ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL & INDUSTRIAL ENGINEERING

MASTER OF SCIENCE IN MECHANICAL ENGINEERING
(THERMAL ENGINEERING)

Design, Manufacture and Testing of Improved Biomass *Injera* Baking Stove Integrated with Thermoelectric Generator

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Thermal Engineering

BY

SALEAMLAK ABERA ADMASU

(GSE/8508/11)

Advisor: Kamil Dino Adem (PhD)

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Approved by Board of Examiners

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DECLARATION

I, Saleamlak Abera, declare that this thesis is my original work and has not been presented in other universities for the fulfillment of any degree. The research is focused on designing, manufacturing and testing of an improved *Injera* baking stove integrated with small scale power generation. All references that are reviewed have been cited.

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ABSTRACT

Most of Ethiopian population, as a sub-Saharan African community, depends on traditional biomass for cooking purposes and almost half of the biomass is specifically used for baking *Injera*. Most people in rural area use biomass to bake *Injera* in low efficient traditional open fire stove which leads to excessive firewood consumption, significant indoor air pollution, environmental degradation, and deforestation *(Tadesse, 2020)*. In addition, urban-rural access to electrification shows that almost two third of people lives in rural area of Ethiopia which more than half people has no access to electricity. The life style of people living without access to electricity is difficult compared to those who has access *(WBG, 2023)*.

In this research an improved biomass *Injera* baking stove integrated with thermoelectric generator was designed, manufactured and its performance was comparatively evaluated with *Mirt* stove according to standard to "Ethiopian Standard Test Protocol ES ISO 19867-1:2018". The test was conducted fifteen times, five tests for *Mirt* stove, five tests for the manufactured stove with natural draft and five test for tests for the manufactured stove with forced draft. And each test is conducted for an hour and the results are generated by WBT 4.2.3 Excel evaluation setup.

The forced draft stove which is designed and manufactured by this research has an average of 37.32% thermal efficiency. This value has an average of 3.26% efficiency improvement compared to *Mirt* stove which has an average of 34.06% thermal efficiency in addition to small scale power generation. In addition, the test of the natural draft stove which has an average of 35.82% has a 1.5% efficiency improvement compared to *Mirt* stove. In addition to the efficiency improvement, the integrated TEG was generating an open circuit voltage of 14.2V and output rated power of 1.4w (8.6 V x 0.16) while running a DC fan and DC LED lamp at an average temperature difference of 140^{0}C. So, as it is, the generated power can run the DC fan which helps the process of forced draft and can light up an LED lamp in order to help baking and cooking at night which gives the light for the room.

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ACRONYMS AND SYMBOLS

WHO	World Health Organization
IEA	International Energy Agency
WEO	World Energy Outlook
WBG	World Bank Group
TEG	Thermo-Electric Generator
TE	Thermo-Electric
PV	Photo Voltaic
IAP	Indoor Air Pollution
CO	Carbon monoxide
PM	Particulate Matter
LED	Light Emitting Diode
TDR	Turn Down Ratio
WBT	Water Boiling Test
CCT	Controlled cooking Test
KPT	Kitchen Performance Test
CS	Cold Start
HS	Hot Start
SFC	Specific Fuel Consumption
SFC_{NS}	Specific Fuel Consumption of New Stove
TSF	Three Stone Fire
ICS	Improved Cook Stove
W_b	Wet Basis
HHV	Higher Heating Value

LHV Lower Heating Value

HV_{Fuel} Heating Value of Fuel

DC Direct Current

RHS Rectangular Hallow Section

IBIBSITG Improved Biomass *Injera* Baking Stove Integrated with Thermoelectric Generator

EREDPC Ethiopian Rural Energy Development and Promotion Center

ES Ethiopian Standard

ISO International Standard Organization\

FP Fire Power

Q_1 Useful energy delivered, kJ

C_p Isobaric mass-specific approximate heat capacity of water between 20 °C and 100 °C: 4.18 kJ $kg^{-1}K^{-1}$

G_1 Initial mass of water in the cooking vessel, kg

G_2 Final mass of water in the cooking vessel, kg

T_1 Initial temperature of water in the cooking vessel, °C

T_2 Temperature of the local boiling point or the highest temperature attained of the water in the cooking vessel, °C

γ Latent heat of water vaporization at the local boiling point, kJ/kg

P_c Cooking power, kW

t_3 Final time at end of a test phase, s

t_1 Initial time at beginning of a test phase, s

η_c Cooking thermal efficiency with no energy credit for remaining char, %

B Mass of the fuel fed, kg

$Q_{net.af}$ Lower heating value of fuel, as fired, kJ/kg

Ψ_c Cooking thermal efficiency with energy credit for remaining char, %

C Mass of the remaining char, kg

$Q_{net.char}$ Lower heating value of remaining char, kJ/kg

E_{char} Char energy productivity, %

m_{char} Char mass productivity, %

D_{mitad} Diameter of *Mitad*

d Diameter of Fire Bed

h Height b/n bottom of pot and fire bed

W_{FC} Weight of fuel consumed

M_{TA} Mass of Theoretical Air

V_{TA} Volume of Theoretical Air

V_{TTA} Volume of Total Theoretical Air

V_{TRA} Volume of Total Required Air

V_{FR} Volume of Flow Rate of Air Supply

A_{AI} Area of Air Intake

A_{AIH} Area of Air Intake Hole

d_{AIH} Diameter of Air Intake Hole

A_{AFI} Area of Air and Fuel Intake

A_{FI} Area of Fuel Intake

A_{EA} Area of Exhaust Air

A_{AEO} Area of Air Exhaust Opening

$A_{chimney}$ Area of Chimney

$d_{chimney}$ Diameter of Chimney

1. INTRODUCTION

1.1. Background

Burning of traditional biomass fuels (wood, dung, crop and plant residues) are still dominantly used especially in developing countries for cooking, heating, lighting and other household energy needs *(/Mamuye et al., 2018/,/Feleke, 2007/,/Mazzoni & Isaac, 2003/)*.

The energy progress reports that approximately 1.8 to 2.4 billion individuals globally rely on polluting open fires or basic stoves powered by kerosene, biomass, and coal for cooking *(Tracking SGD7 Report, 2024)*. Consequently, nearly 3.2 million people succumb each year to premature deaths due to illnesses linked to household air pollution *(WHO, 2024)*. In addition to the health impact, the traditional way of cooking affects environmental and social life of users *(Mazzoni & Isaac, 2003)*.

Among 20 nations experiencing the most significant access deficits represented 74 percent of the worldwide population, 10 countries are located in Sub-Saharan Africa which over 923 million individuals were deprived of clean cooking fuels and technologies. Furthermore, in 8 of the 20 countries including Ethiopia, less than 10 percent of the population had access to clean cooking options *(Tracking SGD7 Report, 2024)*. A significant portion of the Ethiopian population depends on traditional biomass for cooking purposes and around half of this energy allocated to the preparation of *Injera (Figure 1)* *(Tadesse, 2020)*.

Figure 1: Picture of a typical Injera with Wot (Wikipedia)

Injera is recognized for its energy-intensive and time-consuming preparation process. In the majority of households across the country, the baking of *Injera* is performed using a traditional open fire method, commonly referred to as the three-stone system *(Figure 2)*.

The three stones are arranged in a triangular formation to support a baking pan. Firewood is then placed through the gaps between the three stone supports for combustion. As the fire burns beneath the pan, *Injera* is cooked utilizing the heat generated from the burning fuel. In this method, most of the energy produced is dissipated into the environment. The low efficiency of this biomass stove leads to excessive firewood consumption, contributing to significant indoor air pollution and environmental degradation *(Tadesse, 2020)*.

Figure 2: Traditional Open Fire (Three-stone) Injera Baking (Andrew Beahrs, 2013)

Having the problems related to traditional cook stoves and indoor air pollution, different approaches with different programs have been done worldwide in order to have an improved cook stove and to reduce the impacts related to traditional cooking. As well, local and international organizations and personals are also involving for the development of improved *Injera* baking stoves *(Tadesse, 2020)*.

In addition, according to Ethiopian Water and Energy Authority assessment, 48% to 52% of Ethiopian population has access to electricity while World Bank Group recently reported the figure as 55% of the people have an access to electricity. Moreover, among 76.84% people living in rural areas 57 % people has no access to electricity *(WBG, 2023)*. The life style of people living without access to electricity is difficult compared to those who has access.

In order to solve problems related to off grid areas, different rural electrification ways are developed and implemented worldwide. Solar photovoltaics (PV), wind energy, small scale hydropower and diesel generators are the main electric sources for off-grid areas.

Furthermore, with biomass-fired cook stoves, thermoelectric generators represent another category of advanced energy devices capable of directly transforming heat into electricity. Since the required heat is gained from combustion chamber of improved cook stoves, the stove-powered thermoelectric generators which are developed in recent years are technically feasible methods for small scale electricity generation.

1.2. Statement of Problem

Most of Ethiopian population, as a sub-Saharan African community, depends on traditional biomass for cooking purposes and almost half of the biomass is specifically used for baking *Injera*. Most people in rural area use biomass to bake *Injera* in low efficient traditional open fire stove which leads to excessive firewood consumption, significant indoor air pollution, environmental degradation, and deforestation *(Tadesse, 2020)*. Acute respiratory infection which is major cause of children death under five years, chronic obstructive pulmonary disease, tuberculosis, asthma, pneumoconiosis, sarcoidosis, lung cancer, aero-digestive tract cancer, eye disease, low birth weight, perinatal mortality, meningitis, immunological functions, injury on burns, eye irritation and injury on fuel collection are possible diseases related to indoor air pollution and traditional cooking *(Staton & Harding,2002)*. In addition to the health impact, the traditional way of cooking affects environmental and social life of users. Deforestation and environmental pollution are some of environmental effects. Household economy, women's time for fuel collecting, gender roles, relationships and safety are some of social impacts of traditional cooking *(Mazzoni & Isaac, 2003)*.

