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ACE One cook stove: Determination of optimal feedstock and performance of integrated home charging system.

Thato Qoola

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Abstract:

The study was conducted to evaluate the performance of ACE One cook stove which is manufactured by African Clean Energy (ACE) in Lesotho by assessing the performance of different solid biomass fuels within the stove. Pellets, pine wood, corn cobs and cow dung provided by ACE were used in this study where cooking time, energy consumption, heat transfer, combustion temperature and particulate matter emissions were assessed. The heating values were determined using Proximate Analysis, the values ranged from 13.43 MJ/kg for cow dung to 17.65 MJ/kg for corn cobs. Measurement of air pollutants were performed using mobile air quality monitor and combustion temperature measurements were performed using infrared thermometer. The temperature was measured for each fuel and the highest temperature was found when using wood, about 460 °C, followed by corn cobs with 370 °C, pellets with 340 °C and cow dung with 290 °C. However, the pellets had the most sustained heat compared to other fuels. Using wood and corn cobs transferred heat faster due to their big flame and raised the temperature of the water quickly. When using wood, water in a pot gained 610 kJ in 9 minutes, with corn cobs, pellets and cow dung, energy gained was 410 kJ, 350 kJ and 240 kJ respectively. Water Boiling Tests (WTB) results showed that the use of cow dung required much more fuel and an extended cooking time compared to other fuels. The second WBT using a different mass to test refuelling showed that refuelling slowed the cooking process. When burning the fuels in a closed room, the $PM_{2.5}$ emissions for all the fuels were above 425 μg/m^3, which was considered as hazardous level. Cow dung emitted more particles than other fuels during combustion which lasted longer in a room. The pellets showed the lowest emissions of them all in both open and closed room. In a closed room, the highest value for the pellets was 800 μg/m^3 while other fuels had reached 999.9 μg/m^3. The values obtained when burning the fuels in an open room had shown a significant decrease in emissions, 60.3 μg/m^3 for pellets, 144.7 μg/m^3 for wood, 234.2 μg/m^3 for corn cobs and 612.4 μg/m^3. The study further assessed the performance of the charging system that comes along with the stove. The power dissipated by the solar panel in this study was less than its rated power. The highest value from 4 experiments done one different days was 8.57 W. Time taken to charge the stove with a wall charger was shorter than using a solar panel. Using the battery of the stove to charge a cell phone has shown high power usage but using it for powering LED lamp has shown to be discharging the battery at a very slow rate.

Chapter 1: INTRODUCTION

1.1 Background

The unfavourable outcomes of climate change have imposed the need to consume energy resources efficiently and to ensure sustainably with minimum negative impact on the environment. The use of biomass as a primary energy source is one of the major contributing factors to climate change, by both land degradation and air pollution caused by smoke [1]. The resulting air pollution from Household Air Pollutions has been associated with global climate change since emissions mostly include chlorofluorocarbons [2]. Burning biomass in open fires requires huge quantities of fuel to complete the cooking process, it is also associated with high energy losses and high emissions of smoke.

The air pollution from the smoke causes respiratory diseases and about 3 million people are reported to be dying every year from pulmonary diseases resulting from burning biomass. This intensive use of biomass is driven by huge gap between energy demand and supply in developing countries [3]. In Lesotho, about 60 % of the population living in rural areas live without access to electricity and rely on other forms of energy such as burning coals and trees to cook [4]. People living without access to the grid depend on biomass and fossil fuels to meet daily energy needs, and the country has to import these fossil fuels [5]. Over 95 % of the rural population depends on solid biomass for lighting, heating and cooking [6]. In Table 1, the data collected to find the number of households and the type of energy source they use for cooking only is shown.

Table 1 ; Number of households and energy sources;[7]

	Energy Sources					
Districts	**Electricity Grid**	**LPG**	**Paraffin**	**Wood**	**Animal dung**	**Straw/shrubs/grass**
Botha-Bothe	149	384	399	8,807	292	583
Leribe	240	784	603	13,724	225	244
Berea	62	261	257	7,602	102	317
Maseru	187	667	480	13,423	412	850
Mafeteng	26	177	177	3,544	228	63
Mohale'shoek	18	355	251	4,970	75	5,651
Quthing	95	465	321	8,490	299	134
Qacha's Nek	130	380	271	6,596	794	39
Mokhotlong	68	671	456	9,888	2,967	2,730
Thaba-Tseka	25	748	477	17,069	1,639	4,862
Total	**1,000**	**4,892**	**3,692**	**94,113**	**7,033**	**15,473**

From Table 1, it could be seen that, out of 126 203 households interviewed from all districts of Lesotho, total of 116 619 households depend on wood, animal dung and straws while other households use other fuels (electricity grid, LPG and paraffin). Wood is the most consumed fuel with 94 113 households, followed by straws/shrubs/grass with 15 473 households. Wood and shrubs are harvested from communal owned woodlands, This could create an environmental hazards as the wood resources are rarely replenished in Lesotho [8].

In developing countries, the need for biomass as a source of energy is expected to remain significant for the next 30 years [9]. About 2.7 billion people in developing countries will depend on wood as their fuel by 2030, of which 720 million people will be from Sub-Saharan Africa [10]. Therefore, shifting to clean and efficient energy strategies is very crucial to reduce high consumption of solid biomass [11]. The harmful effects of biomass on the ecosystem can be reduced by adopting modern energy efficient technologies.

Improved Cook Stoves (ICS) make part of such technologies because they are generally equipped with combustion chamber and some with fans to reduce Indoor Air Pollution (IAP) from smoke created by the burning fuel. A properly designed stove has a thermal efficiency greater than 20 % as compared to open fire with less than 10 % efficiency [12]. With this improved efficiency, the productive use of biomass has a potential to displace fossil fuels [13].

On the other hand, the cost of fossil fuels is very high because Lesotho has to import them, and is one of the reasons locals depend on the biomass fuels for the foreseeable future. Therefore, deploying ICS can help the country to use available fuels in a sustainable manner and achieve Sustainable Development Goals (SDGs) by 2030, mainly SDG 7.

The differences in stove designs and testing protocols are expected to result in different combustion efficiencies, heat creation, emissions and cooking time [14]. Likewise, depending on its physical and chemical properties, each fuel will create a different heat mechanisms and emissions [12]. Detailed information regarding fuel efficiency and emissions from burning different types of biomass from different types of stoves is necessary to help identify the types of biomass which create more heat and one with more emissions during combustion. The information can lead to appropriate measures being taken for reducing the biomass pollutants, so that biomass becomes a preferable form of sustainable energy [15].

There is a wide array of studies that evaluate performance of different cook stoves without incorporating multiple fuel usage such as [16], [14], [17], [18], [19], [20], [15] . Also, fuels species differ from country to country. Some studies carried out by [21], [22], [23], [24], [25] were aimed at assessing performance of fuels and stoves which were used at the regions of their studies, and concluded that different fuels and different stoves resulted in different thermal performances and emissions. This study will therefore evaluate performances of commonly used fuels in Lesotho in ACE One cook stove.

ACE One cook stove is manufactured by a Lesotho based company which manufactures energy systems to help people living in rural areas to use biomass efficiently while meeting other electricity needs such as lighting and charging cell phones. The energy systems have an improved cook stove equipped with a built in fan and battery, solar home system used for charging the stove and LED lamp. The stove can also be used for charging cell phones.

1.2 Problem statement

Household fuel selection depends on affordability, accessibility and availability and people go for locally available fuels usually due to their lower costs [9]. Unfortunately, efficiency and health risks seem to be way down the priority list of factors commonly considered when choosing fuels. One of the key factors hindering achievement of Sustainable Energy for ALL (SE4ALL) in Lesotho due to limited number of technologies which improve efficiency [6]. In addition, there is no detailed information about the performance of available fuels in Lesotho using ACE One cook stove which states their emissions, heat creation, fuel consumption and their impacts to the user.

The focus of previous researchers has been mainly on comparing efficiency of different cook stoves. Since the combustion process does not depend on the stove design only, fuel used is also an important factor which has to be incorporated when evaluating the stove performance. This combustion process itself is also affected by physical and chemical properties of fuel such as density, moisture content, size, shape, quantity, carbon content and surrounding air, it also varies with fuel species which need to be determined [13].

The ACE One Cook stoves, which will be the subject of our studies, have been appraised by some buyers in Cambodia. The buyers appreciated features such as LED lamp which they used to provide light and Solar Photovoltaic (PV) system that comes with the stove which they use for charging their cell phones. The Solar PV system seemed to be contributing to the decision of buyers as it would help them meet their basic electricity needs [26]. So it is important to know the performance of the charging system maximum power, battery capacity and charging times since the stove does not indicate when the battery is fully charged and how long it can last the owner if used for different purposes

1.3 Research Questions and Objectives

This research work seeks to determine the optimal feedstock and performance of integrated charging system of ACE One cook stove. This is done so that the stove can be used optimally to benefit the end user. The evaluation is done by comparing the performance of different types of solid biomass fuels generally used in Lesotho by the users of the stove. The performance of the stove with different fuels will be based on the following parameters: thermal performance of fuels, concentration of pollutants of particulate matter inside the room during cooking and the impacts of each fuel based on duration of cooking and fuel consumption.

Additionally, this study tested the performance of the charging system of the stove. In this case, the scope of the study is not extensive. Rather it, seeks to provide anecdotal evidence that will open room for more detailed and systematic studies in the future.

The research is conducted by answering the following questions;

- Which solid biomass fuel is more efficient?
- How are the stoves owners likely to be affected by the behaviour of these fuels?
- How much power can be harvested from the Solar PV system that comes along with the stove?
- How long does it take for a solar panel to fully charge in comparison to a wall charger?
- At what rate does LED lamp and a cell phone discharges the battery of the stove?
- How many times can a full charged battery of the stove be used to charge a cell phone?

In order to achieve the goal of determining the performance of the ACE One cook stoves, this goal is broken into the following objectives;

1. To assess efficiency of biomass fuels in terms of thermal performance and emission of pollutants using local fuels.
2. To assess how each fuel affects user in terms of cost: collection time, availability, affordability, accessibility.
3. To find how much power can be harvested from the solar panel on a clear day.
4. To evaluate how long it takes for a solar panel to fully charge in comparison to a wall charger.
5. To assess the power usage of LED lamp over time and mobile phone.
6. To find a number of times a cell phone can be fully charged using the fully charged battery of the stove until the battery of the stove is fully discharged.

1.4 Justification

This research sought to find efficiency and efficacy of locally available and commonly used fuels in Lesotho using ACE One modern cook stove which is also made and sold in Lesotho. This will help users of the stove to make an informed choice of fuel. Using a fuel with minimal smoke will reduce the number of deaths resulting from respiratory diseases by users. Assessment of costs of fuels helped identify which type of fuel is less costly in terms of health impacts, time consumption, and fuel consumption.

Results obtained from different studies are often characterized by testing methods, and may not represent real-world performance [27], [28]. Therefore, more tests needed to be done on cook stoves to improve existing technology by implementing strategies of clean energy dissemination and develop more effective technologies. Identifying the types of biomass with more emissions during combustions will lead to measures for reducing such pollutants. Estimating pollutant amounts from solid biomass fuels is also essential for environmental evaluation [2].

Solar panels are rated at specific conditions, those do not represent the maximum potential output. There might be a difference in power dissipated by the solar panels which are at different geographical locations due to different conditions such as irradiation, operating temperature, air mass, etc. It is very important to know how much power the panel of the stove gives when operating at different locations beside Standard Test Conditions (STC). It is also important to know charging time of the stoves to avoid overcharging, power that the stove users are able to get, which will also differ from place to place and also give an overall view of performance of the stove and the Solar PV system in real life situation.

The significance of the study

The study will provide information regarding performance of different fuels in ACE One cook stoves on how fuel properties affect the performance of the stove. This will also help stove manufacturers to know the performance of their product without comparing with other stoves but when using different fuels.

1.5 Lesotho's energy background

Access to modern energy remains an issue for people living in rural areas of developing countries, Lesotho is not an exception. It is small country with area 30, 355 km^2 with a population estimated to 2 million, about 66 % of the country is sparsely populated, villages are scattered over mountain sides [29]. The country has 4 ecological zones, foothills covering 15%, lowlands with 12 % and the smallest portion is Senqu valley with 8 % and finally the mountains which constitute 65 % of the country's area [30]. This means that majority of the population is found in rural areas, this makes it expensive to connect such villages to the national grid, and as a result only 40 % of the population has access to the grid [4]. About 60% of the population has to use conventional fuels and biomass fuels to meet their energy daily needs. Since Lesotho is a very cold country with some regions at an altitude of 1, 800 m and above; temperatures often fall below freezing point in winter, fuel for space heating is a basic need, people in rural areas mostly depend on biomass fuels while people in urban areas are less reliant on biomass, they mainly depend on paraffin [7].

From the 1970s to 1998, Lesotho was fully relying on imported electricity from Electricity Supply Commission (ESKOM), is a South African electricity utility [31]. 'Muela hydro power plant was only completed in 1998 with 72 MW installed capacity but could not meet the local demand entirely yet electricity import declined steeply [31]. Although 'Muela hydro power is a vital relief, it depends on rainfalls in which during dry seasons, electricity generation decreases. As the country further developed economically, the electrification rate also increased from 22 % in 2011 to 42 %

in 2015, which then increased demand-supply gap, the peak demand can be as high as 155 MW in winter, with the national deficit of 44 % [31]. The demand is sometimes met by importing from Mozambique's electricity utility, Electricidade de Moçambique (EDM) [32]. Although the country is a member of Southern African Power Pool (SAPP), the electricity supply is not guaranteed, people therefore have to rely on multiple fuels for energy security.

