance national, mini, micro, and nano grids. This paper outlines a multi-criteria decision analysis (MCDA) technique that takes into consideration a wide range of socio-cultural, political, technological, and other factors. Economic considerations that are predicted to influence eCook's adoption and potential effect in a range of African situations. It demonstrates that the concept has significant viability in many African countries, that there are significant sizeable markets (millions of potential users), and that the anticipated costs of e Cook are highly competitive against existing 'commercialized polluting fuels' within the next five years.

Arghya Saha et al (2019)[26], in this paper, described a cooking method that comprises a Maximum Power Point Tracking (MPPT) based Electric Cooker with temperature control that can be powered by a solar panel or a battery in this study. The Perturb & Observe technique is the MPPT's algorithm, which ensures battery charge by drawing maximum power from the PV Panel. A relay and a K-type thermocouple were used to control the temperature. Photovoltaic (PV) Panels, MPPT, Temperature Control circuits, and batteries were used in the hardware investigation. To assess the electric cooker's performance, time spent cooking various foods was recorded, as well as other important data. However, the study failed to explain the technical feasibility of solar electric cooker.

2.4. The voltage level and protection of household appliances

Based on established procedures and knowledge, the voltage levels for DC microgrids in residential structures that are located between a distributed generator and loads. Voltage values ranging from 12V to 800V have been suggested in the literature due to a lack of standardizations. To lessen system complexity and losses, standard voltage levels for DC distribution systems are proposed. These DC voltage levels may be inspired by current traditional uses, such as data centers that operate at 380–400 V, even if some attempts are still being made to define these standards., telecommunication applications with 48V, transportation camping vehicles with 12–24 V. The protection of a DC system is a big challenge, as DC has no natural zero points. 3-phase AC circuit breakers (CBs) were suggested by connecting the three contacts in series as a DC protection to remove the spark. Besides, some articles discussed DC short-circuit problems [17]. A protection circuit for a low voltage DC microgrid proposed in, where different faults at different locations on the DC grid have been addressed, the results demonstrated that the commercial AC protection elements are possible to use with DC, such as CBs and fuses to protect loads and batteries. In the same context, converter circuits with IGBT modules are more sensitive to over current and require faster protections that can be

represented by a hybrid ultra-fast DC CBs ,Additionally, it was shown that protection issues might develop in the event of high-impedance ground faults. As an alternative to CBs, authors have developed a low-cost method using rapid DC switches to identify and isolate fault for a multi-terminal DC microgrid. This technique was based on disconnecting all AC CBs in order to eradicate any DC problems. The current arcing problem during the unplugging of household appliances in the DC system was discussed in [20]. Their method is to add a shunt diode and capacitor branches with the plug. This method has been modified in [21], where these components were included within the electronic circuit of converters in the system to interrupt the current faults. It was presented that the DC system can be fast detected and isolated by combining the converters by associating relays and by using overcurrent protection criteria for those relays. Furthermore [22], and [23] compare mechanical and electronic CBs of 400V DC system, and they were shown that electronic CBs perform better than mechanical ones concerning current limitations, remote controllability, trip time curve adjustment, rated current controllability, wire break indication, monitoring functions for voltage and current. In [24], the author presented a DC hybrid CB with very fast contact opening and Integrated Gate Commutated Thyristor (IGCT), which comprises the fast-speed switching and bi-directional features. installed plant capacity[18]. Based on the mentioned research output on DC system, it encouraging to integrate a DC solar powered electric cooker. The following chapter, presents the mythology followed in order to achieved to the main objective of the present research.

CHAPTER 3: METHODOLOGY

3.0. Overall approach of the research

This research aimed to develop a solar-powered cooker, which involved field data collection, analysis, and design of the electric cookers. Survey (CTO) was used for collecting all the field data during the surveying. Excel software was employed for data analyses and Proteus was used for electric circuit simulation. The research methodology was detailed as follow.

3.1. Desk Research

This research phase was done by reading on previous works and review of different documents related to this research to get a baseline understanding of the situation. Papers and books published by different researchers and different documents documented by keys actors and players of the sector working group were mostly the tools under this phase.

3.2. Data collection

To address the key research objectives, this research employed a mixed type method of qualitative and quantitative and combination of primary and secondary sources. The qualitative data supported the quantitative data analysis and the result obtained is triangulated to enable utilization of the qualitative and quantitative data types in the data analysis. In order to gain an in-depth understanding of the cooking dairies and load profile, field researchers conducted a structured survey and structured interviews with households. Additionally, the research also employed a descriptive research design method to specialized groups of the society, mainly the women and youth to gather data from a wide range of respondents on the cooking behavior ,cooking practice and fuels to understand the its impact on health and other aspects of the phenomena of interest from an individual. The research was conducted in Eastern province, Bugesera District, Nyamata sector. The households that were surveyed are connected to electricity by Arc Power Mini-grid.

The chose location is the mini grid area developed by a company called Arc Power Ltd. The community was visited in order to meet with the community leaders to introduce the activity that will be conducted within their territory