In addition, urban-rural access to electrification shows that almost two third of people lives in rural area of Ethiopia which more than half people has no access to electricity. Access to information as a result of using a radio, access to communication as a result of lack of electricity to charge mobile phones, serious eye illness by using traditional light that uses diesel (*kuraz*) to study at night, and not using electric appliances for cooking, boiling and heating are some difficulties for people with no access to electricity in Ethiopia *(IEA, 2020)*.

Even if there are different researches and tested prototypes for improved *Injera* baking stoves and TEG integrated stoves independently, there is no research yet which integrates having an improving *Injera* baking stove and having a small scale power generation to give a solution for the two main problems related to people living in rural areas. This research tries to give a solution by producing a new improved *Injera* baking stove (that can decrease the fuel consumption and reduce indoor air pollution) integrated with TEG to power a light and charge a mobile phone.

1.3. Scope of Research

The main focus area of this research is designing, manufacturing and testing of an improved *Injera* baking stove and integration of thermoelectric generator with it in order to generate small scale power generation.

1.4. Research objectives

1.4.1. General objective

The general objective of this study is to design, manufacture and test an improved biomass based *Injera* baking stove integrated with thermoelectric generator.

1.4.2. Specific objective

The specific objectives of this study are:

- To design an improved biomass based *Injera* baking stove
- To manufacture the stove based on the final design
- To size and integrate thermoelectric generator
- To test the performance of the designed stove

1.5. Significance of the study

The developed improved cook stove with reduced emissions, greater fuel efficiency and small scale power generation can mitigate health risks and preserve lives by minimizing exposure to indoor air pollution (IAP) reduce time and money to collect or buy fuel, reduce deforestation, improve health condition of people and environment by reducing CO, PM and black carbon emission, improve social and economic life of people by generating small scale electricity, reduce toxic emission from traditional diesel burning light (like: *Kuraz and Fanos*) by the produced electricity to light up an LED light and lowers the fuel gathering responsibilities for women and children.

In addition, since the work is new, the findings of this research will serve as a valuable reference for future studies that aim to design, manufacture, and evaluate an enhanced *Injera* baking stove with a thermoelectric generator (TEG).

1.6. Limitation of the Research

The main limitation of this research is to find a liable TE module and its electronic accessories locally for the small scale electric power generation. In addition, the performance on emission is not carried due to insufficient equipment and setup necessary for measuring the emission rate. Moreover, considering the time and cost of a field test (KPT), only laboratory based test (CCT) which is water boiling test (WBT) was conducted for the evaluation of the performance of the stove.

2. LITERATURE REVIEW

2.1. Technical Aspect of Cook Stoves

In order to develop an efficient and low emission cook stove, a one should concern on the technical considerations, classifications, guidelines, principles, materials, accessories and geometric variables of cook stoves.

2.1.1 General Cook Stove Considerations

A cook stove designer should focus on design considerations related to social, technical and economic issues in order to have a better and acceptable improved cook stove design. Social considerations encompass aspects such as dietary practices, availability of local fuel resources, and functional requirements. Economic considerations include factors such as capital expenditure, fuel expenses, and maintenance costs. Technical considerations involve process and performance factors, which address parameters related to heat transfer, fluid dynamics, and combustion. Additionally, they encompass materials and durability, safety and cooking comfort, as well as environmental considerations, which include health impacts and global warming issues *(Sedighi & Salarian, 2017)*.

Controlling of the heat output is directly related to fuel consumption of a typical cook stove. A poor heat output control increases fuel consumption. As compared to rocket or direct stoves, a gasifier stove has a poor heat output control which leads to a higher fuel consumption. Direct combustion stoves offer a greater turn down ratio (TDR) compared to gasifier stoves *(Kshirsagar & Kalamkar, 2014)*.

Cook stoves ought to be constructed from appropriate materials to ensure they are efficient, safe, and long-lasting, while also being cost-effective and simple to produce *(Sedighi & Salarian, 2017)*. Mud, ceramics and metals are mostly used materials with their advantage and dis-advantage over each other. A combination of metal and ceramic materials for stove construction is getting attention and has a better performance.

Diameter and height of combustion chamber with stove to pot gap are the basic geometry parameters that should be considered while designing an improved cook stove.

2.1.2 Classification of biomass cook stoves

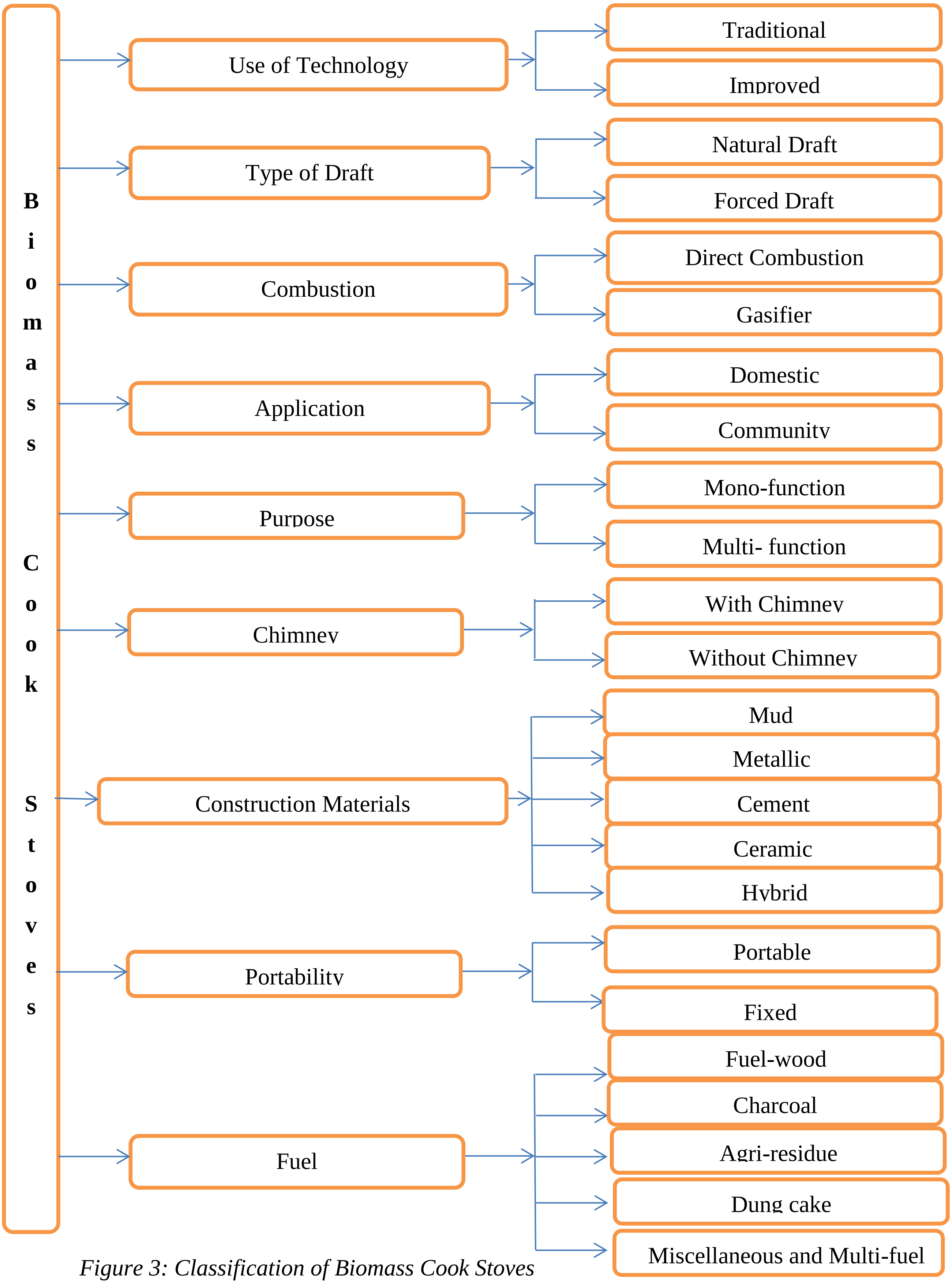


Figure 3: Classification of Biomass Cook Stoves

2.1.3 Biomass Fuel Characteristics

Various fuel types yield distinct levels of energy content, as well as differing emissions of carbon monoxide and particulate matter. Wood is considered a preferable and superior solid fuel option *(Manoj et al., 2013)*. In addition to fuel type, a fuel feeding interval will affect the important parameters.

When the fuel size increase the heating value of produced gas will decrease and when small particles gasify the amount of gases produced will be increased *(Sedighi & Salarian, 2017)*. As a result, a special consideration for the fuel size should be taken when designing a cook stove especially for gasifier stoves *(Sutar et al., 2015)*.

Decreasing the moisture level of a fuel is critical for the better function of a cook stove. Many findings and tests indicate that the use of wet fuel leads to higher fuel consumption, increased emissions of pollutants, and longer cooking times in comparison to dry fuel *(Sedighi & Salarian, 2017)*.

2.1.4 Cook Stove Accessories

A grate specifically engineered to facilitate the flow of primary supply air through the fuel bed can enhance efficiency and minimize pollutants by optimizing the fuel-air mixture. A properly installed damper will use for the optimization of the amount of supply air in order to control the fire power which improves the combustion efficiency.

Most findings indicate that the installation of a chimney necessitates a longer duration for boiling and results in increased fuel consumption. However, a chimney that effectively expels smoke and other emissions from the living area serves to safeguard the family by diminishing their exposure to pollutants and associated health hazards. Moreover, even stoves that burn more cleanly but lack a chimney can still generate unhealthy levels of indoor air pollution *(Bryden et al.,2013)*.

A skirt which covers the side portion of the cooking pot with an acceptable gap, keeps the hot gas to pass through touching the pot which can increase the convective heat transfer and improves the efficiency of the cook stove.

Insulating the stove's wall will reduce heat loss to the surrounding environment, thereby enhancing the stove's performance and emissions by raising the internal temperature of the combustion chamber. In addition, it prevents a user from burning and safety perspective.