Ministry of Energy and Meteorology (MEM) started to invite and attract local and foreign investments in energy programmes as stated in the energy policy (2015-2025), its target is to ensure that by 2020 and beyond, the country's energy demand can be met by local generation [31]. Lesotho has a potential to make use of various renewable energy resources: biomass, hydro, wind and solar, these can be exploited to meet the local demand. These resources require planning and evaluation before tapping into them to achieve stability in the energy sector. However, there are some constraints limiting renewable energy technologies' development in the country. These include lack of awareness among citizens about environmental benefits of using renewable energy and, financial barriers [32]. Large scale power plants require high initial costs hardly affordable to a poor country like Lesotho. Commencing such big projects will need the involvement of foreign investments [1].

Houses in rural areas are mostly single room huts with thatched roof, the daily energy demand is very low in such households, those with access to the grid consume about 0.5 to 1.5 kWh per household each day [29]. Most households generally consume a combination of energy sources such as biomass, LPG, kerosene and electricity for cooking. Biomass fuels are mostly used for cooking. Alternative energy options are limited to candles and kerosene for lighting, as a result electricity consumption by households is very low in the country [29].

Income levels in rural areas are lower than in urban areas because of underemployment and unemployment in those areas [29]. Moreover, income levels of households are constraints to their fuel choices. Biomass is therefore likely to remain an important source of energy for the majority of people living in the rural areas. Shifting to cleaner fuels is a challenge to people living in Lesotho which has the poverty rate of over 50 %, among the highest in the world [33]. The poverty rate lowers efficiency because household fuel selection also depends on affordability in low and middle income countries [34].

The shift from traditional fuels to modern fuels is discoverable in urban areas as some are employed and do not have time to harvest wood. Others are also more informed about pros and cons of different fuels. The types of houses in urban areas also do not allow the residents to use biomass due to the soot from the fuels which would sojourn in their houses. They can also access fuels like paraffin and LPG easily as transportation is more accessible while people living in rural areas have to walk long distances to obtain these fuels. Transportation in such villages is a problem, they have to carry heavy loads or use donkeys as a means of transport. This lack of transportation discourages some households that can afford to shift from traditional fuels to modern fuels.

Lack of clean energy results in little economic growth as energy is a key to socio-economic progress for developing nations, it can be used in income generating activities. People living in places without electricity lack facilities such as health facilities, information sources such as radios, televisions and cell phones and this therefore leaves them in the dark about current affairs. Lack of energy also subsequently leads to poor education. Sometimes children spend time collecting wood instead of focusing on their studies and when they eventually have time to study in the evening, they have to use candles, kerosene or biomass. Energy insufficiency in schools is another contributing factor to poor education, learning materials cannot be multiplied to facilitate learning and frequent assessment is prohibited because of lack of electrical equipment.

Some villagers use small diesel generators for power demands such as lighting, charging cell phones, powering radios and televisions in their homes, but high costs of diesel force them to use their generators at night only to save energy. Use of these systems often result in high energy losses, breakdowns and post a threat to peoples' lives due to lack of skills in accurate connections [29].

As a result, Lesotho's energy sector faces a challenge of energy security because of low access to clean energy and reliance on imported fuels and electricity. There is no security of energy supply where often there is no connection to the main grid [35]. Reliance on traditional practices of biomass consumption and declining wood sources have captured the country's attention to improve the energy production, promotion of energy efficiency and conservation of energy resources. Economically viable option for rural areas is the use of sustainable energy resources, household sized systems to lower installation costs of large scale power plants.

Over 95 % of households use biomass for cooking, wood is the mainly used fuel [6]. The country has small areas of woodland cover but deforestation has become a serious problem, woodland cover has been lost at a rate of 0.5 % per year from 1990 to 2010, only 1.6 % of the area was left forested in 2012 because of high households' demand for wood fuel. The country has started importing fuel wood as well [32]. Woodlands covers are important to rural communities as they provide construction materials for their houses and to fence their compounds. Wood also serves as habitat for other animal. Losing forests means some of Sustainable Development Goals are not going to be achieved such as protecting life on land. Up to the present day biomass has been used to meet energy basic needs, which means that land degradation is a long-term problem that will consequently lead to a decline in other biomass sources like agricultural wastes and animal wastes.

Furthermore, degraded land means no grazing land which automatically leads to a decline in livestock. There is also a sharp decline in livestock due to theft in most rural places [31]. This implies that even animal waste used as fuels are limited nowadays. The waste which should be used to improve soil fertility are used elsewhere, crop production decreases as a result and this means a decline in agricultural wastes which can be used as fuels such as stalks and corn cobs.

Declining biomass resources also result in people having to walk long distances to obtain firewood if they can no longer obtain it around their villages where they walk short distances. According to African Clean Energy's 2015 survey of 2,652 rural households in Lesotho, households spent about 31 hours per month travelling for fuel and it is a burden that falls on females because they are the ones who manage energy consumption in the households [32].

The main problem of the use of biomass is that it is burnt in enclosed areas with inadequate ventilation, therefore directly exposing humans to hazardous emissions. When burnt in open fires, combustion temperatures are also reduced due to air entering the fire. This also depends on operating temperatures, when it is cold, and the cooking process will take a long time as cold air affects the burning process. Use of biomass fuels, through burning in low efficient technologies such as traditional cook stoves, result in incomplete combustion and contribute to approximately 2 % of world's GHGs emissions [36]. Thus, there is a need to improve biomass use through adaptation of improved technologies which reduce pollution and increase efficiency.

Excessive dependency on biomass burned in open fires requires a huge consumption of fuel and results in increased emission of pollutants. This also accelerates climate change because forests help in regulation of local temperatures reduces the country's ability to address it. Lesotho is already experiencing climate change which is expected to worsen by 2030, it is expected to see a

1 °C increase in annual mean temperature, which will result in dry seasons and affect Basotho's livelihoods badly [32]. Countries including Lesotho have been conducting clean energy interventions to relieve people depending on biomass from pollution caused by solid fuel combustion.

Adaptation of technologies which could improve efficient use of biomass such as improved cook stoves is crucial to reduce negative effects of biomass. Many intervention studies attempt to shift people up the energy ladder by introducing ICS. Nevertheless, adoption has been low in this country due to reasons which include the stove designs, cultural problems and failure to appreciate the need to save energy especially for people living in rural areas where biomass can be freely accessible [6]. As a response strategy, improved cook stoves have been introduced in Lesotho to overcome these negative effects of inefficient biomass use.

Lesotho is among the countries with the highest solar radiation in the world, with the average of 5 -7 kWh/m^2, majority of the places in the country get about 300 days of sunshine per year [29]. The end users of the ACE cook stove therefore enjoy the benefits of exploiting solar energy to meet their daily energy needs. The stove is sold for $109 (M1560.00) each, to avoid the pressure on household budget, customers are not compelled to pay a lump sum. They are allowed to pay monthly instalment for a period of 9 months. Customers are also given a 2 year guarantee. ACE concentrate on distributing clean energy for people living in rural areas of Sub-Saharan Africa (SSA). The company has been operational in Lesotho since 2013.

1.6 Structure of the thesis

The rest of the paper is organised as follows: chapter 2 is the literature review, chapter 3 presents the methodology and equipment used for undertaking the experiments. Chapter 4 presents the results with their discussions. Lastly, chapter 5 provides the conclusion and some recommendations.

Chapter 2: LITERATURE REVIEW

2.1 Global energy situation

Energy is the commodity that constitutes important aspects of human life and is needed for the existence of everyday life activities. However there is still a large number of people who do not have access to clean energy globally, around 2.8 billion people rely on biomass for cooking and still use traditional methods of cooking [37]. In Africa, over 82 % rely on biomass, only 11 % use clean cook stoves and fuels [38]. Since energy has been and remains the fundamental requirement of humankind, global energy consumption is expected to increase at an annual rate of 1.6 % by 2050 [39]. Over 640 million people living in Africa are expected to rely on biomass by 2040 [39]. This has drawn worldwide attention to mitigate the negative effects of inefficient use of biomass by: supplying clean energy utilities which increase efficiency while reducing emissions [38]. The shift from traditional use of biomass to modern use is not only adopted to reduce climate change but also to avoid household pollution and energy poverty in households. The former and the latter will keep increasing if no immediate action is taken.

2.2 Biomass use

Biomass is often available and scattered over many locations unlike fossil fuels which are mined at certain places. Biomass is also highly heterogeneous in quality and nature but has low heating value compared to fossil fuels and needs to be improved [39]. Although biomass fuels have low calorific value, they are an option to reduce emissions when consumed efficiently. They are also renewable sources which will help in achieving low-carbon electricity supply for power plants while meeting environmental targets on emissions [40]. They can also be used in stoves or burners directly to produce heat or be converted to different forms of biofuels by various chemical and biochemical processes [41]. Biomass fuels can be used in many technologies such as thermochemical, biological conversion and physiochemical rather than being used as fuel [42]. Unlike coal ash, which may contain toxic materials and other trace elements, biomass ash can be used as soil supplement to help replenish nutrients and protect vegetation [43].

To increase biomass efficiency, thermal upgrading of biomass can be carried out whereby pre-treatment of biomass fuel is carried out. Most common processes of upgrading biomass are drying fuels with an aim to reduce moisture of a biomass fuel. They can also be densified through pelletisation to get a more energy-dense fuel. Torrefaction process (heating of biomass to convert biomass into more densified fuel than original biomass) and pyrolysis (a process to convert biomass to other fuels like bio-char, bio-oil and bio-gas) can be carried out [44]. Both processes involve heating of biomass but result in different products because of different heating conditions. Densified biomass fuel has potential applications where coal is currently being used because torrefied pellets have similar properties to coal, such as co-firing, fuel in heating sectors and gasification [45].

These processes of densifying biomass give it a potential to compete as a renewable energy and the only one source of energy which can directly be used in place of coal in many applications. Densifying has raised interest in partially replacing coal with biomass in coal power plants without changing equipment but to decrease consumption of fossil fuels [41].

2.3 Traditional vs modern use of biomass

Traditional cooking is today's largest global environmental health risk [46]. Burning biomass in traditional stoves is considered inefficient, the effects of emissions go beyond risk to human life and affects the environment negatively as well. Traditional cooking may prohibit use of biomass as a sustainable energy [15]. Efficiency of traditional stoves can be as low as 15 % [47]. Meanwhile, a well-designed solid biomass cook stove has efficiency above 20 % [12]. Because of low burning efficiency, biomass used in traditional cook stoves or open fires result in large fuel consumption, relatively high emissions and makes biomass to be a major source of air pollution [48].

From the study carried out by [49], which was aimed at comparing efficiency of different stoves using wood, traditional stove had efficiency of about 14 % while the ICS Greenway, Envirofit, Onil and Natural Draft had efficiencies of about 24.54 %, 23.73 %, 18.23 % and 28.81 % respectively. Efficiencies from different studies carried out to compare traditional stoves against improved ones are shown in Table 2 . The results show an increase in efficiency when using improved cook stoves against the usage of traditional cook stoves. The latter had an efficiency of 18 % when using wood, an increase of about 92 % for New Design and FD, 50 % for Sugam II. When using pellets in a forced draft, the efficiency was found to be as high as 91 %, which is 4 times higher than using a traditional stove with wood and 2 times higher than the efficiency of

New Design stove and FD when using wood. This shows that with densified biomass and a well-designed stove, high efficiency can be achieved.

Table 2; Efficiencies found in different studies when using different fuels

Fuel	Type of stove	Thermal efficiency (%)	References
Wood	New Design	34.72	[49]
	Traditional	18	[50]
	Traditional	13-18	[9]
	Sugam II	27	[51]
	Traditional	16	[21]
	FD	34	[21]
Cow dung	New Design	29.45	[49]
	Traditional	10.5	[50]
	Traditional	12	[9]
	Sugam II	25	[51]
	Traditional	14	[21]
	FD	32	[21]
Crop residues	New Design	27.31	[49]
	Traditional	11	[50]
	Traditional	9-12	[9]
	Sugam II	28	[51]
	Traditional	19	[21]
	FD	31	[21]
Pellets	Forced draft	91	[17]
Wood pellets	Turbo stove(TLUD)2000	31.8	[51]

2.4 Effects of inefficient use of biomass

2.4.1 Household Air Pollution

Burning biomass releases large amount of pollutants like Black Carbon (BC), particulate matter (PM), Organic Carbon (OC), Carbon Monoxide (CO) and other pollutants [21]. PM is sum of particles suspended in air, resulting from man-made activities. Particles' size range from 2.5 µm

($PM_{2.5}$) to 10 µm (PM_{10}). $PM_{2.5}$ particles are also referred to as fine particulate matter, the particles are small enough to penetrate deep in the respiratory tract and reach alveoli [52]. It is a pollutant in both rural and urban areas which is generated by various sources such as dust event, volcanoes, fuel combustion, transportation, etc [53]. Although it is was discovered to be generated by different sources, in African countries, emissions of $PM_{2.5}$ and BC are found mainly in burning biomass [54]. About 43 000 premature deaths in Africa are linked to biomass burning [38].