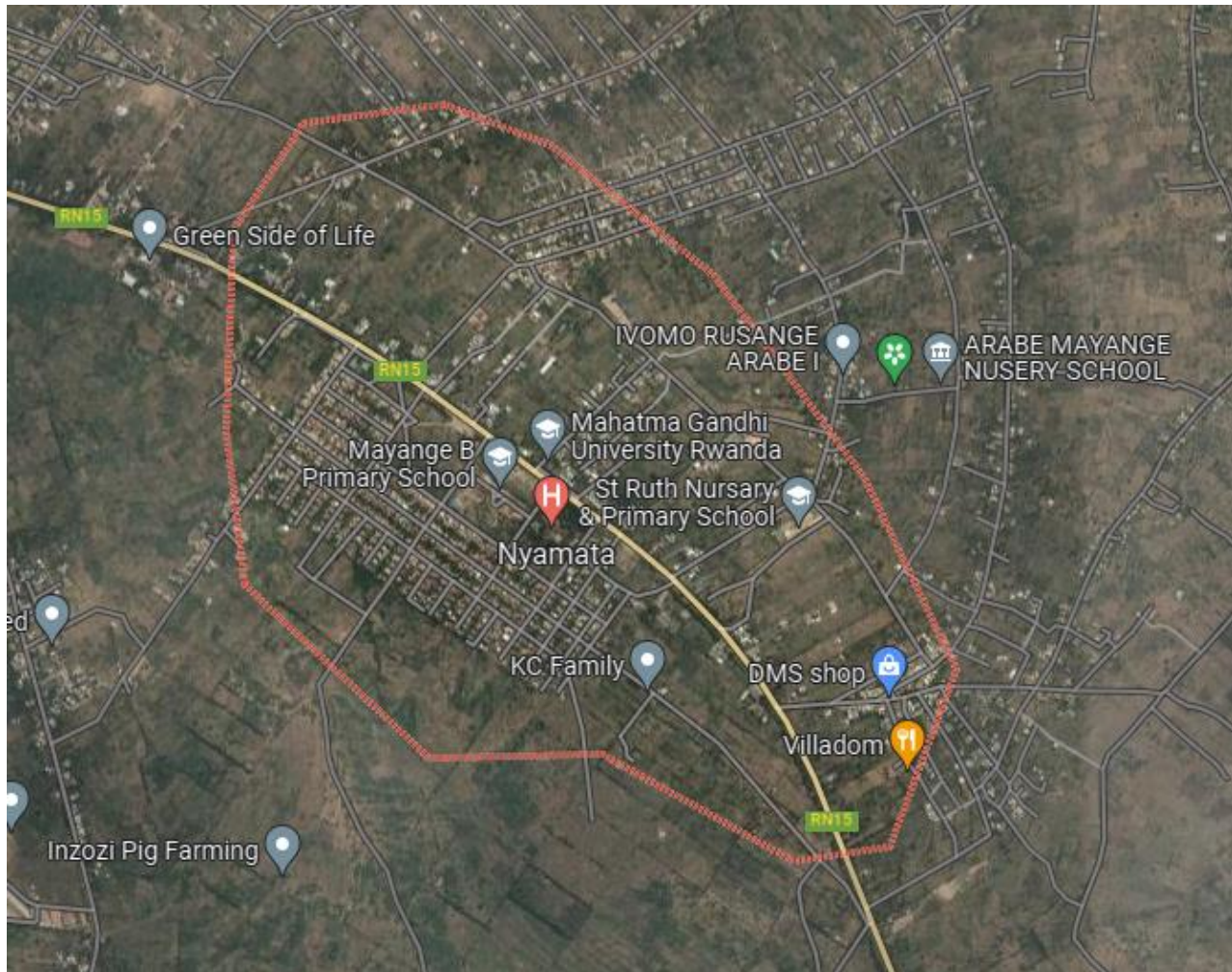


Figure 4: Nyamata sector map

3.2.1. Questionnaire development

Four questionnaires were developed, namely: pre-screening questionnaire, launch survey questionnaire, households visit survey questionnaire, cooking diaries questionnaire in order to collect the data that will help to achieve the target objectives of the project.

3.2.2. Conducting surveys

Local leaders and active local members were selected as ambassadors. These ambassadors were given criteria to select 100 households to be studied on. In collaboration with Electrocook Ltd and Africa Energy Services group, 50 Electric Pressure Cookers and 50 energy meters were distributed in 50 selected households to understand the cooking diaries, cooking behaviors and load profile of

the consumers which in return helped in the design of a solar powered pressure cooker for off grid dwellers.

3.2.3. Sampling technics

To draw valid conclusions from our results, different methods were explored to select a sample that is representative of the group as a whole. There are two types of sampling methods:

- ✓ **Probability sampling** involves random selection, allowing you to make strong statistical inferences about the whole group.
- ✓ **Non-probability sampling** incorporates non-random selection based on practicality or other factors, making it simple to collect data.

Although this research has employed non-probability sampling in determination of the number of respondents namely Multistage stratified sampling with purpose. This research involved four stages, explained as in table 2.

Table 2:Sampling stages.

Phase of data collections	Descriptions	Tools	Duration of Actions
1stPhase: Pre-screening	The pre-screening survey was meant to select 75 households among the 100 chosen by ambassadors. Criteria like, level of education, number of people living in a house, meals cooked and fuel used to cook were used to be able to select 75 households.	Digitalized questionnaire was used where enumerators had tablets loaded with the questions using Survey CTO Collect.	1 day

2rd Phase: Launch survey	<p>The Launch survey was meant to select 50 households that will be given EPC during the actual data collection. The logic behind is that when one household drops out from the program, we can replace it with another one qualified from 25 households remaining. The one who cooks in the household was chosen basing on the level of education (at least completed 6 years of primary school education).</p>	<p>Digitalized questionnaire was used where enumerators had tablets loaded with the questions using SurveyCTO Collect</p>	<p>3 days</p>
3rd Phase: Households visit survey	<p>After 50 households has been selected, a household visit survey was organized to make sure that the 50 households chosen are willing and ready to continue to the next step which is cooking diary and actual data collection using EPC and energy meters</p>	<p>Digitalized questionnaire was used where enumerators had tablets loaded with the questions using SurveyCTO Collect</p>	<p>1 day</p>
4th Phase: Cooking Diaries	<p>Cooking diaries survey was conducted where 50 households were given, printed questionnaires, digital weighing scales to measure fuels used when cooking, record the time it takes to prepare a meal in order to understand how rural dwellers prepare their meals (breakfast, lunch, and supper) using traditional methods.</p>	<p>Printed questionnaires. Digital Weighing scales</p>	<p>2 weeks</p>

5th Phase: Actual data collection	Households were given EPCs and energy meters to understand the load profile developed when cooking using electricity from minigrid .	EPC and Energy meters	3 months
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3.3.Data analysis

3.3.1. Cooking habits in Rwanda

The study revealed that 80% of the respondents have the regular three meals at home; namely Breakfast, Lunch and supper. Figure 5 shows the starting time while figure six shows the ending time for the three types of meals.