2.2. Traditional Cook Stoves

In numerous developing nations, the practice of cooking is typically conducted by utilizing traditional biomass fuels in conventional stoves *(Mehetre et al., 2017)*. Traditional stoves have evolved over millennia, shaped by regional cultures and culinary traditions. These stoves are generally inexpensive, and users are well-acquainted with their functionality, which contributes to their widespread acceptance in various communities. There are two primary types of traditional stoves, the first being the "three-stone fire," *(Figure 4)* which consists of a fire constructed directly on the ground supported by three stones, with a cooking vessel positioned at top *(Kshirsagar & Kalamkar, 2014)*.

The three-stone fire, while traditional, offers certain technical advantages over some modern stoves. One notable benefit is that it does not absorb energy into the mass of the stove body. In contrast, high-mass stoves can retain energy that could otherwise be utilized for heating the pot. Additionally, three-stone fires are capable of boiling water relatively quickly.

However, an enhanced stove can still provide superior combustion and fuel efficiency compared to an open fire *(Bryden et al.,2013)*. Laboratory studies conducted on three stone-fired systems have indicated a moderate boiling time, elevated fuel consumption, significant emissions of CO and PM, and a low thermal efficiency of approximately 20% *(Aprovecho Research Center)*.

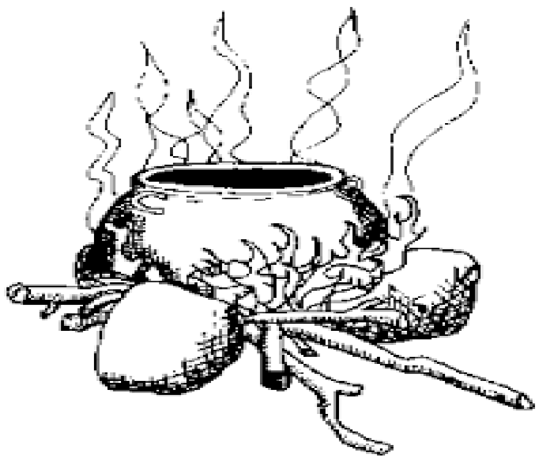


Figure 4: Traditional Three Stone Fire (Humanity Development Library)

The second category of traditional stove is known as the "Built-in stove" or "Mud-stove" *(Figure 5)*, which represents an adaptation of the three-stone fire method. A "Built-in Stove" is characterized as a semi-permanent structure made of mud that surrounds the fire on at least three sides, excluding the ground.

Built-in stoves offer several benefits compared to the three-stone fire system: they contain the fire, which reduces heat loss through radiation; they limit the amount of fuel that can be added at one time, thus conserving fuel; and they create an enclosed gas pathway that minimizes the intake of ambient air. However, the reduction of primary air supply to the fuel may lead to incomplete combustion, which can increase indoor air pollution (IAP). Laboratory tests of mud stoves have indicated rapid boiling times, elevated CO/PM emissions, an average thermal efficiency of approximately 29%, and a moderate safety rating, primarily due to the enclosed nature of the fire *(Aprovecho Research Center)*.

Figure 5: Traditional Mud Stove (Wikipedia)

2.3. Improved Cook Stoves

A stove which is designed using a certain scientific principles is called an improved stove. The advancement of enhanced biomass stoves is driven by numerous factors, including environmental, health, and socio-economic advantages. These improved stoves can be engineered to operate more efficiently, produce less pollution, and minimize the release of various harmful emissions. According to the biomass cook stoves technical meeting summary report, an improved cook stove should satisfy at least 90% emission reduction and 50% fuel reduction compared to traditional open fire cook stoves *(U.S. Department of Energy, 2011)*.

2.3.1 Testing of Improved Cook Stoves

Thorough testing of stoves has led to a more precise comprehension of how to improve stove design. In the absence of experimentation and testing, the advancement of a stove relies on speculation. Diligent examination can swiftly distinguish fact from belief. Testing serves a dual purpose: to uncover issues and to highlight potential solutions. It is a crucial component for advancement.

Various cook stove testing protocols are employed in different countries to assess the thermal performance of cook stoves under both laboratory and field conditions. Combustion and emission characteristic fuels on cooking stoves are tested using laboratory and field performance testing protocols of cooking stoves such as water boiling test (WBT), controlled cooking test (CCT) and Kitchen performance test (KPT) are developed to evaluate the combustion and emission characteristics of fuel on cooking stoves.

Water boiling test is a test that conducts by boiling a measured quantity of water to boiling temperature on its cold and hot start high power test and simmer the water for about 45 minutes below the boiling temperature of the water by technicians on controlled manner. The main aim of water boiling test is to analyze how the heat is reaching the cooking pot, how much emissions is produced and how to make efficient the cooking stove. Combustion and emission characteristics of fuels on cooking stoves compared using WBT.

Controlled cooking test (CCT) is also a laboratory test which is testing the cooking stove by cooking common meal by technicians. It is mainly used to evaluate the specific fuel consumption of an improved cook stove

Kitchen performance test (KPT) is a broader and uncontrolled performance evaluation test which intended to compare the cooking stove with existing ones by any means of comparisons the user specified test of cooking stove *(Bryden et al.,2013)*.

2.3.2 Performance of Improved Cook Stoves in Ethiopia

The Energizing Development (EnDev) Program Ethiopia, carried out by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in partnership with the Rural Energy Technology Development and Promotion Centre (RETDPC) under the Ministry of Water and Energy (MoWE), has taken a significant step by commissioning ES ISO standard tests on twenty-six prominent solid biomass cook stoves in Ethiopia. These tests were executed at the RETDPC, which serves as the national authority for testing biomass stoves in Ethiopia. They adhered to the Ethiopian Standard protocol 19867-1:2019, designed to align with the ISO 19867-1:2018 guidelines, specifically “Clean cook stoves and clean cooking solutions — Harmonized laboratory test protocols - Part 1: Standard test sequence for emissions and performance, safety and durability,” issued by the International Organization for Standardization (ISO) *(EnDav Ethiopia, 2024)*.

In total, 26 solid biomass cook stove systems were evaluated, classified into three categories: seven *Injera* baking stoves, fourteen traditional cooking stoves (non-*Injera* baking), and five charcoal stoves.

The seven *Injera* baking stoves are: *Mirt* Classic, *Mirt* Slim, *Mirt* with Concrete Chimney, *Yekum Mirt*, Institutional *Mirt* Stove (IMS), *Mirt* Modified for *Harar* and *Gonzye* for baking.

The fourteen traditional cooking stoves are: *Tikikil* rocket stove, Flexi multi-fuel stove (for fuelwood), EZY stove, Efoy stove, Loo metal stove, *Beredu* stove vr.1, *Beredu* stove vr.2, *Upesi* stove, *Gonzye* for cooking, *Gambela* fuelwood stove, *Gambela* multi-fuel stove (for fuelwood), Gasifier stove, Institutional Rocket Stove (IRS) 40L and IRS 20L A & H.

The five charcoal stoves are: *Lakech* charcoal stove, *Merchaye* charcoal stove, Flexi multi-fuel stove (for charcoal), *Gambela* multi-fuel stove (for charcoal) and *Kulbich* charcoal stove.

The analysis of the cooking stoves' energy performance indicates that their thermal energy efficiency, whether using char or not, falls between 20% and 30%, with specific results ranging from 21.5% to 28.1%. Consequently, the majority of non-*Injera* cooking stoves are classified at Tier 2 for thermal efficiency. The *Tikikil* rocket stove achieved the highest thermal efficiency without char at 28.1%, while the *Upesi* clay stove recorded the lowest at 21.5%. The cooking power for these stoves is approximately 1 kW, specifically between 0.99 kW and 1.1 kW. Importantly, the two larger cooking stoves evaluated, known as Institutional Rocket Stoves, surpassed 30% thermal efficiency, with ratings of 33.1% and 30.2%, thus qualifying for a Tier 3 classification *(EnDav Ethiopia, 2024)*.

Furthermore, *table 1* present the summary test results for non-*Injera* cooking stoves.

Sr. No.	Cookstove name	Picture	Thermal Energy Performance		Safety (Score)
			Thermal efficiency (without char), %	Thermal efficiency (with char), %	
1	Tikikil rocket stove (for household)		28.1 (Tier 2)	29.5 (Tier 2)	73.5 (Tier 2)
2	Flexi multifuel stove (for fuelwood)		22.9 (Tier 2)	23.5 (Tier 2)	69.5 (Tier 2)
3	EZY stove		22.0 (Tier 2)	23.5 (Tier 2)	65 (Tier 1)
4	Efoy stove		24.1 (Tier 2)	27.4 (Tier 2)	81 (Tier 3)
5	Gonzye for Cooking		25.9 (Tier 2)	28.0 (Tier 2)	76 (Tier 2)
6	Gambela fuelwood stove		22.2 (Tier 2)	25.3 (Tier 2)	69 (Tier 2)
7	Gambela multifuel stove (for fuelwood)		21.5 (Tier 2)	24.3 (Tier 2)	70 (Tier 2)
8	Upesi clay stove		21.5 (Tier 2)	23.9 (Tier 2)	69 (Tier 2)
9	Loo metal stove		23.2 (Tier 2)	24.8 (Tier 2)	65 (Tier 1)
10	Beredu stove vr.2		23.5 (Tier 2)	24.2 (Tier 2)	65 (Tier 1)
11	Beredu stove vr.1		24.4 (Tier 2)	25.1 (Tier 2)	71 (Tier 2)
12	Gasifier stove		24.6 (Tier 2)	30.1 (Tier 3)	85 (Tier 3)
13	Institutional Rocket Stove (IRS) – 40 L		30.2 (Tier 3)	33.3 (Tier 3)	71 (Tier 2)
14	IRS (20L) – A & H		33.2 (Tier 3)	35.6 (Tier 3)	71.5 (Tier 2)

Table 1: Test Summary of non-Injera Cooking Stoves by EnDev Ethiopia

The charcoal stoves most extensively advertised and sold in Ethiopia, Lakech and Merchaye, have demonstrated thermal efficiencies of 33.2% and 30.9%, respectively. Both models are classified as Tier 3 in terms of thermal energy efficiency performance *(EnDav Ethiopia, 2024)*.

Furthermore, *tables 2* present the summary test results for charcoal stoves.