The National Air Quality standards set by World Health Organization (WHO) recommended average target exposure level of kitchen concentrations (PM) of about 25 µg/m^3 daily and 10 µg/m^3 annually, these values are mean concentrations of the pollutant in the kitchen for the entire period of cooking [51], [52], [54]. However, PM exposure related to biomass use in low income and middle income countries ranges from 200 – 3000 µg/m^3 [52], [54]. This means that people living in these countries are still at high risks of the diseases caused by PM. Air quality monitoring is therefore necessary to assess the pollutant levels in areas where biomass is highly used [55]. Better characterization of indoor air pollution is also essential because residents spent much time indoors than they spent outdoors [27].

Air quality is another concern in the environment which is characterised by Air Quality Index (AQI) [56]). AQI summarises concentrations of multiple pollutants present in the air. Air quality monitoring indicates the level of exposure for particulate matter and AQI. The levels of exposure are categorised against the concentration of pollutants in the air as shown in Table 3. If the air is concentrated with $PM_{2.5}$ of 0-15.4 µg/m^3, then the air quality is considered good. If the concentration of $PM_{2.5}$ is above 65.4 µg/m^3, air is unhealthy to sensitive groups and if it is above 150.4 µg/m^3 then air is unhealthy to all.

Table 3;Levels of pollution exposure [56]

$PM_{2.5}$ (µg/m^3)	**PM_{10} (µg/m^3)**	**AQI range**	**AQI Category**
0-15.4	0-54	0-50	Good
15.5-35	55-154	51-100	Moderate
35.1-65.4	155-254	101-150	Unhealthy to sensitive group
65.5-150.4	255-354	151-200	Unhealthy
150.5-250.4	355-424	201-500	Very unhealthy
≥250.5	≥425	≥501	Hazardous

High emissions from solid biomass combustion affect over 3 million people around the world and cause health issues such as Acute Respiratory Infections (ARI) and Chronic Obstruct Pulmonary Disease (COPD) [57], [27]. Approximately 3.1 million deaths and 3.1 % of global disabilities have been due to $PM_{2.5}$ exposure only [21]. A comparison of the emission of PM from Improved Cook Stoves (ICS) showed that they emit 50 % lower as compared to traditional stoves [58]. If a shift from traditional cook stoves to ICS is done effectively, there is a chance to reduce the high number of deaths related to $PM_{2.5}$ emissions.

Long-term exposure of indoor pollutions put females and children at high risk of sicknesses. The level at which different groups of people are affected by PM emission is different. The comparison was done between women, children, youth and men, where women seem to inhale 1.9 mg/m^3 of PM particles while men inhale 0.6 mg/m^3 [59]. This is more than 2 times lower as compared to inhalation levels in women. Children also seem to be also highly exposed in comparison to men and youth because they spend most of the time indoors with their mothers. Men and youth are not at high risks because they spend more of their time doing outdoor activities.

Emissions from biomass are dependent on the mass of fuel burned and duration of burning. Spending more time in cooking means inhaling more of the pollutants. The results from the study of [1] shows reduction of firewood usage by 15.6 - 37.1 % and time spent for cooking reduced by 22.8- 26.8 % when using ICS compared to open fires. The similar study which was aimed at comparing cooking times for different cook stoves as compared to traditional stove, the findings showed that it took 28 minutes to boil 2.5 litres of water using a traditional stove, a time reduction of 57.1 %, 53.5 %, 42.9 % and 35.7 % when using Rocket stove, Fan stove, Gasifier stove and charcoal stoves respectively [60]. Reducing such impacts which are associated with household energy requires changing technology and behaviour in the cooking styles, by promoting use of ICS which can be fed by already existing fuels yet emit fewer pollutants [61].

2.4.2 Loss of significant amount of time

Besides high emissions, traditional stoves also require dedication of significant amount of time for cooking and collecting large amounts of biomass fuels which takes up several hours [50]. Females are the ones who play a major role in managing and selecting fuels for cooking in the households, collecting firewood is an additional household daily chore to them. The prevalence of depression was significantly higher in women who cook with biomass due to added responsibility [62]. Fuel collection involves long distance walk carrying heavy loads and about 20 % of the time is estimated to be lost every day for collection of firewood, which also leads to drudgery for females by preventing them from engaging in income generating activities [35].

2.5 Challenges of accelerating clean energy adoption in cooking

2.5.1 Stove Designs and fuel feasibility

Interventions of clean cooking solutions with fuel saving and reduced emissions is an important renewable energy solution with far reaching sustainability. ICS action programs were long initiated in the 1970s, driven by the link between deforestation and household consumption of fuel but recently the focus has shifted to the health impacts, therefore interventions are also valued in terms of emission rates [63]. ICS can reduce local and global environmental impacts as well as improving quality of life in the households. However, poor ICS adoption remains an issue. This reflects that stove designs have yet not met user' s needs, there is a need for designing stoves with features that are highly valued by users [64].

Challenges to adoption of cleaner fuels and ICS include, fuel feasibility and its cultural acceptance, female literacy rate and their decision making [54]. There are also important health, environmental and social implications of traditional biomass use [47]. Inaccessibility of fuels is another restricting factor. If cleaner fuels are accessed easily in terms of transportation, availability and affordability, people can adopt easily and shift to sustainable ways.

2.5.2 Social practices

Current practices are shaped by community traditions, for example, women and girls being entitled to gathering wood. Cooking fuel demand and consumption pattern also vary in different households and villages. There are factors affecting the choice such as household size and socio-economic factors [65]. Large households require a significant amount of fuel to prepare food and would therefore opt for cheaper fuels. Open fires in some African countries serve in some societal functions, therefore ICS do not meet these functions and space heating requirements [11].

Women are primary cooks in the communities, but as participants, if they do not see connection between a fuel choice and its negative health impact, they cannot easily adopt the use of improved cook stoves and shift to cleaner fuels. Perception on the risk of Household Air Pollutions plays a big role in the kitchen behaviour. Findings from the study of [34] about solid fuel users' perceptions of household fuel reveal that in some places, smoke was perceived as a positive effect as it protected newborns from insect borne diseases. Smoke was therefore considered as an unavoidable part of daily life. Cooking with cleaner fuels in the communities while the rest are using solid fuels can be considered as disassociating from the community [34]. Time spent on collecting fuel is perceived as an opportunity for social interaction.

On the other hand, women can be a convincing force in ensuring the entire community adopts modern styles of cooking because they have stronger interactions with other women. They can copy the utilization of cleaner fuels from other women. As main players in the fuels selection, intervention of clean energy practises must fully engage them.

2.5.3 Lack of awareness

Technology access is often inadequate in rural areas of developing countries and this reduces the ability to shift from traditional cooking to sustainable options. This is mainly because of lack of knowledge about availability of alternate technologies and lack of awareness about the risks of traditional cooking [66]. In Bangladesh, ICS were not adopted because they were promoted based on health benefits but women as users were not identifying Indoor Air Pollution (IAP) from traditional cooking as a significant health hazard [64]. Most successful stoves programs were found to be in areas where people pay for wood or have to walk long distances to obtain it [47]. This implies that people who can easily access fuelwood and those lacking information about clean energy are still comfortable with traditional cooking and do not see need to shift.

Another convincing force in the community maybe key members. If key members such as ministers, teachers, nurses, etc., adopt clean energy technologies, they could be a very convincing force in the entire community to adopt these technologies [34].

2.6 Factors affecting combustion process and sources of variations in the results from previous studies

2.6.1 Stove Design and fuel type

Technical challenges in the development of clean and user- friendly cook stoves have received attention from researchers leading to implementation of new cook stove designs [51]. Key determinant of adoption of ICS is fuel efficiency, therefore it is important to evaluate the performance of stoves [47]. Stoves which use gasification route with forced air supply are the fundamental design to reduce emissions by providing excess air for the combustion process [51]. Such stoves are equipped with built- in fans.

Performance of biomass cook stove can be characterized by thermal performance in terms of efficiency, fire power, fuel consumption, cooking time and emissions. Emissions are measured by emission factors and emission ratios of pollutants [51], [67]. The performance of the stove also shows a strong dependence on operation parameters [51]. Such parameters are fuel characteristics, ways of refuelling during the cooking process, ambient conditions, ventilation level and material of the pot used. There is a variability in performance results in the literature which is based on different operating conditions such as sampling procedures and combustion technology. Therefore, different stove designs are expected to result in different efficiencies and amounts of emissions. Different fuels will also behave as thus.

For fuels, combustion process is affected by physical and chemical properties of a fuel and components of fuel such as, Moisture Content, Ash Content, Volatile Matter, Fixed Carbon and apparent density [24]. These properties help in determining heating values of fuels. Denser wood contains more energy and tend to burn for longer periods. Increased moisture in the fuel results in decreased amount of heat obtainable because more energy is used to evaporate water contained in a fuel, therefore lowers combustion efficiency [24].

2.6.2 Heating value

Calorific value is heat value released when a fuel is burned in air. It is measured in terms of energy per unit mass for solid fuels. Energy content of fuels can be reported in 2 bases; Higher Heating

Value (HHV) and Lower Heating Value (LHV). The HHV represents the maximum amount of heat obtainable from a fuel, including latent heat of vaporisation [68]. Although heating value of a fuel is an important factor when assessing usefulness of a fuel, there are other factors that dominate heating value like combustion technology [69]. Therefore, actual amount of heat obtainable varies with combustion technology.

Heating values can be determined by using computer models which depend on results from elemental analysis, structural analysis and proximate analysis. Use of proximal determination has gained importance, due to ease the analysis can be performed [70]. Generally, the HHV for biomass fuels ranges from 14-23 MJ/kg, Agricultural biomass have about 15-19 MJ/kg while woody fuels have 18-19 MJ/kg [70].

In Table 4; Results from using different fuels and different cook stoves are shown. The variations of efficiencies, PM concentrations, time taken to cook 1 kg of specific food using different stoves: traditional stove, Natural draft 1 (ND 1), Natural draft 2 (ND 2) and forced draft [21]. The highest emissions were recorded when using cow dung in all types of the stoves, also, time spent when using cow dung was the longest in all the stoves. However, cow dung showed the highest calculated efficiency of 37 % amongst all the fuels when used in FD. The value of efficiency in this case represents useful energy obtained when using cow dung. From these results, it can be concluded that high value of efficiency does not mean a fuel is clean.

The lowest emissions in Table 4 were found when using wood in a Forced Draft. Forced Draft has shown to be the lowest emitting type of stove for all the fuels. The emissions when compared to that of traditional stove have been reduced by 55 % when using wood and cow dung and 21.8 % when using crop residues. The design of the stove also contributed highly to the emissions for example Natural Draft have higher emissions in comparison to traditional stove. Since the aim of adopting ICS is also to reduce pollution caused by traditional stoves, stoves with higher emissions than traditional stoves are not addressing biomass problem of emissions.

Table 4; Results from using different fuels and different cook stoves

Type of stove	fuel	Amount of fuel (g)	Cooking time (mins)	Efficiency of stove (%)	$PM_{2.5}$ concentations ($\mu g/m^3$)
Traditional	Wood	1000	75	15	1055 ± 61
	Cow dung	1300	90	16	2142 ± 82
	Crop residues	1180	65	18	852 ± 104
ND 1	Wood	850	77	16	1373 ± 32
	Cow dung	1200	92	20	1439 ± 160
	Crop residues	900	75	18	1223 ± 26
ND 2	Wood	820	80	25	1976 ± 41
	Cow dung	1200	100	28	1244 ± 54
	Crop residues	830	78	27	1106 ± 194
FD	Wood	470	64	35	470 ± 28
	Cow dung	800	79	37	960 ± 9
	Crop residues	480	63	34	666 ± 132

2.6.3 Different cooking practices

Besides fuel type and stove designs, regional differences in cooking styles also contribute to the variations of emissions. This was demonstrated when using wood for testing traditional stoves and ICS in 4 different countries: China, Uganda, India and Honduras where the PM emission factors (EF) were found to be different. EF from the traditional stoves were approaching 50 g/kg in China, 4.9 g/kg in Uganda. In India 7 traditional stoves were tested, the emissions were ranging from 2.5 – 8.5 g/kg in all the stoves. In Honduras, 4 traditional stoves were tested, the emissions ranged was from 6.5 – 30 g/kg [28].

The problem of quantifying exposure to emissions is complicated by the differences in individuals' practices. Users add fuel differently, some add sporadically, others fill the stove to its maximum capacity from the beginning of cooking [28]. These different styles result in different results on emissions and thermal performances. Therefore it is not enough to take average and assume each household is affected equally.

Kitchen area concentrations also depend on the type of house and roofing. Household Air Pollutions were found to be twice as high in households with corrugated metal roof as compared to households with straws roofing [54]. Natural roof materials allow the smoke to flow outside through the spaces between the straws and reduce concentrations in the house. For people living in one roomed houses, the level of exposure to PM concentrations are said to be higher than for people living in houses with more than one room. Less kitchen emissions were recorded because the PM particles had spread over to other rooms [71].

2.7 Testing methods commonly used for cook stoves

Testing methods also contribute to the variation of results, some commonly used methods are Water Boiling Test (WBT), Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT). WBT is used to evaluate technical performance of the stove, performance indicators from WBT are fuel consumption and emissions generated to complete the task of boiling water[19]. WBT also gives estimation of time needed to boil a predetermined quantity of water under controlled conditions [72]. Therefore, it may not reveal the actual performance of the stove during actual cooking. The second method, CCT uses standardized local cooking process, it measures the amount of fuel consumed with the performance of the stove in cooking particular food [72]. Results for one study cannot be transferred to a different study. The third method, Kitchen Performance Test (KPT) can be used to evaluate performance, effectiveness and impacts of the stove in actual cooking but due to lack of controlling like in WBT and CCT, there is a high possibility of variation of results.