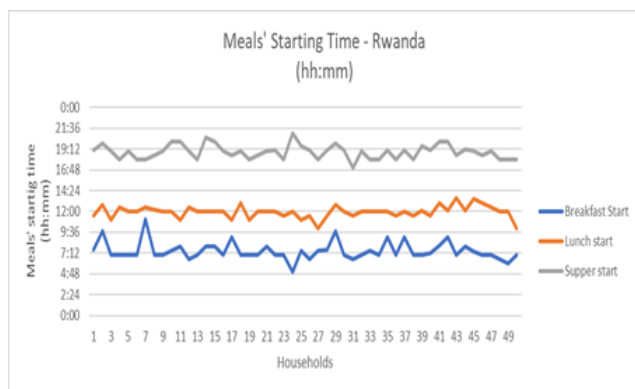


Figure 5: Meals' starting time in the inquired households

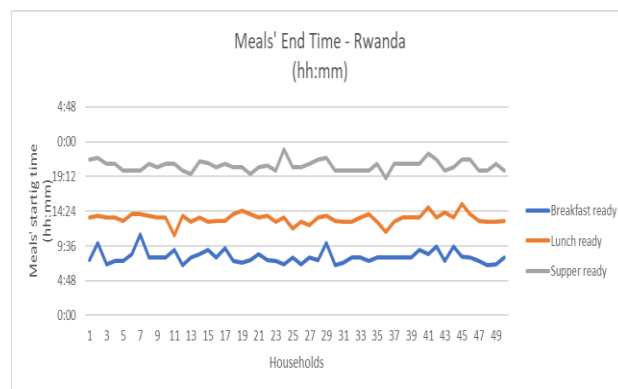


Figure 6: Meals' end time in the inquired households

The cooking times for the three regular meals is presented in table 3 and figure 7. In this case the the majority of households take around 30 min to cook breakfast, 2 hours for lunch and 2 hours for supper.

Table 3: Meals' cooking duration

	Average (hh:mm)	Mode (hh:mm)	Max (hh:mm)	Min (hh:00)
Breakfast	00:53	00:30	04:29	00:15
Lunch	01:30	02:00	03:30	00:32
Supper	01:49	02:00	03:00	00:45

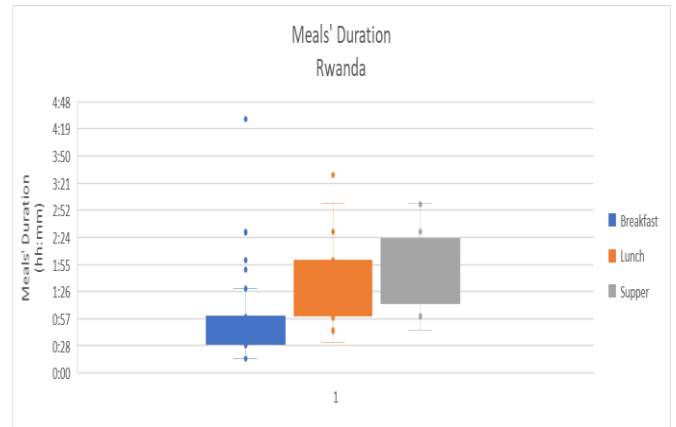


Figure 7: Meals' duration

Figures 8 and figure 9 present the results obtained from the respondents regarding the primary source of fuel used in each household and the most used cookstove types.

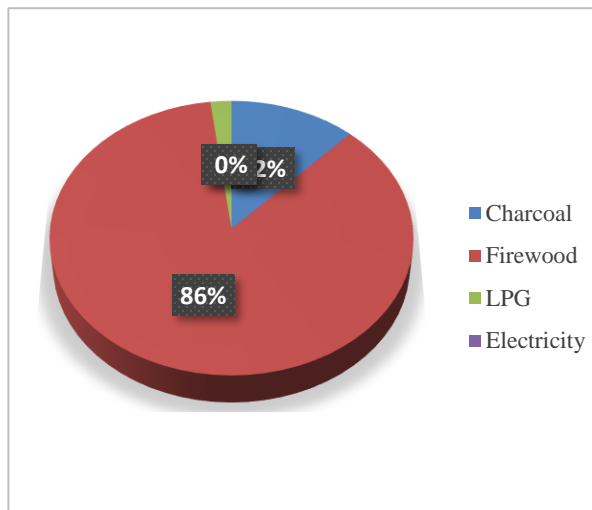


Figure 8: Primary source of fuel used

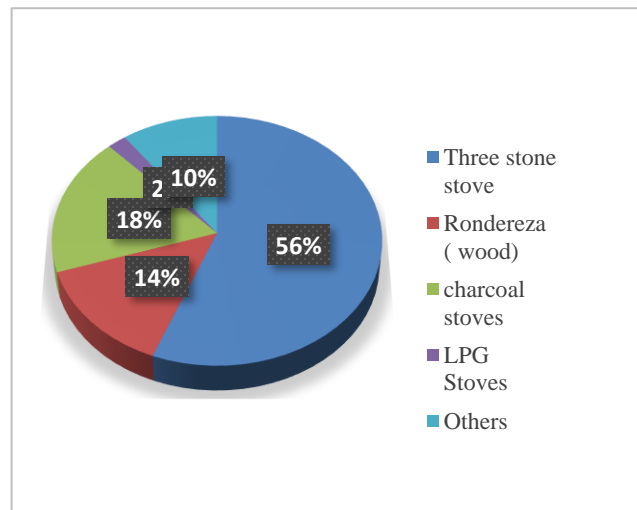


Figure 9: Primary cookstoves used

Cooking diaries were collected using electric pressure cookers (EPC) with a smart meter recording the following information: “Device name”, “Time”, “Meal”, “Cook time” and “Units (kWh)”. In the next sections, a brief control and quality results as well as the characterization of the overall experimental campaign are provided.