Sr. No.	Cookstove Name	Picture	Thermal Energy Performance		Safety (Score)
			Thermal efficiency (without char), %	Thermal efficiency (with char), %	
1	Lakech charcoal stove		33.2 (Tier 3)	N/A	86.5 (Tier 4)
2	Merchaye charcoal stove		30.9 (Tier 3)	N/A	86.5 (Tier 4)
3	Flexi multifuel stove (for charcoal)		24.6 (Tier 2)	N/A	92.5 (Tier 4)
4	Gambela multifuel stove (for charcoal)		27.7 (Tier 2)	N/A	90 (Tier 4)
5	Kubich charcoal stove		20.2 (Tier 2)	N/A	86.5 (Tier 4)

Table 2: Test Summary of Improved Charcoal Cooking Stoves by EnDev Ethiopia

2.4. Improved *Injera* Baking Stoves

The predominant method for baking Injera among Ethiopians involves the use of a traditional three-stone cooking stove over an open flame. This stove, as its name suggests, consists of three distinct stones that serve to elevate the *Mitad*, a clay pan utilized for baking. In terms of fuel efficiency, the average consumption for a three-stone open-fire stove is approximately 929 grams of wood per kilogram of Injera, as determined by the CCT testing protocol. Additionally, the indoor air quality measurements associated with this cooking method indicate carbon monoxide levels of 80 ppm and particulate matter concentrations of 1.10 milligrams per cubic meter *(Adem & Ambie, 2017)*.

2.4.1 Review of Improved Injera Baking Stoves

Since the 1980s, initiatives have been undertaken to enhance the design of *Injera* baking stoves. The enclosed traditional *Injera* baking stoves represent the initial advancements implemented in the northern regions of Ethiopia, particularly in Tigray and *Wollo*. These stoves are constructed either directly on the ground or on an elevated platform composed of mud and stones. Users typically design the stove based on their own measurements. A standard *Tigrian Injera* baking stove generally features two smoke outlets and stands approximately 35 cm tall.

The efficiency of a properly constructed enclosed *Tigrian Injera* baking stove is approximately 12%. In contrast to the traditional three-stone open fire *Injera* baking stove, it utilizes less fuel, offers greater ease of use, and provides protection against burns. The *Tehesh Injera* baking stove was created through a collaboration between GIZ (formerly GTZ) and the Rural Technology Promotion Center in *Mekelle*. The concept behind the *Tehesh* design aimed to enhance the functionality of the existing Tigrian *Injera* baking stove.

In another region of the country, the *Sodo Injera* baking stove is produced by the Rural Technology Promotion Center located in *Sodo*. This stove is constructed from 2 mm sheet metal and features an enclosed design. It accommodates *Mitad* (stove) sizes ranging from 54 to 56 cm. The overall height of the stove measures 42 cm, while the combustion chamber has a diameter of 60 cm and a height of 15 cm. It also includes an ash collection box situated beneath the perforated metal grate. A controlled cooking test performed by *Sodo* using a 45 cm diameter *Mitad* indicated that the average fuel wood consumption for the stove was 0.343 kg of wood per *Injera* *(Adem & Ambie, 2017)*.

Awuramba represents an enhanced *Injera* baking stove that has been utilized within the community since 1971. This stove not only serves the purpose of baking *Injera* but also accommodates various other cooking functions. Notably, it achieves a fuel consumption reduction of 35% when compared to traditional open-fire *Injera* baking stoves *(Adem & Ambie, 2017)*.

The alternative enhanced In*j*era baking stove, constructed from clay, is referred to as *Gonziye*. This versatile cooking appliance is designed for multiple functions, including *Injera* baking, water heating, coffee preparation, and the cooking of wot. The specific fuel consumption for the *Gonziye Injera* baking stove is 617 grams per kilogram of *Injera* *(Gulilat, 2014)*.

In the early 1980s, initial initiatives involved the production of mud *Injera* baking stoves by the *Burayou* Basic Technology Center, which operated under the Ministry of Education. This stove was designated as the '*Burayou* mud-stove.' Each component of the stove was crafted from clay and *chid*, leading to its designation as the *Burayou* mud-stove.

In 1986, the Ambo team enhanced the *Burayou* mud-stove, resulting in the creation of the Ambo mud-stove specifically designed for baking *Injera*. In the early 1990s, a group of specialists from the Ethiopian Energy Authority, in collaboration with international consultants, initiated a survey aimed at establishing a foundation for the development of *Injera* baking stoves within the country. Subsequently, significant improvements were made to the Ambo stove, leading the experts to develop a more efficient mud *Injera* baking stove, which they named '*Mirt*,' signifying excellence. As a result, the mud composition of *Mirt* was altered to incorporate a cement mortar mixture for constructing the fire chamber enclosure, as illustrated in (*Figure 6*). This stove has been extensively promoted by the GIZ-Energy Bureau Office in Ethiopia and is referred to as *Mirt*.

The specific fuel consumption of the *Mirt* stove has been assessed by various researchers and developers. On average, the *Mirt* stove consumes 535 grams of wood for every kilogram of *Injera* produced. Testing was carried out at the Approve Cho Research Center, employing the water boiling test (WBT) methodology, which recorded a boiling time of 35.8 minutes and utilized 6407 grams of fuel. The carbon monoxide (CO) emissions measured were 192 grams, while particulate matter (PM) was recorded at 5322 grams. The enhanced design resulted in significant reductions: 18% in boiling time, 81% in fuel consumption, 90% in CO emissions, and 83% in PM levels *(Adem & Ambie, 2017)*.

Figure 6: Mirt Injera Baking Stove (Gulilat & Girma, 2011)

The first *Injera* biomass gasification baking stove *(Figure 7)* is introduced, along with an assessment of its performance. This stove attains a thermal efficiency of 16%, while specific fuel consumption is decreased by 12.8%, and baking time is shortened by 19% in comparison to the traditional three-stone fire method. Furthermore, emissions of carbon monoxide (CO) and particulate matter (PM) are significantly lowered by 99% and 87%, respectively, when contrasted with the three-stone fire *(Dino Adem et al., 2019)*.

Figure 7: The first Injera biomass gasification baking stove (Dino Adem et al., 2019)

2.4.2 Summary of Improved *Injera* Baking Stoves Test Results from Research

Table 3: Summary of performance for improved Injera Baking Stoves in Ethiopia

Summary of performance for Improved Injera Baking Stoves in Ethiopia

No	Type of Stove	Developed By	Performance: Specific Fuel Consumption (g wood/kg of Injera)	% Reduction in SFC with Three Stone Stove	CO Concentration or % Reduction	PM Concentration or % Reduction	% Reduction in time to boil with Three Stone Stove	Thermal Efficiency	Reference
1	**Three Stone**	Traditional Way	929 (Average)	_	80 ppm	1.1mg/m^3	_	10%	(Adem & Ambie, 2017)
2	**Tigrian**	Tigray & Wollo People	_	_	_	_	_	12%	(Adem & Ambie, 2017)
3	**Sodo**	TRPC in Sodo	343 g wood per injera with 45 cm diameter mitad	_	_	_	_	_	(Adem & Ambie, 2017)
4	**Awuramba**	Awuramba	_	35%	_	_	_	_	(Adem & Ambie, 2017)
5	**Gonziye**	_	617	_	_	_	_	_	(Gulilat, 2014)
6	**Mirt**	GIZ - Energy Bureau Office	535 (Average)	81%	90%	83%	18%	_	(Adem & Ambie, 2017)
7	**Gasification**	Research Article	_	13%	99%	87%	_	16%	(Dino Adem et al., 2019)

2.4.3 Summary of Improved Injera Baking Stoves by EnDev Ethiopia

The thermal energy efficiency of the seven Injera baking stoves varies between 30% and 40%, with specific measurements ranging from 31.2% to 36.7%. Consequently, all stoves are classified as Tier 3 in terms of thermal efficiency. The Gonzye stove achieved the highest thermal efficiency at 36.3% when operating without char, whereas the Yekum Mirt recorded the lowest efficiency at 31.2% *(EnDav Ethiopia, 2024)*.

Furthermore, *Table 4* outlines the summary test results for seven Injera baking stoves.

Sr. No.	Cookstove Name	Picture	Thermal Energy Performance		Safety (Score)
			Thermal efficiency (without char), %	Thermal efficiency (with char), %	
1	Mirt Classical		34.4 (Tier 3)	39.6 (Tier 3)	81 (Tier 3)
2	Mirt Slim		33.7 (Tier 3)	38.1 (Tier 3)	81 (Tier 3)
3	Mirt with Concrete Chimney		32.3 (Tier 3)	38.7 (Tier 3)	78.5 (Tier 3)
4	Mirt Yekum		31.2 (Tier 3)	36.5 (Tier 3)	76.5 (Tier 2)
5	Mirt Modified for Harar		31.7 (Tier 3)	38.8 (Tier 3)	81 (Tier 3)
6	Institutional Mirt Stove (IMS)		34.7 (Tier 3)	38.1 (Tier 3)	81 (Tier 3)
7	Gonzye stove (for baking)		36.3 (Tier 3)	39.6 (Tier 3)	76 (Tier 2)

Table 4: Test Summary of Improved Injera Baking Stoves by EnDev Ethiopia

2.5. Cook Stoves with Thermoelectric Generators (TEGs)

2.5.1 Thermoelectric Generators

In 1821, Thomas Seebeck made a significant discovery regarding the behavior of a compass needle in relation to heat. He observed that when one junction of two dissimilar metals was heated, a nearby compass needle would rotate. This phenomenon was initially referred to as the thermomagnetic effect *(figure 8)*. Subsequent investigations revealed that the heating of the junction induced a voltage, which in turn generated an electric current. According to Ampère's law, this current produced a magnetic field. The voltage induced by the heating of the junction eventually became recognized as the Seebeck effect *(Applied TE Solutions, Internet)*.