2.7.1 Literature synthesis on testing cook stoves.

Important observation from the literature is that the results obtained from different researches differ. The results show that thermal performance and emissions depend on the type of fuel used stove used, house characteristics, cooking preferences and testing methods. This leads to different results from different regions and countries. And it implies that more tests should be done at different regions. Therefore, evaluating performance of ACE One stove in Lesotho’s context will add new results in the field of research.

2.8 SOLAR ENERGY

Solar energy is a renewable energy source with minimal impact on the environment as compared to other form of electricity generation because it is also accessible to everyone. Solar energy has been growing rapidly because it does not depend on fossil fuel which are mined, little maintenance is required to keep the solar system running [73]. Photovoltaics (PV) cells directly convert solar energy into electrical energy. However PVs have low conversion efficiency of about 16-23 %, non-linear I-V characteristics as they depends highly on irradiance that it receives and temperature [74]. They also require high initial cost which makes it difficult to adopt. Due to its abundancy, cleanliness and universality, PV systems are the most promising technologies that can address world energy crisis [74].

Different locations with varying geographical and meteorological conditions affect the performance of a solar panel, these factors influence the tilt angle and orientation of a solar panel [75]. Intensity of solar radiation that falls on PV panels keeps on fluctuating due to weather changes. This greatly affects the power output of the panel; hence characteristic curves vary with environmental conditions. There are specific positions to be considered when installing PV system for their good performance. The positions differ according to locations. In the Northern hemisphere PV panels facing South with a tilt angle equal to the latitude were reported to have achieved the maximum yearly performance [79]. Lesotho being in the Southern hemisphere, the panel performs well when facing north. The panels can be fixed or rotated to track the sunlight. Tracking panels produces more power output than fixed panels [75]. The suggested optimal tilt angle for PV panel is equal to latitude ±15 to achieve maximum solar incidence, the plus sign in winter and minus sign in summer [75], [76]. However the rule does not work very well in latitude over 45^0 [76].

To find the maximum power dissipated by the solar panel, the characteristic (I-V) curves can be extracted. There are some several methods for obtaining I-V curve for solar panels. The simplest and cheapest technique is the variable resistor where an array is connected to a variable load, resistance is changed from zero to infinity, values of current (I) and voltage (V) are recorded, the method is also easily applicable to low power modules [74]. However, the process of this method is very slow due to manual change, therefore solar irradiation and thermal conditions could change in the middle of the process. The method can sometimes not give accurate results. There are other methods that can be used to obtain I-V curves such as Capacitive Load or power MOSFET, where the high quality capacitor is used and acts as a variable load and four-quadrant power supply (the most accurate) [74]. These methods are more accurate than the first method but expensive to perform. Non-linear graph that can be obtained from this methods as shown in **Error! Reference source not found.**. Maximum Power Point (MPP) exist at the knee of the graph.

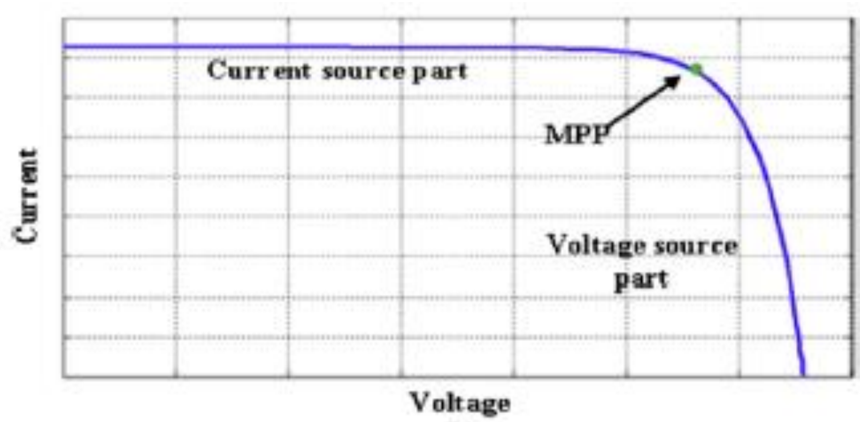

Figure 1; I-V Characteristic curve of PV cell [74]

The solar systems also involve use of batteries. However, batteries in a solar system are usually affected by discharge patterns of the users and by uneven or low charge current from the panel, this damages battery capacity as they deteriorates [77]. It is important to slow down this process to keep lifetime of battery as long as possible.

Chapter 3: EXPERIMENTAL METHODOLOGY

3.1 Determination of optimal feedstock

3.1.1 Fuel preparation

The study was conducted using four different biomass fuels; wood, corn cobs, cow dung from grazed livestock and wood pellets produced by ACE. The kind of wood selected for use in this study was pine wood because it is common tree species used for cooking. Except for the wet wood which was used immediately after being picked from the tree, other fuels, corn cobs, dry wood and cow dung were collected dry. Wood pellets were used as readymade from ACE. The idea was to use these fuels in the manner in which the end-users find and use them.

3.1.2 Determination of heating value

In order to evaluate the potential of biomass energy, and also make a technical assessment, it is crucial to determine heating value of biomass fuels which estimates the heat released by a fuel during combustion. Characterisation of these fuels in terms of their heating value is critical in a case where we want to identify which of the fuels have high energy content so that such fuels can be targeted. Heating value is therefore an important property when selecting feedstock. Correlation equation are often used for estimation of heating values of solid fuels and biomass fuels from their proximate analysis. The proximate analysis was then carried out to determine the Moisture Content (MC), Volatile Matter (VC), Fixed Carbon (FC) and Ash Content (AC), which are calculated as percentages by weight. The analysis was carried with the use of Oven, Furnace and Analytical Balance (Sartorius). Based on the results of proximate analysis, Higher Heating Value (HHV) of the fuels were estimated using empirical formulas.

Ultimate Analysis another way to determine HHV, which involves determination of Carbon, Nitrogen, Hydrogen and other elements in biomass fuels, but it requires very expensive equipment and dependent on highly trained technicians [78]. Whereas Proximate Analysis requires standard laboratory equipment and can be carried out easily as compared to Ultimate Analysis. Proximate Analysis does not require skilled technicians.

Mass of 5 g from each fuel was used to carry out the proximate analysis, the fuels were cut into small pieces that would fit into crucibles.

Moisture Content (MC)

MC is the quantity of water contained in the fuel. To determine MC, mass of the fuel were measured and kept at 5 g each in pre-weighed crucibles and kept in an oven at a temperature of 105 ˚C for 1 hour to drive off moisture. The fuels were kept below the temperatures of 110 ˚C as higher temperatures would lead to breakdown and loss of matter. [19]. The crucibles were then taken out of the oven and let to cool in a desiccator (equipped with Sodium Chloride to keep them dry) for 1 hour to avoid hot samples damaging the fragile Analytical Balance. Their masses were then measured, MC was calculated using Equation 1 [24], [25], [19].

Equation 1

$$\%\boldsymbol{MC} = \frac{\boldsymbol{sample\ mass\ loss}}{\boldsymbol{initial\ mass}} \times \mathbf{100}\%$$

Volatile Matter (VM)

The samples used for moisture content determination were taken and kept in the furnace at 950 ˚C for 7 minutes. After heating, the crucibles were taken out of the furnace and let to cool in a desiccator for 1 hour. Volatile Matter content of the sample was then calculated from the mass loss of the sample using Equation 2 [24].

Equation 2

$$\%\boldsymbol{VC} = \frac{\boldsymbol{mass\ of\ oven\ dried\ sample - mass\ of\ sample\ from\ furnace}}{\boldsymbol{mass\ of\ oven\ dried\ sample}} \times \mathbf{100}$$

Ash Content (AC)

AC represents the incombustible component remaining after the sample is completely burned. Samples used for Volatile Matter content determination were heated at 750 ˚C in a furnace for 2 hours and Percentage AC was calculated from mass loss using Equation 3.

Equation 3

$$\%\boldsymbol{AC} = \frac{\boldsymbol{mass\ of\ ash}}{\boldsymbol{mass\ of\ a\ sample}} \times \mathbf{100}\%$$

Fixed Carbon (FC)

Amount of non-volatile carbon remaining in a sample, it is calculated from other parameters measured in the proximate analysis. Percentage fixed carbon will be calculated indirectly by subtracting the sum of percentages of VM, AC and MC [79]. It is calculated using Equation 4.

Equation 4

$$\%\boldsymbol{FC} = \mathbf{100}\% - \%\boldsymbol{MC} - \%\boldsymbol{VM} - \%\boldsymbol{AC}$$

Higher Heating Value (HHV)

The higher heating value of the fuel was determined by the use of an empirically derived Equation 5 [78]. The equation and method used to calculate HHV was as described by [78]. Calculation of higher heating value is usually performed on dry basis [68]. The percentages of AC, VM and FC were calculated assuming 0 % of moisture content of a fuel. Each one was calculated as a percentage of their sum. The results were used to calculate HHV.

Equation 5

$$\boldsymbol{HHV\left(\frac{MJ}{kg}\right) = 0.353FC + 0.1559VM - 0.0078AC}$$

3.2 Thermal performance of the fuels

3.2.1 Combustion process in ACE One cook stove

ACE One cook stove is a gasifier stove where external air is driven by a fan which is powered by a built-in battery. Fuel is fed into the stove chamber and ignited from the top. Combustion chamber of the stove has openings at the bottom where primary air enters, also secondary air inlets at the top. Fuel consumption proceeds downwards. The primary air results in oxidization of fuel in the primary combustion zone [80]. The heat above this zone decreases some of water contained in the fuel below. It also reduces chances of the formation of carbon monoxide and hydrogen.

If the fuel is entirely consumed before the completion of the cooking process, the stove is refuelled by adding the fuel from the top of the chamber with hot char If the fuel is entirely consumed before the completion of the cooking process, the stove is refuelled by adding the fuel from the top of the chamber with hot char bed produced while the stove is in operation. When the cooking process is completed, the fan is left on to supply air to the chamber until it has cooled down to avoid damaging of the built-in battery that will conduct heat if the stove is left hot. The ash is removed from the top of the stove.

3.2.2 Heat gained by water when using different fuels

The biomass fuels were cut into small pieces such that they were short enough to fit into the stove chamber. They were then put on weighing scale (ADP 210/L) to measure their masses. It was found that the mass of pellets needed to cover the bottom air inlets as required by the manual 145 g. As a result masses of other fuels were also restricted to 145 g. Aluminium pot was used to heat water. The fan was turned to its maximum speed for all the experiments in this study.

Figure 1; Biomass fuel cut into pieces that can fit into the chamber

The cookpot was weighed before and after filling it with water, 2 litres of water was poured into the pot and the temperature of water was measured using a thermocouple, NEDA 1604. The pre-weighed fuel was loaded into the heating chamber and the dry leaves and grass were used to start fire. Once the feedstock began to glow, the pot (without a lid) was put on the stove and water temperature was recorded with 3 minutes intervals until the temperature of water dropped, and for other fuels, it reached boiling point of water. The fan of the stove was turned to its maximum speed for all the experiments carried out in this study.

The temperature of water was used to calculate heat gained (Q_{gained}) by water at every interval using Equation 6,

Equation 6

$$Q_{gained} = m_w C_p (T_f - T_i)$$

Where m_w is mass of water in the pot before heating, C_p is constant, used as 4 200 J/kg.°C a is the specific heat capacity of water, T_i is the temperature of water before heating and T_f is the temperature of water after heating.

3.2.3 Water Boiling Test I

3.2.3.1 Mass of fuel and heating time

To determine the mass of fuel used to take 4 litres of water to a boiling point, arbitrary mass of fuel was first taken. And then fire was started on a small of the measured fuel. If it ran out, refuelling by using more portions of the measured fuel was done. This was repeated until the water reached a boing point. The mass used to get the water to a boiling was calculated by subtracting the remaining mass of the measured fuel from the initial mass of the same fuel. The temperature of water was recorded in 3 minutes' intervals until the boiling point. The time it took to reach the boiling point was also taken. The experiment was repeated 3 times and the average was taken.

3.2.4 Water Boiling Test II

The stove chamber was filled with pellets to its full capacity, which weighed 500 g. The same mass was used for other fuels. The previous tests had a limitation of flame height being too low for some fuels.

Two pots were used in this experiment to boil water. First pot with 1 litre of water was put immediately after starting fire. When the water reached the boiling point, the procedure was repeated with the second pot, still with 1 litre of water. The procedure was repeated with one pot replacing the other until the water in the last round could no longer be made to boil. Boiling time was recorded for all boiling episodes to find which fuel boiled more litres. When using wood, cow dung and corn cobs, the required mass filled the chamber and another portion was left, therefore refuelling was required, and it was done sporadically since the fuels burned at different rates.

3.3 Emission of fine particulate matter

3.3.1 Emissions inside a closed room

The same amount of mass used when calculating heat gained which was 145 g was used again to make fire to measure the amount of particles' concentrated inside a room and amount of PM_{10} and

$PM_{2.5}$ emitted while the fuel was burning. Air Quality Index was also measured. Because cook stoves are meant to be used indoors where there is inadequate ventilation, the level of fine concentrations released from different fuels over the course of heating cycle were monitored in an enclosed room using Air Quality Monitor (Tempton LKC-1000S+, range 0-999.9 µg/m^3). The room was 6.51 m long, 4.67 m wide and 2.5 m high, roofing overlaid with a ceiling. The measurements were done by placing the air quality monitor on the table 210 cm high and 67 cm radius around the stove which is placed on the ground. To minimize influence of wind and temperature change during the day the experiments were all done in the morning [81].