3.3.2. Cooking diaries

Cooking diaries were collected using electric pressure cookers (EPC) with a smart meter recording the following information: “Device name”, “Time”, “Meal”, “Cook time” and “Units (kWh)” data were recorded from the 1st of June to 23 of August 2022. Figure 10 shows the distribution of energy per device for the entire period of the experimental campaign. The minimum total consumed value was observed for device EMO-047 with only 0.01 kWh. On the other hand, the maximum value was observed in device *EMO-044* with 30.93 kWh.

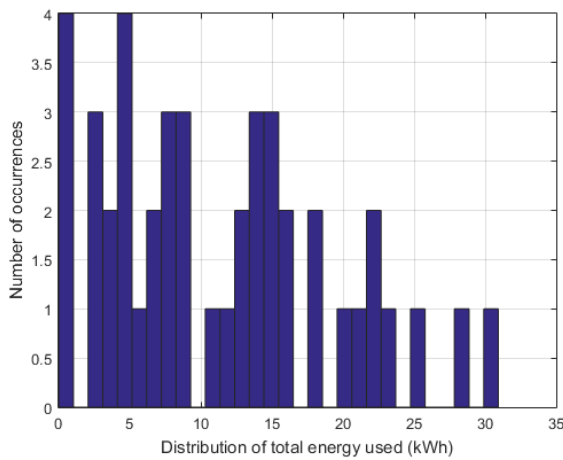


Figure 10: Distribution of the total energy used during the experimental campaign per device

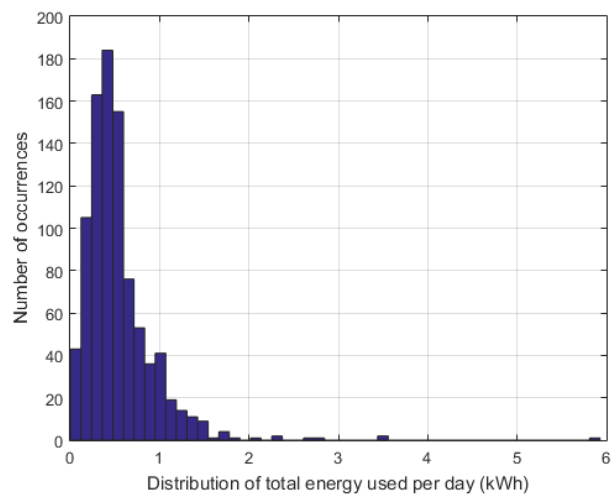


Figure 11: Distribution of total energy consumed per day

Figure 11 show total energy consumed on a daily scale; the maximum value was observed in device 'EMO-044' with 5.92 kWh. In several days the EPCs were not used.

3.4. Demand assessment and development of load profiles

Data collected from the previous action was used to perform the analysis in order to develop suitable load profiles. The experimental campaign enables to determine daily profiles of the electricity demand associated with each smart meter. Therefore, it is possible to understand the cooking daily patterns and the energy needs, which are relevant parameters for properly design a standalone power system. As an example, figure 12 shows the maximum hourly energy identified during the whole period analysed is depicted.

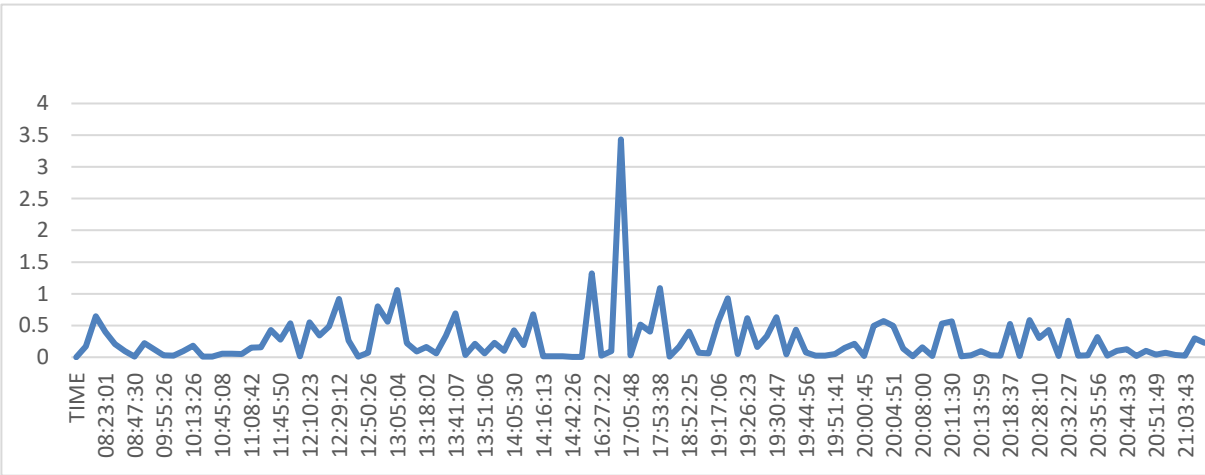


Figure 12: Energy profiles for all days for the device “EMO-044”,

CHAPTER 4 DESIGN OF A DC SOLAR POWERED ELECTRICAL COOKER

4.1 Introduction

Any cooking plate design must respect standards of cooking rated power. Table 3 shows different cooking appliances and their respective nominal power. This research focused on the hot cooking plate. The required power of this cooking plate was around 1000 Watts. The present design is a DC system, with a purpose of reducing power of the existing AC electric pressure cookers. In addition, the V_I characteristics of the PV versus the irradiance variation must take into consideration since in data collection chapter, it is realized that some households can cook in morning in daytime and in the evening. Therefore, a PID control was designed for the DC solar powered electrical cooker.