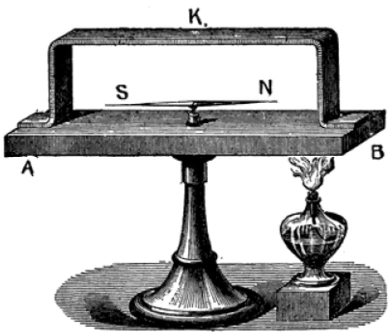


Figure 8: Demonstration of the Seebeck effect (Applied TE Solutions, Internet)

The fundamental component of a thermoelectric generator is the thermocouple. A thermocouple consists of a p-type semiconductor and an n-type semiconductor. These semiconductors are electrically linked in series by a metal strip. The semiconductors are also referred to as thermos elements, dice, or pellets.

Bismuth telluride (Bi2Te3) is the most widely utilized thermoelectric material for applications at ambient temperature. Its high thermoelectric figure of merit (ZT), ranging from 1 to 1.5, significantly enhances its effectiveness in power generation. The performance of Bi2Te3 can be further improved through alloying with elements such as antimony (Sb). Commercial thermoelectric generators (TEGs) that incorporate Bi2Te3 semiconductors represent the most economical options available. Lead telluride (PbTe) demonstrates advantageous thermoelectric characteristics at elevated temperatures. With its low thermal conductivity and high Seebeck coefficient, PbTe shows promise for high-temperature applications. The performance of this material can also be enhanced by adding alloying elements like antimony (Sb) or selenium (Se). Skutterudites have shown encouraging thermoelectric properties, particularly under high-temperature conditions, with examples including $CoSb_3$ and filled skutterudites such as (Co, Fe) Sb_3 that contain guest atoms. The impressive ZT values of these materials are attributed to their complex crystal structures and distinctive electrical properties *(Ismail, 2024)*.

The operation of a thermoelectric generator is fundamentally based on the Seebeck effect. This phenomenon occurs when a circuit composed of two different metals generates an electromotive force when the junctions of these metals are subjected to different temperature conditions. Consequently, these devices are often referred to as Seebeck power generators. Typically, a thermoelectric generator consists of a heat source maintained at elevated temperatures and a heat sink, which must be at a lower temperature than the heat source. The temperature differential between the heat source and the heat sink facilitates the flow of current through the load section *(Elprocus, Internet)*.

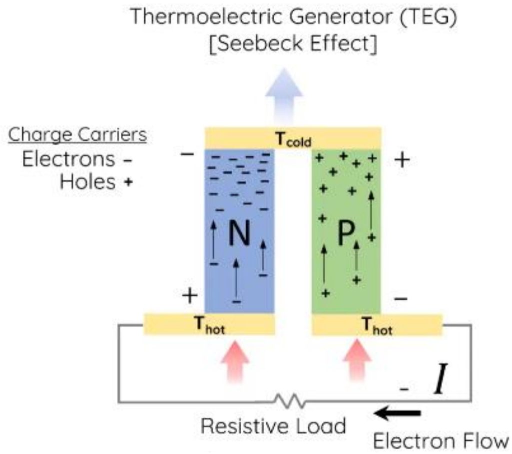


Figure 9: Thermoelectric Generator Charge Carriers (Applied TE Solutions, Internet)

In this energy conversion process, there are no intermediate energy transformations, distinguishing it from other forms of energy conversion. Therefore, it is classified as a direct energy transformation. The power generated through the Seebeck effect is of a single-phase direct current (DC) type, represented by the equation I^2RL, where RL denotes the resistance at the load. The output voltage and power can be enhanced in two primary ways: by increasing the temperature difference between the hot and cold junctions, or by connecting multiple thermoelectric generators in series. The voltage produced by this thermoelectric generator (TEG) is expressed as $V = \alpha\Delta T$, where ‘α’ represents the Seebeck coefficient and ‘ΔT’ signifies the temperature difference between the two junctions. The current flow can be described by the equation:

$$I = (V/R + RL)$$

From this, the voltage equation can be derived as:

$$V = \alpha\Delta T/(R + RL)$$

The power delivered to the load can be calculated as:

$$P_{at\ load} = (\alpha\Delta T/(R + RL)^2 (RL)$$

The maximum power output occurs when R equals RL, leading to the expression:

$$P_{max} = (\alpha\Delta T)^2 / (4R)$$

To construct a thermoelectric generator module, multiple p-type and n-type couples are interconnected electrically in series and/or parallel configurations to achieve the required electrical current and voltage. These couples are situated between two parallel ceramic plates, which offer structural stability, a flat mounting surface, and a dielectric layer to avert electrical short circuits.

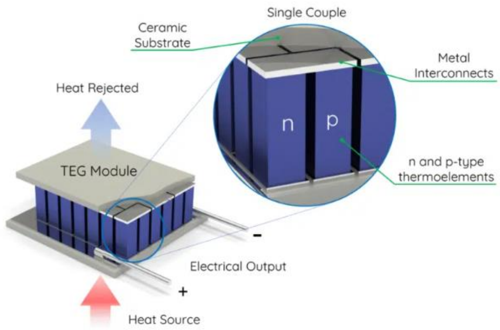


Figure 10: Thermoelectric Generator Module (Applied TE Solutions, Internet)

Currently available commercial modules exhibit a maximum efficiency ranging from 5% to 6%, whereas new materials have demonstrated efficiencies exceeding 10% in laboratory settings; however, it may take considerable time before these materials are available for commercial use.

Application Area of TEG

Thermoelectric generators (TEGs) serve a wide range of applications in multiple sectors, providing effective and sustainable energy alternatives *(Ismail, 2024)*.

Radioisotope Heat Source

A radioisotope thermoelectric generator (RTG) is a straightforward nuclear electric generator. RTGs have found applications in three primary areas: space exploration, remote power supply systems, and medical applications.

Space Domain

The first radioisotope thermoelectric generator (RTG) launched into space by the United States was the SNAP 3B in 1961. By 2010, the United States had deployed 41 RTGs across 26 space systems. Initially, the RTGs utilized silicon-germanium thermoelectric materials in the GPHS-RTG, which were later replaced by lead telluride alloys, or TAGS, in the multi-mission RTG (MMRTG), as illustrated in *figure 11*. The MMRTG was further enhanced through the development of the eMMRTG program, which incorporated advanced skutterudite thermoelectric materials to improve efficiency and reduce degradation rates, crucial for extended missions to the outer planets *(Encyclopedia)*.

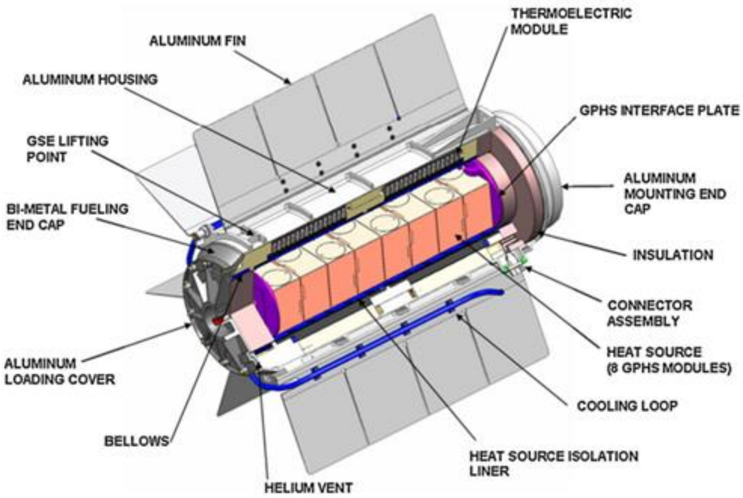


Figure 11: Cutting view of an MMRTG (Encyclopedia)

Natural Gas and Biomass

TEG integrated stoves like Camp stove *figure 12* are designed for general camping purposes. The Camp stove utilizes wood combustion to generate 2 W of power at 0.4 A and 5 V, with electrical devices connected via a USB port *(Encyclopedia)*.

Figure 12: Picture of a CampStove (Encyclopedia)

Human Body

Since 2001, numerous studies have focused on wearable thermoelectric generators (WTEGs) as potential alternatives to lithium-ion batteries for powering portable devices. The first thermoelectric wristwatch, which converted body heat into electrical energy, was introduced by Seiko and Citizen in 1999. The Seiko model produced 22 µW of electrical power and achieved an open-circuit voltage of 300 mV, with an efficiency of approximately 0.1% *figure 13*.

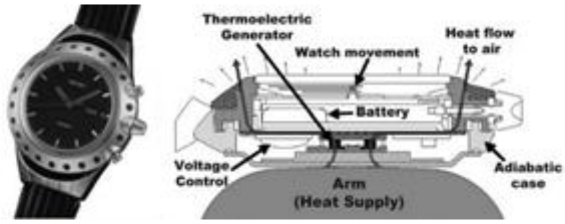


Figure 13: Seiko Thermic, wristwatch (Encyclopedia)

Sun Source

A solar thermoelectric generator (STEG) is a system engineered to harness heat from solar radiation and transform it into electricity through a thermoelectric generator (TEG). This technology is emerging as a viable alternative to the prevalent solar photovoltaic systems, even though it exhibits lower conversion efficiency in comparison to photovoltaic technology.

Waste Heat Source

Over the past thirty years, considerable efforts have been directed towards enhancing the efficiency of thermoelectric technology for heat recovery applications. This advancement is facilitated by the adaptability of thermoelectric technology to various physical parameters, including temperature, pressure, and heat transfer fluids specific to each heat recovery scenario *(Encyclopedia)*.

Waste Heat Recovery from Transport Systems

Automobiles

Leading automobile manufacturers from America, Asia, and Europe are actively working on the development of various types of thermoelectric generators (TEGs) aimed at enhancing the fuel efficiency of their vehicle models. One example is TEG integration into the exhaust line of the BMW X6 prototype vehicle as shown in the *figure 14*.