The fire was started inside the room and emissions were measured immediately, but the emissions were so high in the ignition phase such that the maximum value was reached within first 2 minutes of burning for all the fuels, the fire was therefore started outside the room for 5 minutes before taking the stove back to the room. In the subsequent experiment, the fire initiation outside the room was allowed to take 10 minutes. For the 10 minutes' episode, some fuels were consumed before the stove could be returned to the room. Only the pellets survived the 10 minutes' episode.

When the fuel was fully burned, the monitor was left running for 30 minutes and then the door was opened until the concentration reached 50 µg/m^3. The time amount of time each fuel took to reach this point was recorded. Beside particulate matter concentration, the Air Quality Monitor also measured Number of particles present inside the room and AQI which measures the level of exposure to these emissions. AQI measured the extent to which the air quality is safe for humans in the room.

3.3.2 Emissions in an open room

The fuels of the mass 145 g were later burned in an open room (open windows and the door) to measure particulate matter emitted from these fuels. The fire was started outside the room for 5 minutes before taking the stove back to the room The $PM_{2.5}$ emissions were again measured in an open room with 500 g mass of fuel to assess impact of refuelling on emissions. The amount of mass of 500 g was previously used when carrying out the second WBT.

3.4 Combustion temperature

The Heat temperature of the burning fuel was measured using infrared thermometer (Lasergrip 1022D, range -50 – 500 °C). Fuel samples of mass 145 g were burned. The temperatures were measured at the top of a stove, where the cooking pot is placed when cooking. The readings were taken from when the fuel started burning until the temperature decreased to 50 °C. The burning time of the fuels was also measured.

Lastly, the cost of the fuels was based on availability, accessibility and accessibility of the fuel. This was carried out comparing means of obtaining this fuels and how costly are to the user.

3.5 Effects of each fuels on the user of the stove

The impacts were assessed comparing the following parameters for the fuels

- Mass of fuel required if the fuel is to be used to boil water
- Time required for boiling water
- $PM_{2.5}$ concentrations of the fuel
- Cost of the fuel

3.6 Performance of charging system of the stove

3.6.1 Power dissipated by the panel

The solar panel was tested at National University of Lesotho (27.7206° E, 29.4513° S). It was put in a direct sunlight on a clear day. The experiment was repeated for 4 different days. The measurements were done at different times of the day, in the morning hours (0900-1000hours), around solar noon (1145-1230hours) and in the afternoon hours (1500-1600hours). Different tilt angles were used: 30°, 34°, 40°, 45° and 50°. A variable resistor was used as a load and was varied from zero to infinity for Current (I) and Voltage (V) measurements. RMS multi meters (Agilent U1252B) were used to measure the voltage and current values. IV characteristic curves were then extracted from this values. The specifications of panel tested are shown in Table 5 and experimental arrangement is shown in Figure 2.

Table 5 Module specifications

Model number	ODA10-10-P
Maximum power	10 W
Open circuit voltage	12.12V
Short circuit current	1.05A
Voltage at maximum power	10.1 V
Current at maximum power	0.99 A
Series fuse rating	10 A
0perating temperature	-40 to +85^{o}C
STC	Am 1.5, E= 1000W/m^2, TC=25^{o}C
Tolerance	0- +3%

Figure 2; Experimental arrangement of testing solar panel

3.6.2 Battery capacity and charging times

The build-in battery of the stove was charged using a wall charger with output current of 2 Amps and compared the charging times to charging with a solar panel. A multi meter was connected when charging and voltage increase was observed until there was no increase. When charging with a solar panel, 30° angle was used as it yielded in greater power compared to other angles. The experiment was performed on a clear day.

i. Power usage of LED lamp and mobile phones

An included LED lamp was powered from a fully charged battery of the stove to find power consumption over usage time. The voltage of the battery was measured after lighting for some hours. Lastly, cell phone (Samsung A2- Core) was then used to discharge the stove to find how many times a fully charged stove can be used to charge the cell phone. Time taken to fully charge a cell phone was also recorded.

Chapter 4: RESULTS AND DISCUSSIONS

4.1 Proximate Analysis of fuels

The results from proximate analysis are shown in Table 6, calculated on wet basis. Cow dung had the highest moisture content of 11.5 % and corncobs had the lowest Moisture Content of 5.3 %. It may not be wise to draw comparisons between fuels in terms of Moisture Content because of its high variability even with the same fuel of interest. However, it is generally important for users to avoid fuels with high moisture content since it results in decreased obtainable heat. That is because more energy is used to evaporate moisture of the fuel and also lengthens heating time [82], [24]. In fact, the wood used in this study could not be ignited within the ACE stove. Cow dung also had the highest Ash Content of 21.7 % while Corn Cobs had the lowest Ash Content of 1.9 %. High Ash Content is not desirable the fuel since it represent the part of the fuel from which no heat is derived. It also causes ignition and combustion problems [83].

Table 6; Wet basis

Properties (%)	***Cow Dung***	***Wood***	***Pellets***	***Corn cobs***
Moisture Content (MC)	11.47	9.47	7.86	5.32
Volatile Matter (VM)	58.60	62.66	78.65	81.38
Ash Content(C)	21.70	15.07	2.14	1.92
Fixed Carbon (FC)	8.21	12.80	11.36	11.47

The Volatile Matter represents the part of fuel released as volatile gas when the fuel is heated up. In corn cobs, the highest Volatile Matter of 81.4 % was obtained while the lowest Volatile Matter of 58.6 % was obtained in cow dung. Fuels with high Volatile Matter and high Fixed Carbon ignite easily as the volatile compounds and carbon act as heat generators during combustion [84]. However, fuels with low Volatile Matter and low Fixed Carbon tend to result in incomplete combustion, which leads to significant amount of toxic gases released [24]. The fixed carbon of the fuels ranges from 8.21 % (cow dung) to 12.80 % (wood).

The dry basis results are shown in. Table 7 Water presence in the fuels is neglected on dry basis.

Table 7; Dry basis

Properties	**Cow dung**	**Wood**	**Pellets**	**Corn cobs**
%VM	66.22	69.21	85.35	85.87
%FC	9.27	14.14	12.33	12.11
%AC	24.51	16.65	2.32	2.02
HHV (MJ/kg)	**13.43**	**15.66**	**17.60**	**17.65**

Due low fixed carbon in cow dung, the heating value of cow dung is the lowest, 13.43 MJ/kg. Other fuels have heating values greater than 15 MJ/kg where are 15.66 MJ/kg for wood, 17.60 MJ/kg for pellets and 17.65 MJ/kg for corn cobs. In terms of HHV, corn cobs and pellets are the most preferable.

4.2 Heat transfer

The highest temperature change in Table 8 was recorded when using wood, where water reached the boiling point of 92.9 °C after 9 minutes, which resulted in 610 kJ gained. Temperature change when using other fuels over the same time ranged from 51.9 °C (cow dung) to 68.4 °C (pellets). Temperature difference was 28.6 °C for cow dung, 36.1°C for pellets, 48.9 °C for corn cobs and 72.8 °C for wood.

Table 8; heat gained by water in a pot

	Cow Dung	Wood	Pellets	Corn cobs
Initial temp. of water (^{0}C)	23.3	20.1	23.2	19.5
Temp. of water after 9 mins (^{0}C)	51.9	92.9	59.3	68.4
Temp. difference after 9 mins (^{0}C)	28.6	72.8	36.1	48.9
Heat gained by water, Q (kJ)	240	610	350	410

The corn cobs and pellets had shown higher heating values than wood, but due to fuels' different physical properties such as shape, the fuels burned at different rates which affected heat transfer. For instance, wood transferred more heat because, due to its bulkiness, the amount of wood used could fill the whole stove chamber and the flame reached the pot at a shorter distance, therefore water gained more heat within a short period of time. The increased surface area of the flame allows heat to transfer more quickly than when the heat comes from the bottom of the pot only. Wood was also observed to maintain the flame until boiling and to ignite the whole bulk more easily compared to other fuels.

Whereas corn cobs were easy to ignite, it was not easy for the flame to spread through the bulk as in the case of the wood. Also, it could not maintain the flame through the testing duration. As for the pellets, fuel bed was just above the bottom holes of the chamber, therefore the flame produced was far from the pot, and this led to less heat gained by the water. The results show that, depending on the type of stove used, volume and shape of the fuel also matters how fast heating can go.

4.3 Combustion Temperature

The heat temperatures of the fuels are shown in Figure 3, about 460 °C recorded during wood combustion, followed by corn cobs which recorded 370 °C, pellets with 340 °C and cow dung with the lowest temperature of 290 °C. The peak flame temperature of wood and corn cobs is high because the amount of mass used filled the chamber to its maximum capacity. The flame from wood and corn cobs even reached the sides of the pot as shown in Figure 4.

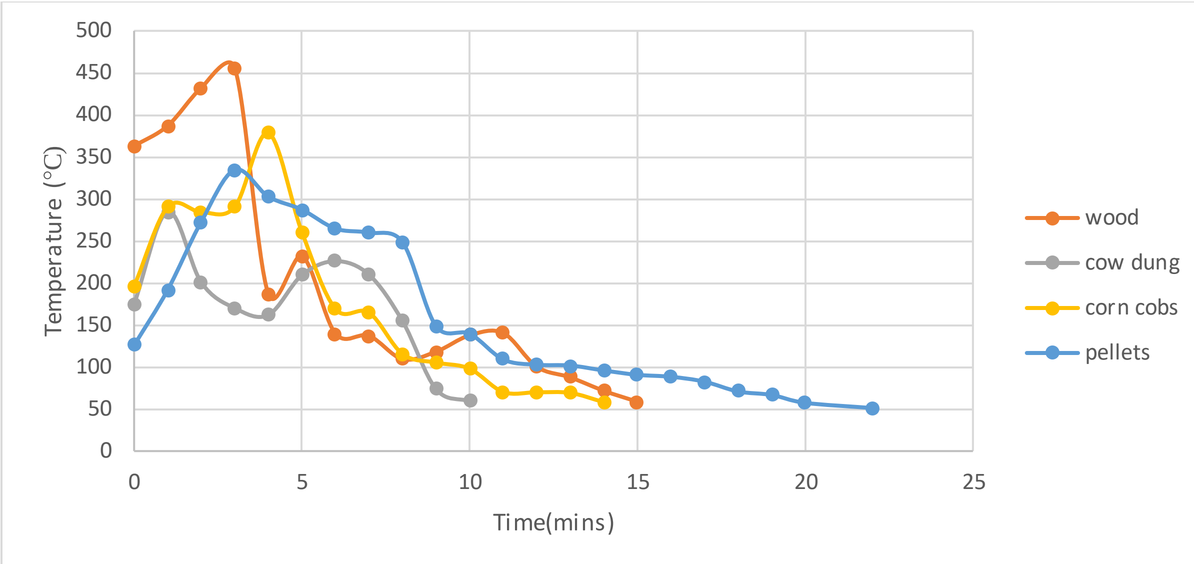

Figure 3; Combustion temperature of the fuels

Figure 4 ; flame produced by wood

However, the heat temperature of these two fuels drops very fast. Pellets did not give out a big flame but the temperature drops at a very slow rate and the heat lasts longer, furthermore the flame of the pellets is consistent, unlike other fuels which have their flame temperature fluctuating because the cut pieces were not uniform. But for the cow dung, small flame was produced, which did not even last. Within 10 minutes of burning, cow dung temperature had already dropped to 50 °C, wood flame dropped to the same temperature after 15 minutes, corn cobs after 14 minutes and pellets after 18 minutes. The burning time (time up to where the flame totally stopped) of these fuels was 13 minutes for pellets, 10 minutes for wood, 9 minutes for corn cobs and 7 minutes for cow dung. After these times, there were no longer flames but only char left in the stove, which also gives out heat.

4.4 Water Boiling Test I

4.4.1 Mass used to bring water to boil

WBT results are shown in Figure 5, the results show different amounts of mass used and different times taken to boil 4 litres of water for each fuel. The estimated mass used ranged from 280 g (dry wood) to 370 g (cow dung). Mass used for corn cobs and pellets was 330.9 g and 330 g respectively.