Table 4: Power output of home appliances

APPLIANCE	WATTS (ON LABEL)	WATTS (DC)*
Slow cooker / crock	285	----
Bread oven	470	480
Snack oven	650	660
Coffee maker (5 cup)	685	704
Frypan (230mm)	700	752
Sandwich maker	750	803
Toaster	900	982
Hot plate	1100	1099
Microwave oven	1200	----
Electric jug	1400	----

4.2 Sizing of a dc solar powered electrical cooker

Any cooking plate must have some technical specifications such as related current, voltage, and power. In addition to this, a cooking plate resistor must be calculated. For the hot cooking plate, the resistor must be in relation with a standard power.

4.2.1 Power and Voltage of a dc solar powered electrical cooker

A required voltage for the designed cooker must fall in the categories of DC voltage levels such as 12Vdc, 24 Vdc, 48 Vdc and others. While sizing the DC electrical cook stove is to select the proper voltage waveform. A constant wave form could cause high sparks while cooking. Therefore, during the present research, a square wave form voltage was selected.

The equations (4.1), (4.2) and (4.3) show how to calculate the voltage RMS for the cooking plate. However, a voltage must be one of the DC voltages levels standards.

$$V_{average} = \frac{1}{T} \int_0^T v^2(t) dt = \frac{1}{T} \left[\int_0^{\frac{T}{2}} (V_m)^2 dt + \int_{\frac{T}{2}}^T (-V_m)^2 dt \right] \quad (4.1)$$

$$V_{average} = \frac{1}{T} [(V_m)^2] \frac{T}{2} + (-V_m)^2 \frac{T}{2} = \frac{1}{T} (V_m)^2 \quad (4.2)$$

$$V_{rms} = \sqrt{V_{average}} = V_m \quad (4.3)$$

Where T: Switching period; V_m: Nominal voltage; V_{average}: Average voltage and V_{rms}: root mean square voltage.

The voltage is calculated based on the power of the cooking plate. Since the designed DC solar powered electrical cooker is qualified as a hot plate appliance, the reference power is 500W. The nominal current for this type of cooking plate varies between 16 A and 20 A. The following table shows resistors and power rating of each appliance. The voltage reference in table 5 is 220 V AC. Yet, this gives the standards of resistors for various cooking appliances. For a hot cooking plate, the resistor is 5 Ohms.

Table 5: Table. (resistor of cooking plate)

Appliance	Watts (on label)	Watts (DC)*	Resistance (Ohms)
Slow cooker / crock	285	---	1.29
Bread oven	470	480	2.13

Snack oven	650	660	2.95
Coffee maker (5 cup)	685	704	3.11
Frypan (230mm)	700	752	3.18
Sandwich maker	750	803	3.40
Toaster	900	982	4.09
Hot plate	1100	1099	5
Microwave oven	1200	----	5.45
Electric jug	1400	----	6.36

A deep analysis was conducted to find out the voltage that can be appropriate for the design DC solar powered electric cooker. While finding out the suitable voltage for the DC solar powered electrical cooker, the highest level of voltages considered is 120 Vdc because many SHs are limited at that voltage. Table 6 shows that the lower voltage is for the cooker, the high current of the cooker is. 48 Vdc and 96 Vdc cooking appliances have respectively 20.83 A and 10.4 A. These currents are reasonable for cooking appliances since their respective resistors fall in the standards values.

Table 6: Different possible DC voltage levels for the DC solar powered electric cooker with 500W

Voltage (DC)	Current (A)	Resistor (Ohms)
12	83.3	0.14
24	41.6	0.57
48	20.83	2.30
96	10.4	9.23
120	8.33	14.44

4.2.2 Compatibility of Energy required for cooking different dishes with Power of a dc solar powered electrical cooker

From the data collected in this research, the energy consumed to cook each type of food has been recorded and the time taken to get the food cooked. Table 7 shows the average cooking duration of different dishes. Based on the data recorded, the DC solar powered electric cooker can have a good cooking performance compared to the cooking appliance which are on the market. For example, time required for cooking dry beans is 1h55 min and it requires 1.91 kWh. A kW dc solar powered electric cooker can perform the same task withing the same time duration or less.

Table 7: Time taken to cook each dish

Dishes	Food quantity	Cooking time	Energy consumed
Banana, green/ ibitoki bitekwa	1000 g	20 min	0.33 kWh
Beans, red (soaked)/ ibishyimbo bitumbitse	1000 g	45 min	0.75 kWh
Beans, red (dry)/ ibishyimbo byumye	1000 g	1h55 min	1.91 kWh
Beans, fresh shell/ ibitonore	1000 g	30 min	0.5 kWh
Beef/ inyama z'inka	1000 g	35 min	0.58 kWh
Cassava/ imyumbati	1000 g	40 min	0.66 kWh
Cassava flour/ ubugali	1000 g	30 min	0.5 kWh
Chips/ ifiriti	1500 g	60 min	1 kWh
Eggs, hard-boiled/ amagi atogosheje	Any amount	15 min	0.25 kWh
Chicken/ inyama z'inkoko	1000 g	30 min	0.5 kWh
Maize flour/ kawunga	1000 g	30 min	0.5 kWh

Peas, green/ amashaza (urunyogwe)	1000 g	25 min	0.41 kWh
Pumpkin, green/ igihaza	1500 g	30 min	0.5 kWh
Rice, white/ umuceli	1000 g	20 min	0.33 kWh
Potatoes, irish/ ibirayi	1000 g	20 min	0.33 kWh
Yam/ amateke	1000 g	25 min	0.41 kWh

4.3. Economic analysis of a DC solar powered electric cooker

DC appliances are known to be cost effective, because the system doesn't need the inverter between the battery and the appliance which also increase efficiency of the system. Particularly, DC solar powered electric pressure cooker is more efficient compared to an AC pressure cooker. Table 7 shows the calorific value of fuel that is used and this gives amount of energy required to cook a dish for a determined time.

Table 8: Fuel calorific values[27].

Fuel	Calorific value
Wood	15.9 MJ/kg
Charcoal	29.9 MJ/kg
LPG	44.8 MJ/kg
Electricity	3.6 MJ/kWh

Taking an example of cooking dry beans, using charcoal and wood cook stoves will take around 3-4 hours to get cooked, while with the EPC it took 1h 55 min which is almost double the time using wood and charcoal.