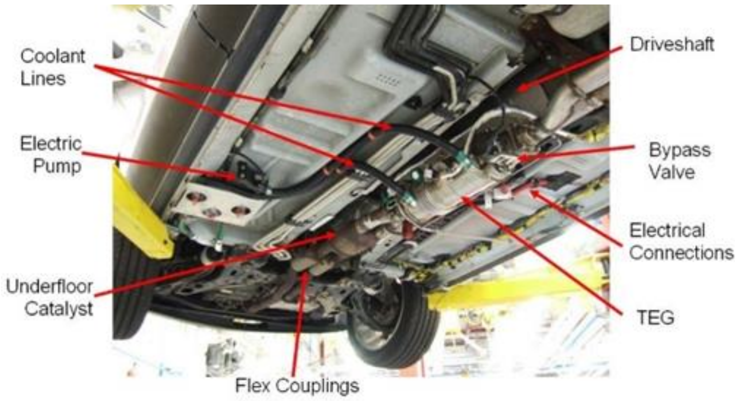


Figure 14: TEG integration into the exhaust line of the BMW X6 vehicle (Encyclopedia)

Aircraft

Contemporary aircraft are progressively being outfitted with sensors and transmitters to enhance control, monitoring, and safety. The adoption of autonomous wireless sensor networks would contribute to a reduction in aircraft weight and complexity, thereby decreasing fuel consumption.

2.5.2 TEG Powered Improved Cook Stoves

The thermoelectric generator has found extensive application in the conversion and refinement of low-grade heat derived from various sources, including solar energy, ocean thermal energy, geothermal heat, as well as emissions from automotive and steel manufacturing processes, into electrical energy. Consequently, the stove-powered TEG represents a viable technical solution for generating electricity to operate the fan.

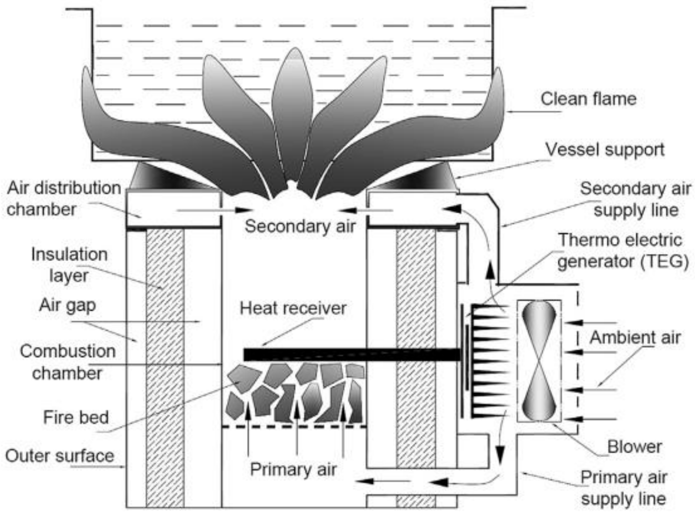


Figure 15: TEG powered forced draft cook stove with its components (Raman et al., 2014)

A conventional stove-powered TEG is composed of three main components: the stove system, the TEG system, and the load system. As biomass fuel combusts within the stove, a portion of the energy is transferred to the (TEG), where it is converted into electrical energy. This electricity is then directed to a power control system designed to optimize power extraction from the TEG. Subsequently, the generated power is stored in a battery, enabling it to be used for charging USB devices.

Furthermore, the electricity generated by the TEG can be utilized to operate a fan, which enhances the fuel-to-air ratio, thereby improving heat output and minimizing soot and particulate emissions from the stove. Additionally, this electricity can empower users to operate lights, radios, charge mobile phones, or fulfill other essential needs, particularly in developing regions.

The most prevalent and straightforward method of cooling is air-cooled forced convection, where the cold heat sink of the TEG is maintained at lower temperatures through airflow generated by a fan. This method allows for relatively low thermal resistances at the cold heat sink due to the effectiveness of forced convection.

The transition from traditional, inefficient stoves to more advanced models presents a significant challenge for developing nations. The integration of TEGs can facilitate electricity generation, enabling the use of electric fans to enhance the air-to-fuel ratio, thereby promoting complete combustion within the stoves. This innovation also addresses fundamental needs such as lighting, charging phones, and powering other electronic devices. Retrofitting existing household stoves with affordable TEGs emerges as a practical solution for electricity generation in these areas. *(Mehetre et al., 2017)*.

Royal Philips Electronics of the Netherlands conducted tests on the Philips Model HD4010 stove *(Figure 16)*, which features a developed air-cooled forced convection design. This stove is equipped with a TEG located at its base and is cooled by a fan. The airflow generated by the fan is preheated prior to entering the combustion chamber, ensuring complete combustion. During the initial start-up phase, the battery supplies electrical power to the fan, while the thermoelectric generator recharges the battery and powers the fan once the stove reaches a high temperature *(/Gao et al., 2016/,/Jetter & Kariher, 2009/)*.

Figure 16: Philips HD4010 Stove with TEG Powered Fan (Gao et al., 2016)

A forced draft cooking stove utilizing TEG was created to ensure clean combustion and enhanced efficiency. An analysis was conducted on the performance of both the TEG and the cooking stove. The TEG produced a power output of 4.5 watts with a temperature differential of 240 degrees Celsius. This cooking stove powered by the TEG achieved an efficiency rate of 44% *(Raman et al., 2014)*.

The TEG-BS-5W-5V-1 model biomass stove *(Figure 17)* is engineered to enhance cooking conditions and improve fuel efficiency. Additionally, it features a 5-watt TEG that provides lighting during cooking and enables the charging of mobile phones, thereby contributing to an improved lifestyle. By harnessing thermoelectric technology, the integrated small generator produces electricity during cooking by capturing a portion of the heat generated by the stove. The stove's unique airflow design ensures optimal combustion air supply, which minimizes smoke through natural ventilation and conserves fuel *(TEG-BS-5W-5V-1)*.

Figure 17: TEG-BS-5W-5V-1 model biomass stove (TEG-BS-5W-5V-1)

The stove's generator comprises thermoelectric modules, a fan, a heat collector, and a heat sink. The thermoelectric modules convert a portion of the stove's heat into electricity, which powers the fan and provides an additional 5 watts. The fan operates using its own generator to cool the cold side of the thermoelectric modules. This stove can heat 3 liters of water from 23 ºC to 100 ºC in just 15 minutes while consuming only 350 grams of wood. The unit is lightweight, compact, and easy to transport, making it ideal for camping or outdoor cooking, as well as suitable for homes in rural areas lacking electricity *(TEG-BS-5W-5V-1)*.

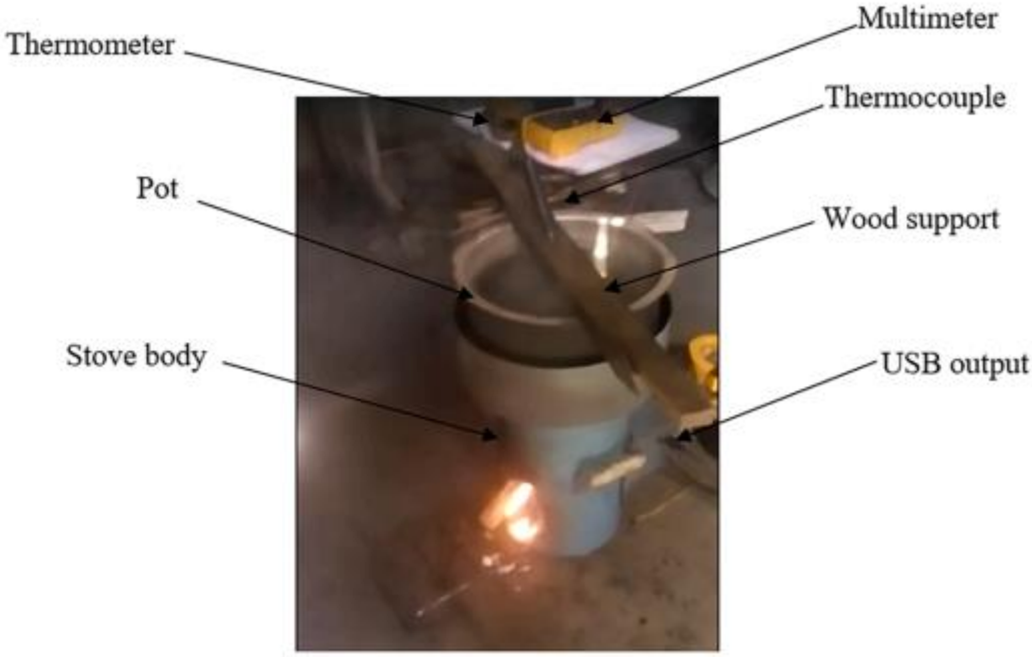


Figure 18: Cost-effective Thermoelectric Rocket Stove (Haile & Adem, 2024)

In addition to the commercially available TEG integrated cook stoves, a cost-effective thermoelectric rocket stove was developed and its performance was assessed by Addis Ababa university student for the fulfilment of master's program recently. The overall efficiency of the stove was found to be 29%, with the capability to produce an output voltage of 5 V and an output power ranging from 3.5 W to 5 W. At an average temperature differential of 90 °C, the stove achieved an output power of 5 W which successfully powered LED lamps requiring a USB input of 2.5 W (5 V and 0.5 A), as well as charged mobile phones, tablets, and a Bluetooth radio that demands an input power of 5 W (5 V and 1 A) *(Haile & Adem, 2024)*.

The performance of the mentioned stoves integrated with TEG are listed in *table 5*.