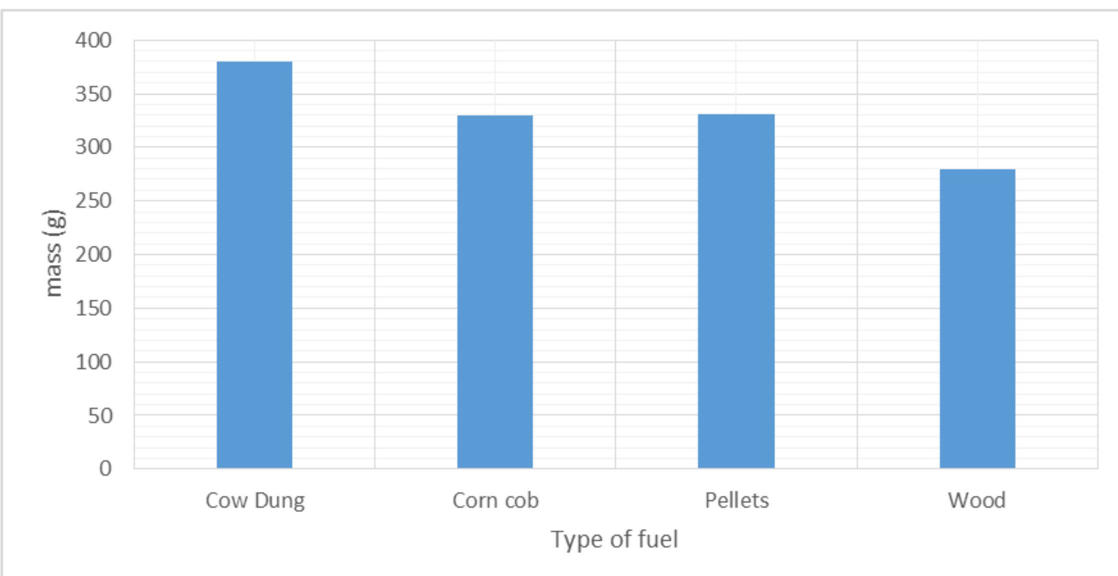

Figure 5; Mass of fuel used to bring water to boil

4.4.2 Time taken to bring water to boil

With wood, the shortest time was recorded as shown in Figure 6, it took 18 minutes to boil water, while it took 20 minutes with pellets, 22 minutes with corn cobs and 25 minutes with cow dung. The results show that amount of time taken depends on the amount of mass needed, increased mass leads to longer time spent on cooking. Fuels which take much time to deliver results and which are needed in larger quantities per cooking episode (if we assume equal cost) are not desirable. This is because Improved Cook Stoves were meant to help families economically by saving on fuel cost or the time devoted by gathering the fuels.

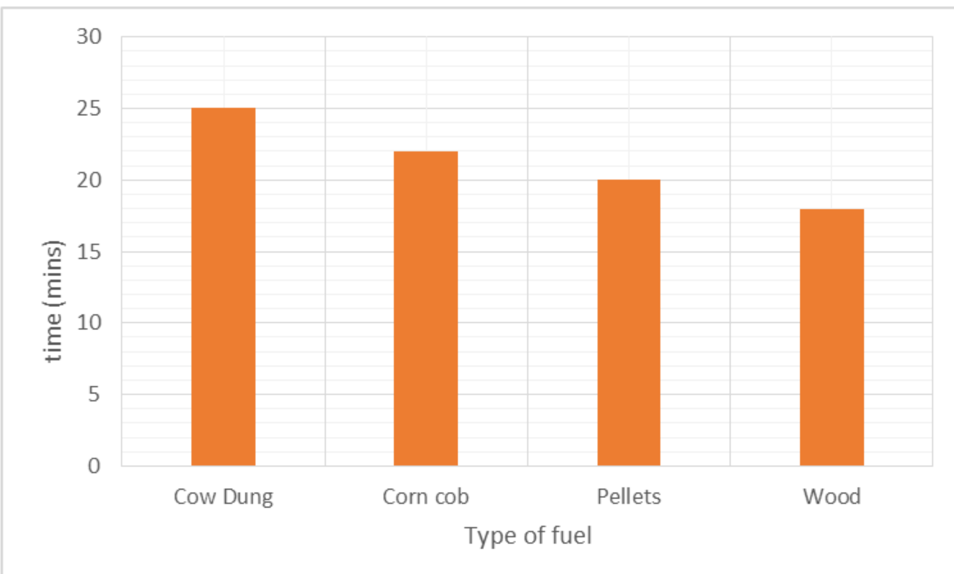

Figure 6; Time taken to bring water to boil

4.5 Water Boiling Test results II

For all the fuels except wood, the first litre of water took longer to boil than the second litre. That is because in the initial stages, the flame is still low and the fuel has not ignited very well. The results are shown in Table 9. As the combustion process continues, the fire becomes stable and a bigger flame is produced. The first litre of water boiled after 6 minutes for corn cobs, 9 minutes for pellets and 12 minutes for cow dung. The water in the second pot boiled after 4 minutes for corn cobs. It took 7 minutes and 5 minutes for pellets and cow dung respectively. For wood, there was no different between the boiling times of water in the first and the second pots (5 minutes in both cases) because, as we have seen, wood does not take much time to ignite.

Table 9 ; WBT when using equal mass

	Pellets (min)	Wood (min)	Corn cobs (min)	Cow dung (min)
1st pot(1L)	9	5	6	12
2nd pot(1L)	7	5	4	5
1st pot(2L)	8	11	8	17
2nd pot(2L)	9	Did not boil, but the temperature was 79.5 °C after 10 minutes	Did not boil, but the temperature was 70.4 °C after 7 minutes	Did not boil, but the temperature was 42.3 °C after 11 minutes
1st pot(2L)	Did not boil, but the temperature of water was 65.3°C after 11 minutes			

All the fuels except the pellets required refuelling in the middle of the cooking process. The idea was to mimic to as close as possible, the real-world situation where the stove user would need to refuel until the desired goal is reached. This extends cooking time as the user has to remove the pot from the stove and refuel. While refuelling, the temperature of water decreases. With pellets, 6 litres of water were boiled without refuelling in the middle of cooking and it took 24 minutes to boil all these 6 litres. For other fuels, only 4 litres were boiled with refuelling in between. The process took 21 minutes for wood, 18 minutes for corn cobs and 34 minutes for cow dung. The time taken to boil water using cow dung was the longest time. Actually, refuelling was required even before the first litre of water could boil.

Cow dung has shown high Ash Content as shown in Table 7. This was also reflected in the results of cooking. For instance, in Figure 7, it is shown that when burning cow dung, the stove chamber was filled with ash even before the weighed mass was completely consumed, making refuelling impossible. In fact, 145 g of 500 g of the fresh cow dung was left unused midway. The ash had to be removed and fire was started again to complete the experiment which, again, would be done in real-life situations.

Figure 7; Stove filled with ash of cow dung

4.6 Emissions in a closed room

The results in Figure 8, Figure 8, Figure 9, and Figure 10 were found when 145 g of each fuel was burned. In Figure 8 the results of $PM_{2.5}$ emissions are presented while in Figure 9 emissions of PM_{10} are shown. Wood and corn cobs had lower emissions in the beginning of combustion process as they got ignited quickly, but cow dung and pellets have high emissions in the first minutes of burning.

In the first 10 minutes, cow dung emissions had reached $PM_{2.5}$ of 779.2 µg/m^3 and PM_{10} over 999.9 µg/m^3 which was the highest. Pellets were at $PM_{2.5}$ of 281.7 µg/m^3 and PM_{10} of 337.1 µg/m^3, corn cobs at $PM_{2.5}$ of 111.7 µg/m^3 and PM_{10} of 140.7 µg/m^3 and wood at $PM_{2.5}$ of 27.1 µg/m^3 and PM_{10} 38.6 µg/m^3. After 20 mins of burning, cow dung had reached 999.9 µg/m^3 while other fuels were around 800 µg/m^3 for $PM_{2.5}$. The particles released by the pellets for $PM_{2.5}$ decreased even before the windows and a door was open to increase ventilation, which shows that particles released when burning pellets were not as high as those of other fuels.

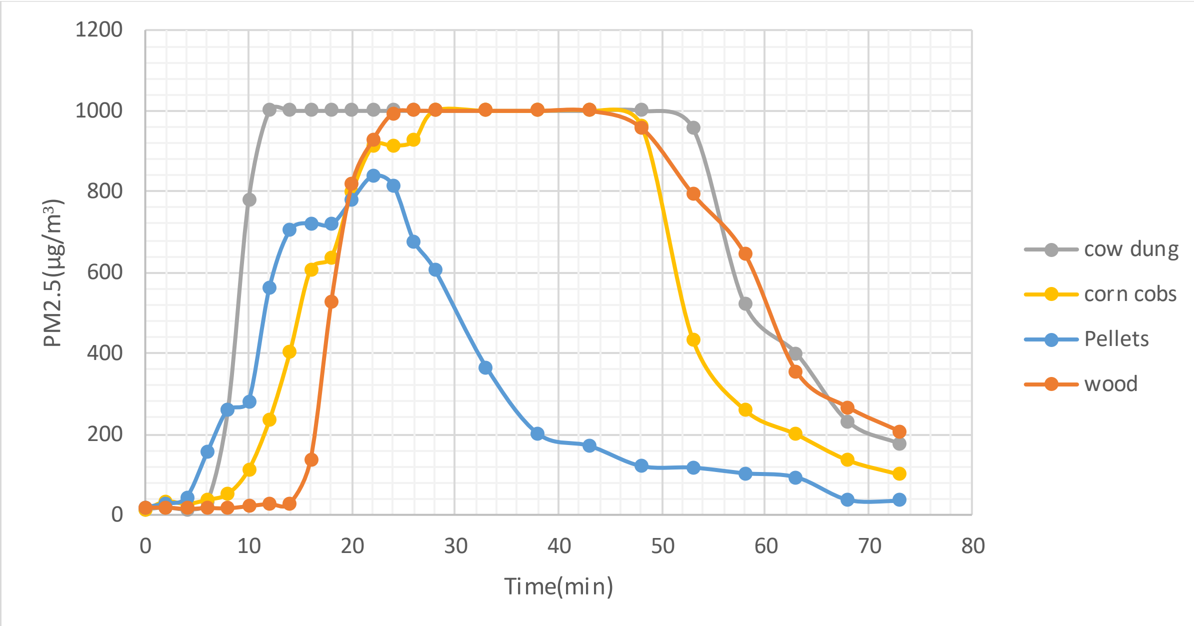

Figure 8 ; $PM_{2.5}$ emissions

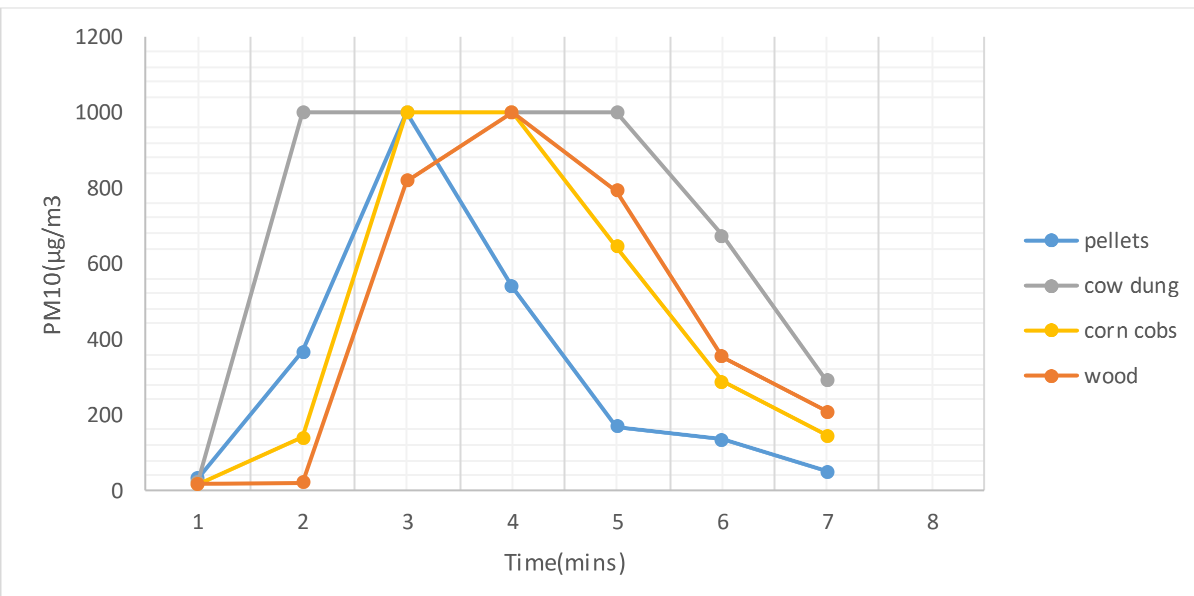

Figure 9 ; PM_{10} emissions

In Figure 10, shows the number of particles per litre concentrated inside a room during combustion of these fuels. The concentrations reached the peaks of 125,997/L in 22 minutes for pellets, 154,099/L in 30 minutes for corn cobs, 168,553/L in 28 minutes and 523,859/L in 26 minutes for cow dung. Cow dung released far greater emissions, in fact more emissions than the rest put together.

None of the fuels remained at a good or moderate level for the entire period of burning. For these fuels, even after opening of the windows and the door, the $PM_{2.5}$ and PM_{10} emission values were still over 250 $\mu g/m^3$ for $PM_{2.5}$ and 425 $\mu g/m^3$ for PM_{10} for about 20 minutes which are hazardous levels according to Table 3. They all reached the hazardous levels before the first 20 minutes.