The use of EPC over wood and charcoal reduces the price of fuel and cooking time by two. For the case of a DC solar powered electric cooker, a hot plate, the time for cooking will be the same. However, referring to the structure of any type of a pressure cooker, electric or traditional, the cooking time can be reduced by factor of two or four. Therefore, the designed DC solar powered cooker can be applied to a DC EPC and the cooking time will be reduced by factor of two or four. The following table gives the cooking time for each dish.

Table 7: Comparison of energy consumed by AC EPC and DC EPC per dish

Dishes	Food quantity	Cooking time	Energy consumed by AC EPC (kWh)	Energy Consumed by DC EPC(kWh)
Banana, green/ ibitoki bitekwa	1000 g	20 min	0.33	0.165
Beans, red (soaked)/ ibishyimbo bitumbitse	1000 g	45 min	0.75	0.375
Beans, red (dry)/ ibishyimbo byumye	1000 g	1h55 min	1.91	0.955
Beans, fresh shell/ ibitonore	1000 g	30 min	0.5	0.25
Beef/ inyama z'inka	1000 g	35 min	0.58	0.29
Cassava/ imyumbati	1000 g	40 min	0.66	0.33
Cassava flour/ ubugali	1000 g	30 min	0.5	0.25
Chips/ ifiriti	1500 g	60 min	1	0.5
Eggs, hard-boiled/ amagi atogosheje	Any amount	15 min	0.25	0.125
Chicken/ inyama z'inkoko	1000 g	30 min	0.5	0.25
Maize flour/ kawunga	1000 g	30 min	0.5	0.25

Peas, green/ amashaza (urunyogwe)	1000 g	25 min	0.41	0.205
Pumpkin, green/ igihaza	1500 g	30 min	0.5	0.25
Rice, white/ umuceli	1000 g	20 min	0.33	0.165
Potatoes, irish/ ibirayi	1000 g	20 min	0.33	0.165
Yam/ amateke	1000 g	25 min	0.41	0.205

CHAPTER 5 SIMULATION AND RESULTS

5.1. Proposed DC solar powered electric cooker topology

Figure shows the proposed topology. The topology is based on a microcontroller, ATmega328P – 8-bit AVR family microcontroller, as the main part of the hot cooking plate. With the microcontroller, the MPPT controller implementation is easier. The MPPT was implemented based on the PID. The PID must follow the V_I characteristics of the PV and the required cooking plate power. The topology has also the temperature sensor, LM35 temperature sensor which is used to control the heat of the cooking plate. The cooking plate sources the current from the MOSFET, IRFZ44N which is a N-channel MOSFET with a high drain current of 49A and low Rds. There is an LCD display to visualize some date related to the cooking plate and a DC power supply of 12 Vdc. In case, the cooking hot plate is integrated into the SHs, the power supply is sourced from the whole SHs whereas in case the hot coking plate is a standalone system, an appropriate PV is sized for the cooking plate. Figure 13 presents different components used in prototyping the DC solar powered electric cooker. Figure 14 shows the experimental set up. The set-up scales down the prototype since the available power supply is 12 Vdc. The target of the experimental set up is to test the feasibility of the cooking hot plate based on a PV system.

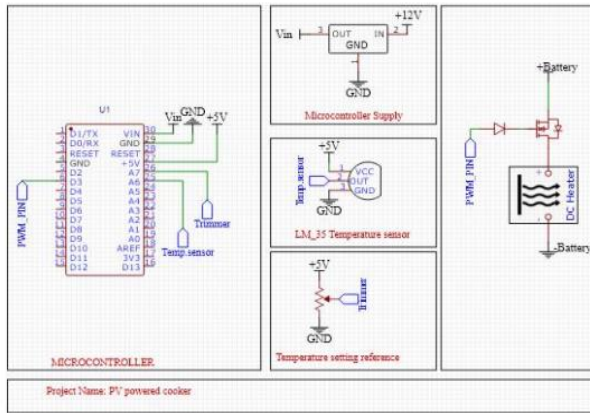


Figure 13: Topology

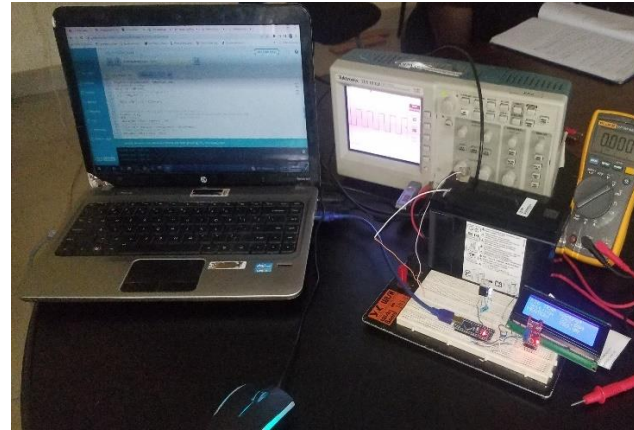


Figure 14: Hardware prototype at earlier stage

The simulation results showing the behaviour of the PID under different temperature. The period is decreasing as the temperature increase. Fig 15, fig16, fig 17 and fig18 show the wave form at 25%,50%,75% and 96% of 100°C. The period of the signal remains constant; However, the signal time remains high and low can vary within a period. Table show how the duty cycle change with the temperature.

$$Duty\ cycle = \frac{T_{on}}{T_{on}+T_{off}} \quad (4.4)$$

Table 8: Duty cycle change with the temperature

Temperature	Ton (ms)	Toff (ms)	Duty cycle
25%	740	260	0.74
50%	500	500	0.5
75%	200	800	0.2
96%	100	900	0.1