2.5.3 Summary of Stove Powered TEG Test Results

Table 5: Summary of Performance for Improved Cook Stoves with TEG

Summary of Performance for Improved Cook Stoves with TEG

No	Type of Stove	Overall Efficiency (%)	Thermal Efficiency (%) CS	Thermal Efficiency (%) HS	Specific Fuel Consumption (g/l)	Fuel Used To Boil (g wood/l)	Time to Boil (min)	CO Emission (g/kg fuel)	PM Emission (g/kg fuel)	Power Generation (w)	Reference
1	**TEG Stove**	44%			108.40	240 g of wood to boil 5 liter of	17.30			4.5	*(Raman et al., 2014)*
2	**Philips HD4010**		39.8%	35.8%			15.10	33.35	1.13	Power Fan	*(Jetter & Kariher,*
3	**TEG-BS-5W-5V-1**					350 g of wood to boil 3 liter of	15.00			5	*(TEG-BS-5W-5V-1)*
4	**Cost Effective TE Cook Stove**	29%								5	*(Haile & Adem, 2024)*

3. MATERIALS AND METHODS

3.1 Research Methodology Flow Chart

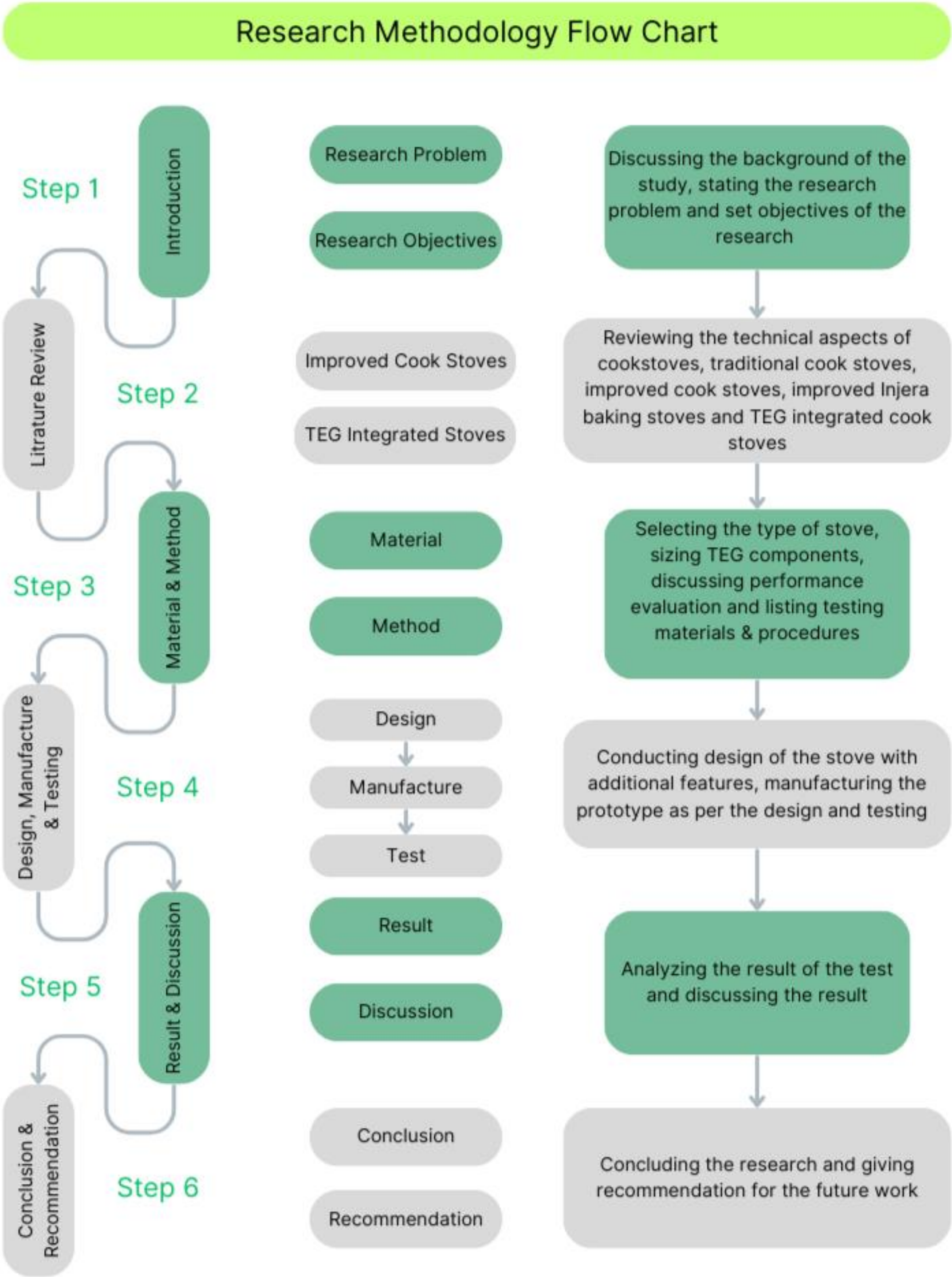


Figure 19: Research Methodology Flow Chart

3.2 Type of Stove Used

3.2.1 Type on Combustion Type

The main consideration in designing a cook stove is deciding the type of the stove to be either direct combustion stove or gasification stove. As having a small size fuel is difficult and needs additional consideration, a direct combustion type stove will be effective designed for this project since we can use a fuel with different sizes.

3.2.2 Type on Construction Material

Stoves can be manufactures with different materials for different areas. As the main part of any stove is the combustion chamber, stoves will be categorized based on the material used for the combustion chamber. The five common materials for stove construction are mud, ceramic, metallic, cement and hybrid of them.

These stoves are constructed using locally sourced organic materials, including clay, sand, mica, straw, grass, sawdust, and dung. The typical composition involves a blend of soil or clay combined with an organic binding agent, with dung added to enhance adhesion. There exists a variety of traditional and improved cook stove designs that differ based on the local materials utilized, the number of cooking holes, and the incorporation of chimneys, among other factors. Mud stoves represent the most economical option available, following the TSF. However, they are susceptible to damage from insects, adverse weather conditions, and excessive fuel usage, which necessitates more frequent maintenance. Consequently, their operational lifespan is generally limited to one to two years.

Ceramic stoves are constructed using a mixture of clay, sand, mica, straw, grass, and sawdust, along with organic binding agents. This type of stoves are subjected to high temperatures in a kiln, which enhances their durability, insulation, and overall finish. Modern ceramic stoves are typically equipped with metal cladding that encases the ceramic body for added protection. When properly fired, ceramic stoves exhibit greater robustness compared to mud stoves.

Stoves made from materials such as steel, sheet metal, or heavy metals like cast iron are prevalent in modern design. Many designers opt for metal as the primary construction material due to its low thermal inertia, which facilitates easy portability and allows for the integration of various features that enhance performance. Metallic stoves are characterized by their lightweight nature, portability, rapid heating capabilities, durability, minimal maintenance requirements, and a wide range of models available in various colors. However, they do have some drawbacks, including susceptibility to corrosion, the potential for burns, and higher costs.

The lightweight nature of a metallic body reduces the energy retention within the stove, which can lead to increased heat loss due to its higher thermal conductivity. This issue can be mitigated through proper insulation of the cook stove, thereby maintaining elevated temperatures within the combustion chamber. While a fully metal portable stove is expected to have a long-lasting outer body, the longevity of a metal combustion chamber may be compromised unless constructed from high-quality, fire-resistant stainless steel.

Numerous ICS models are made from cement. The "*Mirt*" stove, which has been produced in Ethiopia using cement and pumice since the early 1990s, has been reported to have a lifespan of eight years and fuel efficiency reaching up to 40% compared to traditional stoves.

Contemporary prefabricated stoves incorporate a variety of materials, including mud, cement, metal, and ceramic. The majority of modern charcoal and biomass stoves are hybrid in design, featuring a combustion chamber made of ceramic and an outer structure composed of metal. Stoves designed with a metallic exterior and a ceramic combustion chamber are expected to have an extended lifespan *(Kshirsagar & Kalamkar, 2014)*.

Among the given stove construction materials, metallic stove with proper insulation will be used considering the advantage compared to others. We will have a gap between internal and outer chambers to use the insulation material. Stainless steel will be used for the internal chamber and galvanized steel sheet will be used for the outer chamber. In-between, a fiber glass insulation will be used in order to reduce the heat loss through the wall (Conduction).

3.2.3 Type on Air Intake or Draft

The other important issue of stove is type of draft used either natural or forced. Considering the fact that forced draft has the advantage of providing proper air to fuel ratio and gives a better performance, the type of draft for this research will be a forced draft. In addition, since this research will introduce a thermo-electric generator, the power supply could be found easily and the stove can be used in off-grid areas.

3.2.4 Type on Fuel Used

This research is designed to use fuel wood as the primary fuel. The type of fuel wood used for testing of this research is the Eucalyptus tree which is commonly used in most of

Ethiopia. The basic characteristics of the Eucalyptus tree is registered and linked to the WBT 4.2.3 excel sheet as a tree species *Eucalyptus Globules (Southern Blue Gum, Fever Tree)* and the others are values measured. The characteristics of eucalyptus tree are shown in the *Table 6 (WBT 4.2.3 Excel Sheet)*.

Fuel Characterstics	
Fuel wood type	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)
Size	50cm x 3cm x 3cm
Average Moisture content (% Wb)	8 to 10
HHV (kJ/kg)	20,160
LHV (kJ/kg)	18,840

Table 6: Fuel Characteristics

3.2.5 Type on Chimney used and portability

The stove is constructed with removable chimney, one can use the stove with the chimney or without the chimney. Since the flue collector has a pot seat to cook with the flue gas, it is the user preference to cook with the flue gas. Other ways the user can put the chimney at the flue gas collector.

The other parameter is that the stove is portable or fixed. The stove is produced to be moveable and some parts are also removable to help the move stove easily from place to place.

3.3 Thermoelectric Power Generator Components

The main components of thermoelectric power generation system are: Thermoelectric module, Hot plate (heat source), Heat sink (cold side) with aluminum fins for this project, Cooling system (Fan for this project), Screw (to connect hot and cold side plates), Thermal grease (to attach hot and cold side plates to TEG module), High temperature insulation material around the TEG module.