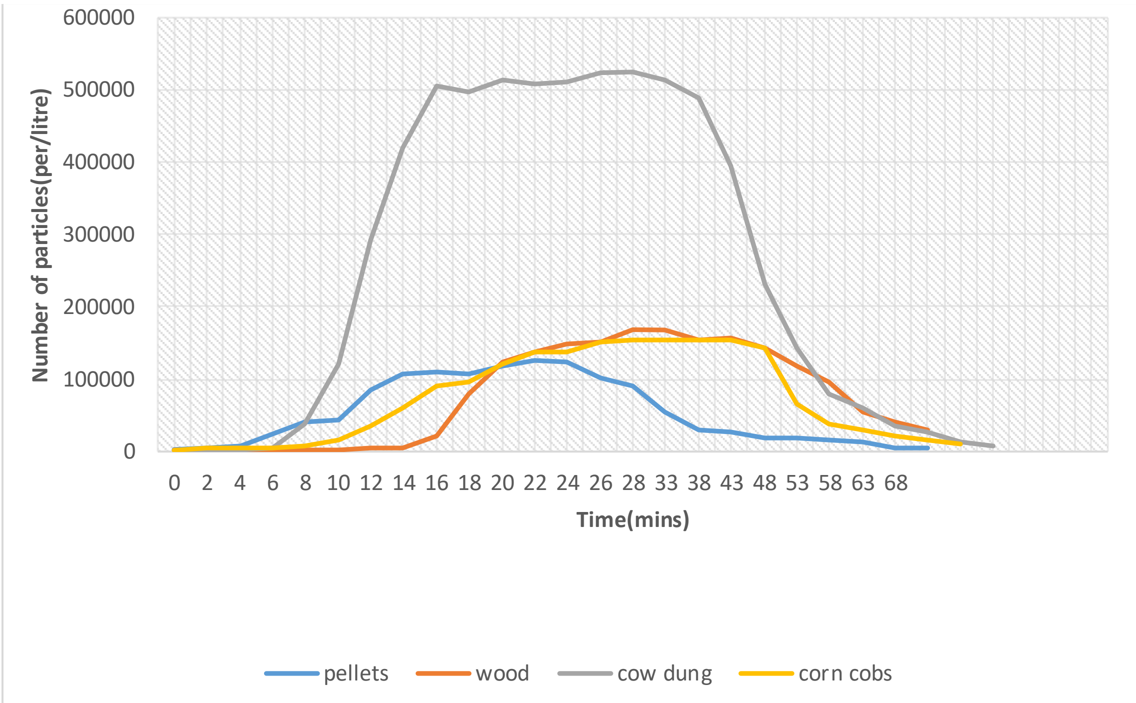

Figure 10 ; Particles concentrated inside a room during combustion

The same thing can be said concerning the Air Quality Index (AQI) in Figure 11. All fuels went beyond the AQI of 500 which is hazardous. For cow dung, 71.2 % of the burning time was spent in hazardous level. Even after 73 minutes from the beginning of burning and the door and windows were already open, the AQI was still above 200, which is under “very unhealthy” level classification. For wood burning 45.75 % of the burning time was spent in hazardous level, the figure was 40.78 % for corn cobs and 25 % for pellets.

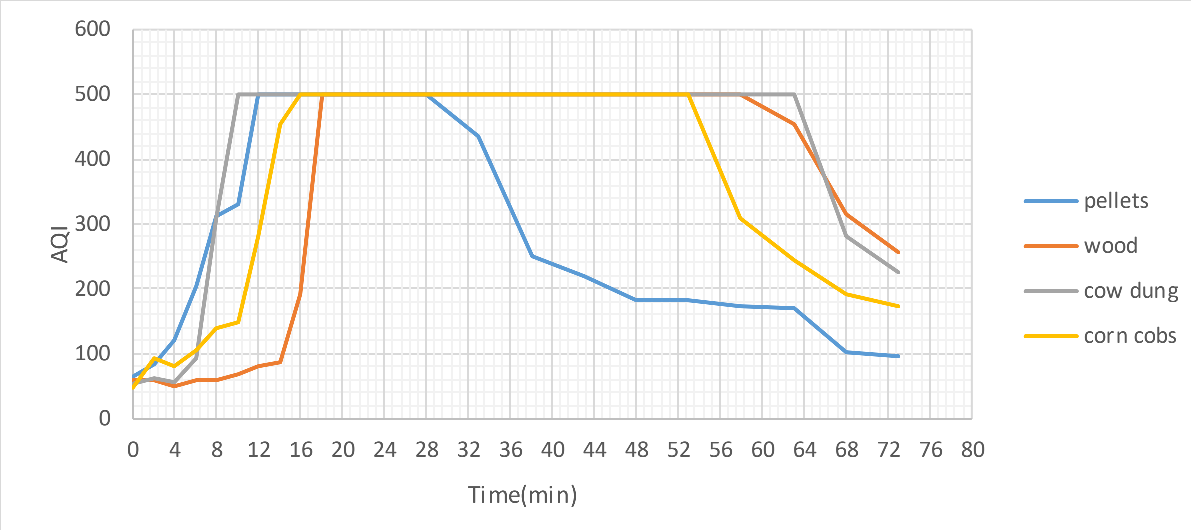

Figure 11; Air Quality Index

Emissions from 10 minutes burning of pellets outside

The emissions of fine particulate matter inside the room when preceded by burning of pellets for 10 minutes outside the room are shown in Figure 12. There was significant decrease in emissions from 10 minutes burning outside the room as compared to the five minutes burning previously done and reported in Figure 8. In Figure 8, the highest value of $PM_{2.5}$ was over 800 µg/m^3 while the highest value in Figure 12 is around 300 µg/m^3. This shows about 63 % decrease in emissions. Even though emissions decrease with this approach, it was accompanied by 30 % decrease in burning time compared to the 5 minutes burning. That means spending more minutes outside the room resulted in loss of obtainable heat as burning time inside the room was shortened. This was because, by the time the stove was taken back to the room, a significant portion of the fuel was already consumed. Interestingly, for 37 minutes of 56 minutes (which is 66 % of the time), the emissions were below 100 µg/m^3 in this case. The implications are, users can reduce inside emissions significantly if they burning the fuel for about 10 minutes outside the room. However, that will be associated with a loss of energy which would otherwise be spent on cooking.

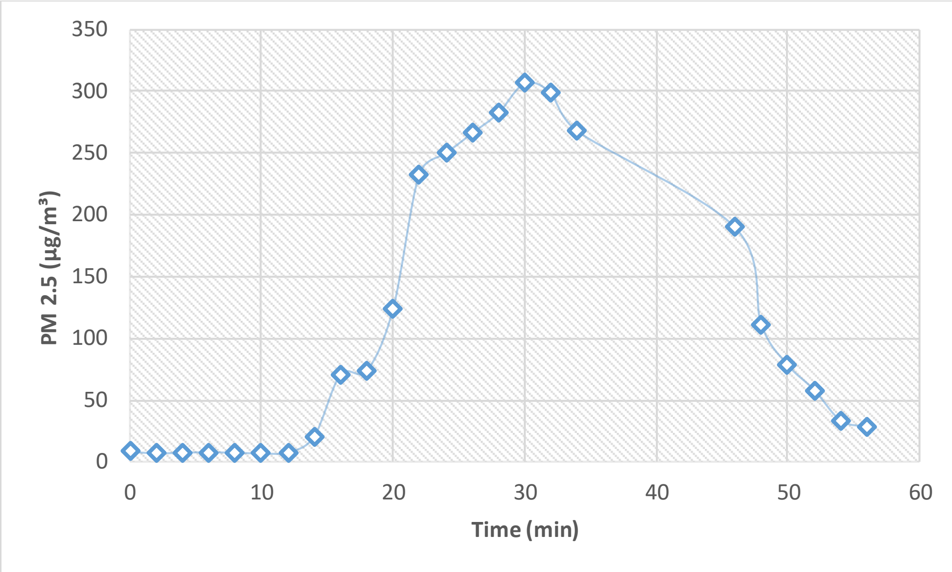

Figure 12 ; *$PM_{2.5}$ emissions of pellets when allowed to burn for 10 minutes before taking the stove back to the room*

4.7 Emissions in an open room

The graphs shown in Figure 13 represent the results obtained when 145 g of each fuel was burned in an open room, that is, with a door and windows open. The maximum values of $PM_{2.5}$ emitted throughout their burning times were 60.3 µg/m^3 for pellets, 144.7 µg/m^3 for wood, 234.2 µg/m^3 for corn cobs and 612.4 µg/m^3 for cow dung. Burning the fuels in an open room had resulted in lower emissions than burning the fuels in a closed room. In general, time taken by the emissions to subside inside the room had also decreased compared to when the room was closed (Figure 8). Cow dung still reached the hazardous level but with a lesser number of particles this time. Pellets, wood and corn cobs had reached the “unhealthy” level but for a shorter time. It must be appreciated that these results can be heavily influenced by the size of the opened door and windows the prevailing weather conditions. However, the picture given is that ventilation during burning of biomass is similar conditions does go a long way in reducing emissions.

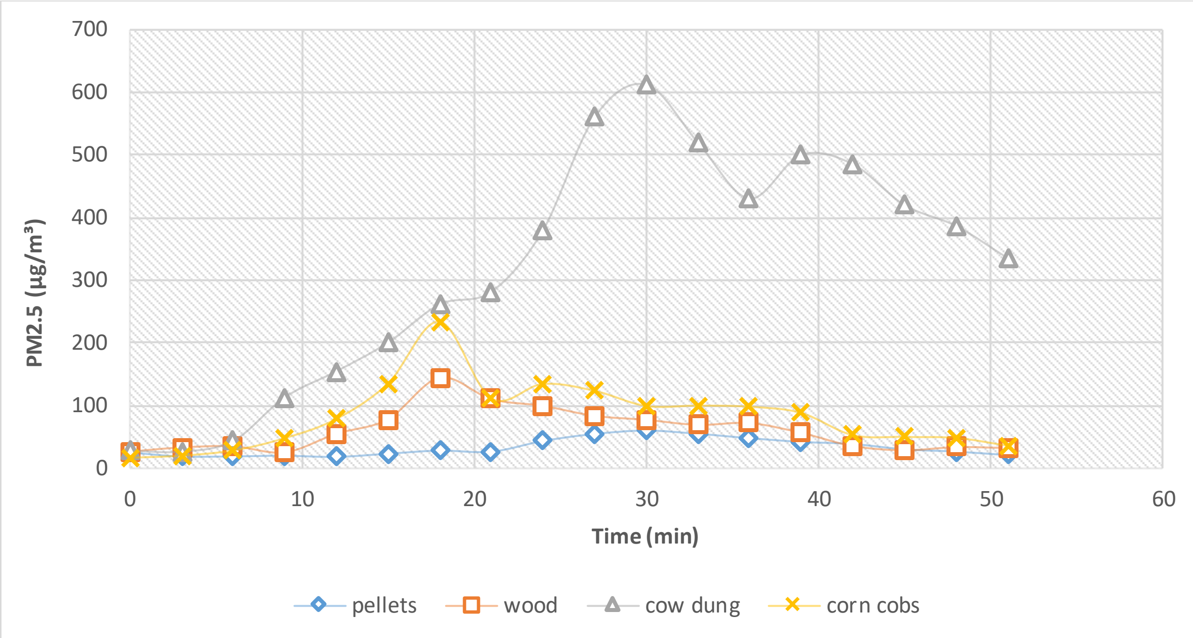

Figure 13; $PM_{2.5}$ emissions in an open room

4.7.1 Impact of refuelling

The results shown in Figure 14 are the emissions of $PM_{2.5}$ when the fuels were burned in an open room with 500 g of each fuel. In this case; wood, corn cobs and cow dung needed refuelling before their 500 g masses were used up. That was due to bulkiness. Thus, their emissions were highly influenced by the refuelling. That is, every time the stove was refuelled with one of these fuels, the emissions increased. However, when using the pellets, since there was no need for refuelling, the emissions were relatively high at the beginning of combustion only; the highest value reached was 151.5 µg/m^3 within first 4 minutes of burning. That is considered unhealthy level but at least few minutes were spent at this level. The emissions then decreased considered.

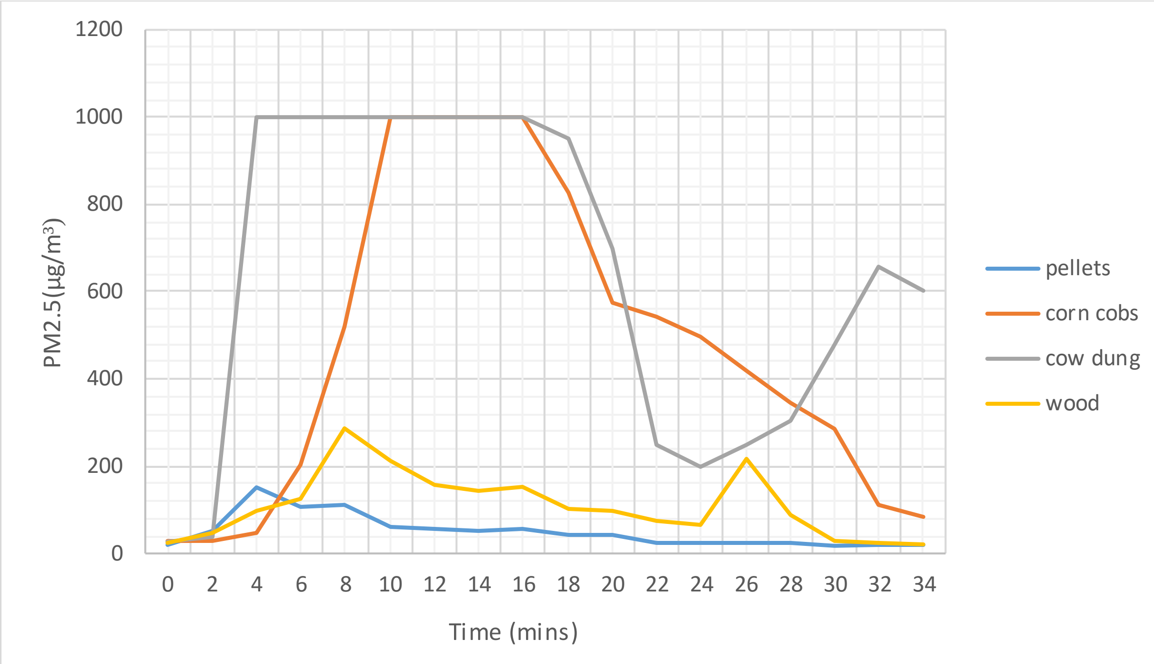

Figure 14 ; $PM_{2.5}$ emissions when refuelling

4.8 Analysis and comparison of the fuels used

The analyses of the nature of the fuels made below pertains to their nature as used in Lesotho and based on the experiments already made and reported in the is work. Where multiple fuels are available, cost of fuels influences fuel choice especially for people who can access them easily [37]. For instance, due to abundance of wood and cow dung available in some villages, time spent on collecting fuel is not a demotivating factor.