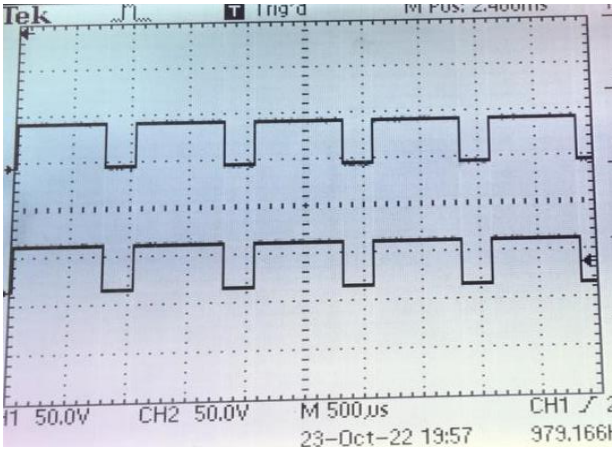


Figure 15: Signal at 25%

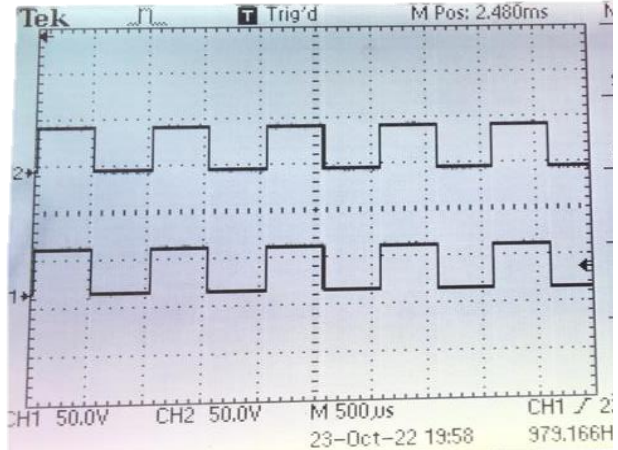


Figure 16: Signal at 50%

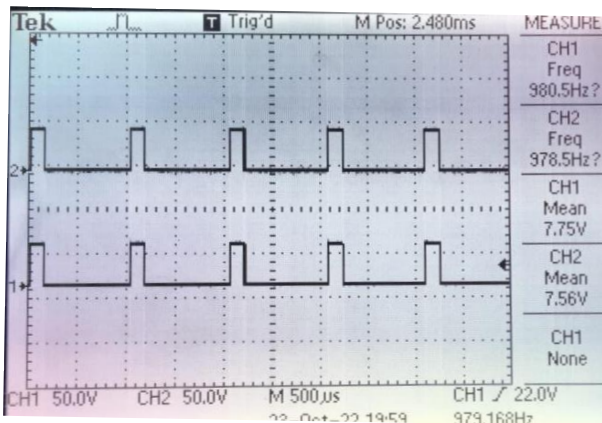


Figure 17: Signal at 75%

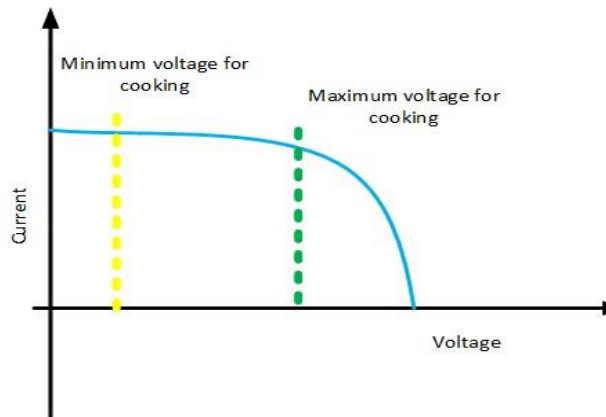


Figure 18: Maximum power control using PID

The developed DC solar electric powered cooker has the ability to control the power referring to the change of the input voltage from a PV system for its supply. This is done by controlling the gate signal for the MOSFET using PID. The PID was implemented in the arduino using the PID library. Figure 15, 16 and 17 show the variation of the voltage and the duty cycle referring to the change of the temperature of the cooking plate which reflects the power and the voltage from a PV system. The minimum voltage is set based on the curve on the figure 18. On the figure, there are minimum voltage and maximum voltage for cooking.

5.4 Conclusions

The world is striving to achieve the total transition to clean energy, Clean cooking is one of the areas that are being prioritized. This study has shown that cooking with electric pressure cooker is economic, clean and time saving. The proposed DC solar electric cooker will halfly reduce energy consumed and time over wood and charcoal to cook the same food. The designed electric DC electric cooker can be extended to a DC electric pressure cooker to reduce significantly the energy consumed while cooking. The most energy consuming dish was dry beans. However, to save energy it is recommended to soak them to reduce energy and time taken to cook. The designed cooker has the ability to control the power referring to the change of the input voltage from a PV system for its supply. This is done by controlling the gate signal for the MOSFET using PID.

5.5 Future work

This study was limited to the electrical design of DC solar powered electric cooker; therefore, it recommends to do further studies on its housing, mass and heat transfer specifically for DC Electric pressure cooker to increase that could improve its efficiency.

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ANNEXES

Annex 1: Pre-screening and Launch survey questionnaire

	District:
	Sector:
	Please enter the respondent phone number
	Background Recorded GPS.
	Please enter the household ID
	Survey Start Time
Section 1: Household Information	
	1. Do you cook for this family?
	2. What is your name?
	3. What is your age?
	4. What is your gender?
	5. What is your marital status?
	6. What is your mother tongue?
	7. What is the highest level of school that you have completed?
	8. What is your occupation or work?
	9. What is the sub category of the occupation?
	10. Occupation details
	11. Where do you do this work? ie location at which they perform these activities
	12. Are you the head of the household?
	13. What is your relationship to the head of the household?
	14. What is the head of the household's age?
	15. What is their mother tongue?
	16. What is the highest level of school that the head of the household has completed?
	17. What is the head of household's occupation or work?
	18. Adscription of the work