4.8.1 Cost of fuels

Another impact of fuels on the user is the cost of getting a fuel which is based on availability, accessibility and affordability. Besides huge amount of money to purchase stoves, poorer households are more likely to be constrained also by cost of fuel. In Table 10, the cost of using fuels is shown. The fuels availability and ignition method are also shown.

Table 10; Fuel cost and ability

Fuels	Cost	Availability	Ignition method
Cow dung	collected	All year	Wood branches
Wood	Collected / sold	All year	Paper, grass
Pellets	$2.46(M30.00) /5 kg	All year	kerosene
Corn cobs	From crops	Only after harvest	Paper, grass

Cow dung is collected from graze lands, it is available throughout the year and it also does not require expensive materials (such as kerosene) to ignite. Shrubs can be used to ignite them. However, the choice of a cow dung forces householders to walk long distance and to carry heavy loads. The fuel has shown a very poor thermal performance among all the fuels as shown throughout the results. It has also proved to be extremely high on emissions. Therefore, it has been shown that householders opting for cow dung might spend a lot of time cooking and a longer time exposed to hazardous pollutants.

Wood can also be collected without necessarily having to pay by fetching it from the surroundings in many parts of the country. It is always available throughout the year but not necessarily accessible to everyone due to issues of ownership. Some trees are available for harvesting and some are privately owned and have to be bought to exchange hands. The price varies from place to place. Even at places where it is free, extensive harvesting has negative impacts on the environment which also affect livelihoods. When wet, wood requires a lot of kerosene to start fire even in the middle of the heating process, which is not acceptable when using ACE One cook stove since such methods are not permitted according to the stove manual. Wood had shown a very good performance when used in the stove. It transferred heat to the pot within a short time and it had lower emissions compared to cow dung and corn cobs

Corn cobs are only available after harvest and accessible to people who are engaged in producing crops although some people exchange labour to get them. They can be ignited easily with easily accessible materials. Although corn cobs had shown a good performance in transferring heat, they get used up quickly. They also recorded high emissions and they came second only to cow dung.

Pellets are sold at ACE, 5 kg bags for $2.46(M35.00) each. They are accessible to everyone, all the time. Since they are ignited easily when using kerosene, they come with increased costs which may not be affordable to some householders. Shrubs or a paper can also be used to ignite pellets but it takes a longer time. However, pellets showed a very good performance in thermal activities and in emissions as well. They showed a long lasting heat temperature, which meant refuelling may not be required in many cases. The lowest emissions of all the fuels were recorded when using pellets. Pellets also save user's time as they are small in size, therefore did not require time for cutting before use.

4.9 Charging system

4.9.1 Performance of solar panel

The characteristic curves in Figure 15 are results from determining power dissipated by a solar panel at different tilt angles, from 30˚ to 50˚. Different power values were obtained at different angles and different times of the day. Although the experiment was repeated for different days with different temperatures, the results presented in this study are for 1 day only, in which the highest value of power was obtained. The experiment was performed on the 19th December 2020 around noon, the ambient temperature was 26.3 ˚C. The results presented in Figure 15 are obtained around solar noon. The highest value of power was obtained at angle 30°. The value of power obtained is 8.57 W with the current at maximum point I_{mp} 0.8234 A and voltage at maximum point V_{mp} 10.356 V. The lowest value of power was from angle 50° with 6.22 W.

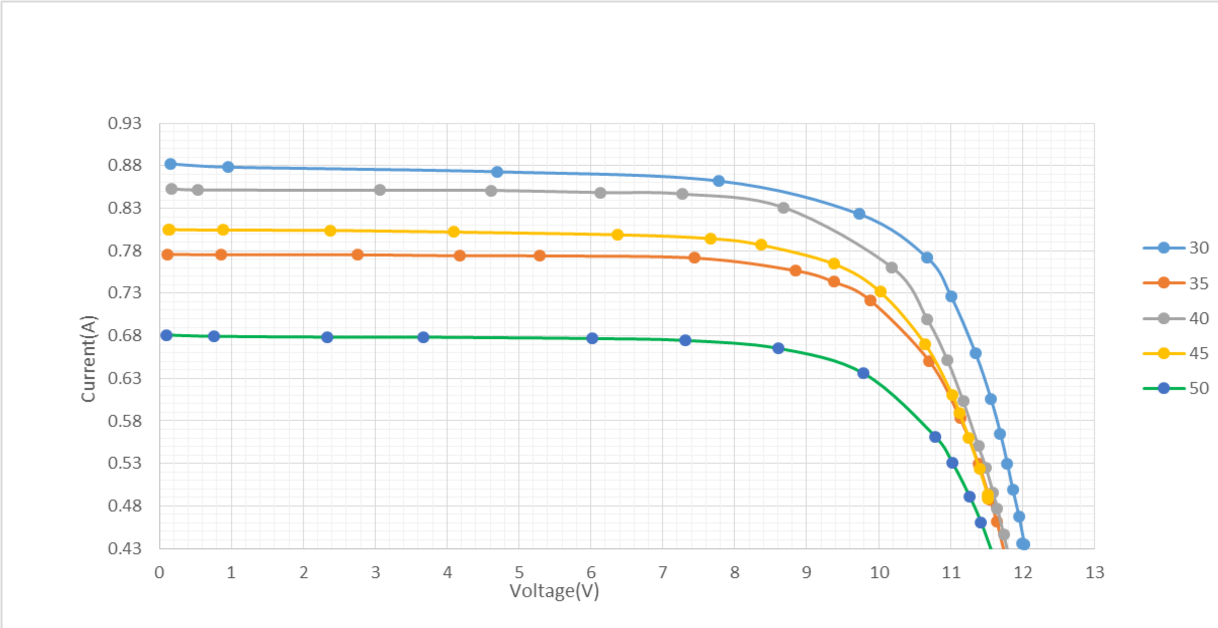

Figure 15; Characteristic curves

The power values obtained at different angles at different times of the day are shown in Table 11. The values obtained are all less than Standard Test Condition (STC) rated value of the solar panel which is 10 W, which is due to difference in locations with varying meteorological conditions which may greatly affect the solar panels' performance. At an angle 30°, the solar panel gave the highest power in all the experiments while at an angle 50°, it gave the lowest power.

Table 11; Values of power obtained from different angles

Angle	Power obtained in the morning(W)	Power obtained around noon (W)	Power obtained in the afternoon (W)
30°	8.31	8.57	8.27
35°	7.32	7.74	7.31
40°	7.26	7.33	7.23
45°	7.04	7.13	7.06
50°	6.03	6.22	6.17

4.9.2 Charging times

When charging with a wall charger, it took about 42 minutes to fully charge a battery of stove. The wall charger has an output current of 2 A. When charging with a solar panel, it took 2 hours and 18 minutes with the charging current of 0.8233 A, temperature was 23.5 °C. On a different day, it took 1 hour and 56 minutes and the temperature was 21.7 °C. However, charging times when using a solar panel will always be different because power dissipated by solar panels depends on weather conditions. The time in this study when using solar may not represent actual charging time of the solar panel. It may take longer or shorter depending on the local weather conditions. But it could be seen that when using a wall charger, less time is spent on charging than when using a solar panel. The voltage of a fully charged battery of the stove was found to be 6.67 V.

4.9.3 Power Usage of LED lamp

The LED lamp was powered using the stove. Voltage of the battery of the stove after 5 hours of operation was 6.432 V as shown in Figure 16. Only 0.23 V of the battery's voltage was consumed by the LED lamp. That is about 3.4 % of the battery's voltage used up by the LED lamp for the recorded time.

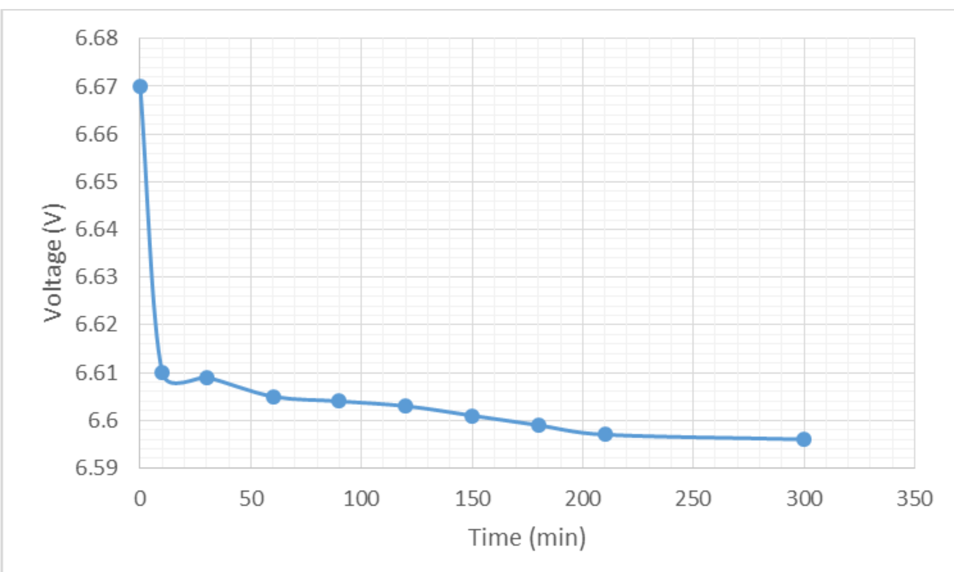

Figure 16; Power usage of LED lamp

4.9.4 Power Usage of cell phone

The Samsung cell phone was fully charged after 3 hours 5 minutes when charged from the stove. The fully charged stove could be used to charge this cell phones to its maximum capacity for at least 3 times.

Chapter 5: CONCLUSION AND RECOMMENDATIONS

The assessment of ACE One cook stove was conducted. The study considered 4 biomass fuels' performance when used in ACE One cook stove and performance of charging system of the stove. Cow dung, pellets, corn cobs and pine wood were used in this study. The performance of these fuels was carried out by determining heat generated by the fuels during combustion. The proximate analysis was first carried out to determine the Higher Heating Values of the fuels. The temperature of flame given out by each of the fuels were measured. Water heating process was conducted to find heat gained by water when using different fuels. Water Boiling Tests were also conducted to find burning time of the fuels and mass of fuels required to boil water.

The concentrations of Particulate Matter were measured in a closed room and in an open room to find which fuel emitted less pollutants. Air Quality Index was also monitored while measuring PM. The fuels were also compared in terms of their availability and accessibility to the stove users.

When considering cleanliness and thermal performance, the pellets had shown lower emissions and longer burning time, therefore, they are concluded to be the optimal feedstock for ACE One cook stove. Cow dung had shown a very poor performance in both cleanliness and thermal performance, it is also not a good fuel to use indoors because of high emissions.

The pellets performed better because they are densified, which makes them burn longer than other fuels. They are also cleaner because when being processed, those toxic compounds found in raw biomass are being burned out under high temperatures.

The solar panel used to charge the stove was also tested and the power dissipated by the solar panel was less than rated power. The battery's capacity was measured. Charging times when using a wall charger and a solar panel, were compared. Finally, power usage of LED lamp, fan and cell phone were studied.

Recommendations

ACE company should consider supplying pellets to their customers when purchasing the stove. At least 1 bag of pellets must be included in the packages so that the customers can have the experience with the use of pellets and compare with other fuels. It may not be easy for people who are used to other, often free, biomass fuels to buy pellets unless they know the differences. Where pellets are always available as the best fuels, end-users should still be able to use other fuels such as wood and corn cobs which performed relatively well. However, the design of the stove seems to be optimised for the use of pellets at the expense of other fuels. For instance, the stove does not allow for ease of refuelling in the case of bulky fuels such as those mentioned above.

Also, increasing the height of the pot from the stove to allow easy refuelling in the middle of cooking process without removing the pot would be advantageous. This can be achieved by manufacturing pot-stands of different heights as part of the package for the stove. This requirement is augmented by the fact that fuels which required refuelling had also produced bigger flames which could still comfortably reach the pot even if the height had been increased.

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Lastly, ACE should consider making cheaper stoves for low income houses by cutting the production costs yet maintaining the quality of the product, it could reduce the consumer costs by 30%-40% to ensure affordability. It is common knowledge that people residing in the highlands face poverty daily and affordability is crucial since ACE could provide the only alternative there is to being connected to electrical grid. With the world turning on green energy, accessibility to various income households plays a key role in inclusivity.

Area for further studies

Fuels' performance assessment may also be carried out by also assessing other components of the fuels which were not explored in this study.

Also comparing pellets with other densified fuels without comparing with raw fuels. The stove can also be tested in the communities where the actual cooking is performed by the end-users using actual fuels.

Comprehensive studies using solar panel can be done at the same location at different seasons of the year and using other methods to find power dissipated.

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