	19. Where does the head of the household work? i.e. location at which they perform these activities
	20. Can you list your relationship with people who live in this household?
	21. How many people are members of this household?
	22. How many members of the household are male?
	23. How many members of the household female?
	24. Whose phone number is this?
	25. What is the name of the phone owner?
Section 2: Cooking Information	
	1. Counting the frequently absent, how many people do you cook for in your household?
	2. Minus the frequently absent, how many people do you cook for in your household?
	3. Counting the frequently absent, what's the total number of people who cook in your household?
	4. Minus the frequently absent, what's the total number of people who cook in your household?
	5. How frequently in a day do they help you to cook?
	6. How many days in a week do they help you to cook?
	7. Which electric cooking appliances do you have in your household?
	8. Which is your most used cookstove?
	9. Which is the next most used cookstove?
	10. How much did cost to buy or to build?
	11.. For how long have you used
	12. Which cooking tasks do you use for?
	13. Which cooking fuels do you use?
	14. Which cookstove(s) do you use ?
	15. On average, how many meals has your household eaten per day in the last 7 days?

	16. On average, how many meals with meat has your household eaten in the last 14 days?
	17. Does your household take breakfast?
	18. Who decides what's taken for breakfast?
	19. What is the most frequent type of breakfast that was prepared in the last 21 days?
	20. At what time does preparation of breakfast normally start?
	21. At what time is the breakfast normally ready for taking?
	22. Does your household eat lunch?
	23. Who decides what's eaten for lunch?
	24. What factors inform the decision of what to prepare for lunch?
	25. What is the most frequent type of lunch that was prepared in the last 21 days?
	26. On average, how many times have you prepared lunch in the last 7 days?
	27. At what time do you normally start preparing lunch?
	28. At what time is lunch normally ready for eating?
	29. Minus the frequently unavailable, on average, how many people have eaten lunch in your household in the last 21 days?
	30. Does your household eat supper?
	31. Who decides what's for eaten for supper?
	32. Who prepared supper more times than everyone who cooks in the last 21 days?
	33. What factors inform the decision of what to prepare for supper?
	34. What is the most frequent type of supper that was prepared in the last 21 days?
	35. On average, how many times have you prepared supper in the last 7 days?
	36. At what time do you normally start preparing supper?
	37. At what time is supper ready for eating?
	38. Minus the frequently unavailable, on average, how many people have eaten supper in your household in the last 21 days?
Section 3: Electricity Information	
	1. Do you have an electricity connection (mini-grid)?
	2. Which mini-grid provider are you connected to?
	3. When were you connected to electricity?

	4. Do you have an electric meter which measures electricity?
	5. Is your meter Prepaid (tokens) or Post-paid?
	6. Is your meter individual or shared with other households?
	7. Do you have rules set up by the head of the family or landlord or mini-grid provider on electric usage or use of electric appliances?
	8. Do any of these rules affect your appliance usage? Please explain.
	9. How many rooms does your main house have?
	10. Can you tell me how many sockets there are in the entire house?
	11. Does your main house have a living/sitting room?
	12. How many sockets do you have in the living/sitting room?
	13. Does your main house have a kitchen?
	14. How many sockets do you have in the main house kitchen?
	15. Do you have an outside kitchen?
	16. Does the outside kitchen have electricity?
	17. Please explain why it wasn't connected
	18. How many sockets do you have in the outside kitchen?
	19. Can you cook in the living room if you get an electric pressure cooker? Note that an electric pressure cooker doesn't smoke
	20. I'd now like to ask some questions about blackouts that you have experienced
	21. How long after power goes off do you consider yourself as being in a blackout?
	22. Why does the time you've mentioned constitute a blackout to you?
	23. Have you experienced any blackouts in the last 7 Days?
	24. How many blackouts on average have you experienced?
	25. How long was the longest blackout in the last 7 Days?
	26. How short was the shortest blackout in the last 7 Days?
	27. You said you cook supper between and $\{supper_ready\}$. How many of the blackouts in the last 7 Days happened around that time?
	28. Think back to the last 3 months - How many blackouts have you had in total?
Section 4: Income and Property Information	

	1. Do you have a cooking business?
	2. What do you cook and sell?
	3. Where do you do the cooking business?
	4. Do you sell cow milk when available?
	5. Do you do any other business?
	6. Which business is that?
	7. Are you a renter, do you live with family or do you own this house?
	8. Does your household own any land?
	9. How many acres of land does your household own?
	10. What size of the land you own is used for agricultural purposes?
	11. Please select all the crops you grow or have grown on the land you own in the past year?
	12. Does your household rent any land from someone?
	13. How many acres of land does your household rent?
	14. What size of the land you rent is used for agricultural purposes?
	15. Please select all the crops you grow or have grown on the land you rented in the past year?
	16. Does your household rent out any land?

Annex 2: Households visit questionnaire

Section 0a - Introduction
Who is conducting the interview?
Please enter your ID
District:
Sector:
village
1a. Household Information: The Cook
1. What's your relationship with person who was interviewed the last time?

2. Do you cook for this family?
3. What is your name?
4. What is your age?
5. What is your gender?
6. What is your marital status?
C7. Are you the head of the household?
8. What is your relationship to the head of the household?
1b. Interest in study participation
1. Are you considered a decision maker by the head of this household?
2. Are you able to make cooking decisions on behalf of this household?
3. Are you willing to progress to the next phase?
4. If yes, what are your expectations?
5. Are you willing to receive a weighing scale?
6. Are you willing to return the weighing scale after this phase which ends in 3 weeks?
7. Are you willing to take care of the weighing scale and ensure that it's in good condition when returned?
8. Are you willing to attend an organized training on how to record your cooking information and how to use the weighing scale?
9. Are you willing to record how you cook meals and the weight of fuel that you use during cooking, once you receive training?
10. Are you interested to use an electric pressure cooker if selected?
11. Will you be willing to use the pressure cooker for cooking meals of your choice for at least 6 months after receiving it?
FO: In a scale of 1-5, how do you rate the Respondents willingness to continue the next rounds of Survey?