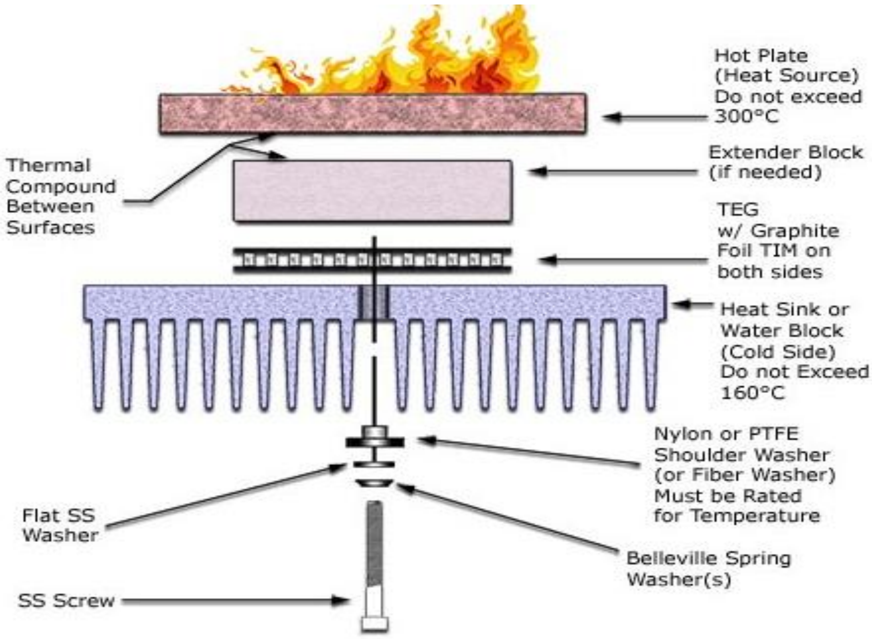


Figure 20: TEG Components (Internet)

A thermoelectric module is specifically engineered and produced to convert thermal energy directly into electrical energy. A standard thermoelectric (TE) module consists of two ceramic substrates that enclose numerous pairs, or "couples," of Bismuth Telluride semiconductor elements. These semiconductor pairs are electrically connected in series while being thermally connected in parallel between the ceramic substrates. One substrate is designated as the "hot-side," while the other serves as the "cold-side."

The thermoelectric module produces direct current (DC) electricity as long as there exists a temperature differential between its cold and hot sides. The voltage and power output are directly related to the temperature gradient present across the module. To minimize thermal resistance at the contact points, the module is enveloped in graphite sheets on both sides of the ceramic plates.

Researchers in materials science are exploring alternative substances to enhance the efficiency of thermoelectric (TE) modules; however, Bismuth Telluride continues to be the most cost-effective material for cooling modules intended for use in ambient temperature settings. Certain Bismuth Telluride-based modules designed for power generation are constructed using high melting point solder or are entirely solder-free. Some of these modules can operate at temperatures reaching up to +400 °C.

3.4 Basic Research Procedure

From the beginning of this research and while working the research for designing, manufacturing and testing stages reviewing different references which have a related topic in every part of the research is done.

Designing the stove with additional features comes after reviewing different related works. Having basic calculations for sizing the stove, air requirements, TEG sizing and integration is done in designing stage. After sizing the stove, material selection is done for different parts of the stove. The final step of design is done by preparing a drawing for manufacturing with Auto Cad and Solid Works.

Manufacturing stage will begin with purchasing locally available and imported materials which are necessary for the preparation of parts from the final design of the stove. In addition, while purchasing materials, finding and preparing a suitable workshop for the production of the prototype will be the other major task.

After preparing materials and workshop, production of parts of the prototype will be conducted using different machines and tools. Machines for the production of the prototype are ; roller machine for rolling sheet metals, galvanized sheet, RHS and metal rod ; Shearing machine for cutting sheet metal and galvanized sheet ; bending machine for bending sheet metal and galvanized sheet ; Welding machine for part and assembly work. In addition, full hand tools including drilling, grinding, rivet punching, hammering, metal scissoring, measuring meter and other will be used for the production.

Assembly of parts including TEG components will be done after having all parts prepared. This time we will have our final prototype. Finally, painting and finalizing of the prototype will be done.

The final step of the research will be testing and performance evaluation of the stove. In order to have a clear comparative result of the stove, two stoves was tested. One is the manufactured (*IBIBSITG*) stove and the other is *Mirt* stove which is available in EREDPC laboratory. The Ethiopian Standard Test Protocol ES ISO 19867-1:2018 guidelines for biomass stove was used for the water boiling test and WBT 4.2.3 excel sheet is used to evaluate the performance of the stoves.

3.5 Performance Evaluation Method

Cook stoves should undergo assessment through standardized tests and protocols to facilitate the comparison of their performance. The most commonly employed protocols for evaluating cook stove performance include the Water Boiling Test (WBT), Kitchen Performance Test (KPT), and Controlled Cooking Test (CCT). The WBT is conducted in a laboratory setting, while the KPT and CCT are performed in real-world environments.

Laboratory-based tests are effective for identifying design flaws and assessing performance. These tests are generally more straightforward, quicker, and less expensive to execute; however, the results obtained in a laboratory may not fully reflect real-world conditions, raising concerns about their accuracy. Conversely, field tests, while potentially more representative, tend to be more expensive, challenging, and time-intensive.

Typically, there exists a compromise between accuracy and the associated complexity and costs of testing. Despite this, a significant majority of researchers favor the WBT over the KPT or CCT. Specifically, WBT accounted for 73% of all cook stove evaluations, whereas KPT and CCT were utilized in only 5% and 12% of cases, respectively (Sedighi & Salarian, 2017).

The Water Boiling Test (WBT) is a concise and straightforward simulation of a typical cooking method, utilizing a consistent volume of water to replicate the cooking process. This test is structured to facilitate the comparison of stoves produced in various locations and intended for different culinary applications through standardized and repeatable assessments. Consequently, the WBT will be conducted for the prototype associated with this project.

Many international and local testing standards and protocols are available to evaluate the performance of cook stoves. Testing of the prototype for this project will done as per testing guidelines developed by The Ethiopian Standard Test Protocol ES ISO 19867-1:2018 guidelines for biomass stove which is adapted from the International Standards Organization ISO 19867-1:2018.

The performance of the cook stove can be classified into two main categories: thermal performance and emission performance. Thermal performance is evaluated based on factors such as firepower or input power, specific fuel consumption, efficiency, and the turn-down ratio *(Ligdi, 2020)*.

3.6 Basic Calculations for Evaluation

The final performance values will be found by inserting the collected data from the test to the WBT 4.2.3 excel sheet and the sheet is prepared to calculate the performance of the stove having the necessary data as per the basic calculation below *(ES ISO 19867-1:2018)* .

Useful Energy Delivered

$$Q_1 = C_P \times G_1 (T_2 - T_1) + (G_1 - G_2)\gamma$$

Where,

Q_1 - Useful energy delivered, kJ

C_p - Isobaric mass-specific heat capacity of water, kJ $kg^{-1}K^{-1}$

G_1 - Initial mass of water, kg

G_2 - Final mass of water, kg

T_1 - Initial temperature of water, °C

T_2 - Temperature of the local boiling point or the highest temperature, °C

γ - Latent heat of water vaporization, kJ/kg

Cooking Power

$$P_c = \frac{Q_1}{(t_3 - t_1)}$$

Where,

Q1 - Useful energy delivered, KJ

P_c - Cooking power, kW

t_1 - Initial time, s

t_3 - Final time, s

Cooking thermal efficiency

a. **with no energy credit for any remaining char:**

$$\eta_c = \frac{Q_1}{BQ_{\text{net.af}}} \times 100\ \%$$

Where,

B - Mass of the fuel, kg

η_c - Cooking thermal efficiency with no energy credit for remaining char, %

$Q_{net.af}$ - Lower heating value of fuel, kJ/kg

Q_1 - Useful energy delivered, KJ

b. with energy credit for remaining char:

$$\psi_c = \frac{Q_1}{BQ_{net.af} - CQ_{net.char}} \times 100\ \%$$

Where,

B - Mass of the fuel, kg

Ψc - Cooking thermal efficiency with energy credit for remaining char, %

$Q_{net.af}$ - Lower heating value of fuel, kJ/kg

Q_1 - Useful energy delivered, KJ

$Q_{net.char}$ - Lower heating value of remaining char, kJ/kg

C - Mass of the remaining char, kg

Char energy productivity

$$E_{char} = \frac{CQ_{net.char}}{BQ_{net.af}} \times 100\%$$

Where,

B - Mass of the fuel, kg

E_{char} - Char energy productivity, %

$Q_{net.af}$ - Lower heating value of fuel, kJ/kg

$Q_{net.char}$ - Lower heating value of remaining char, kJ/kg

C - Mass of the remaining char, kg

Char mass productivity

$$m_{char} = \frac{C}{B} \times 100\ \%$$

Where,

B - Mass of the fuel fed, kg.

m_{char} - Char mass productivity, %

C - Mass of the remaining char, kg

3.7 Testing Materials and Procedure

Before commencing the actual tests for the WBT - Shell Foundation, it is essential to complete the following five steps.

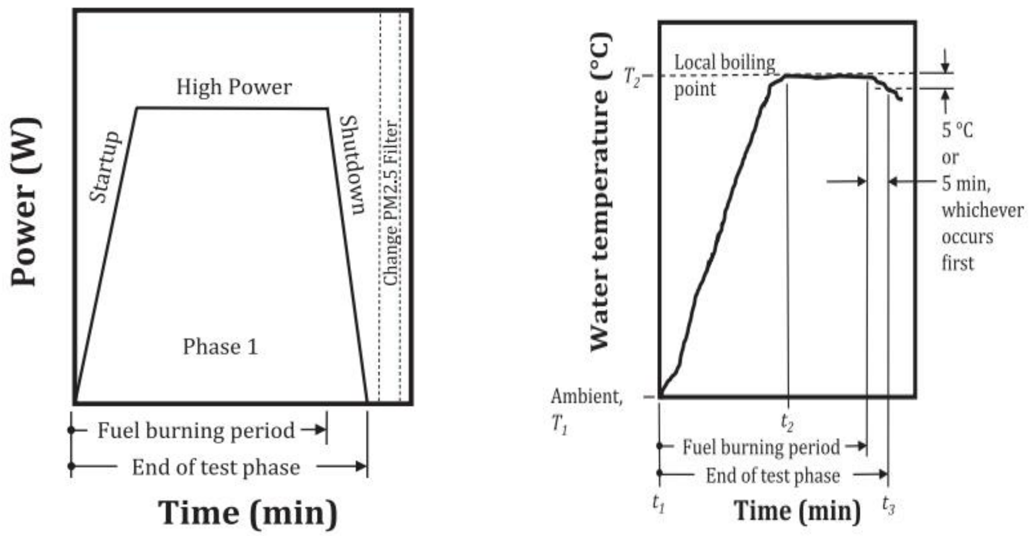
First, ensure that there is an adequate supply of water and fuel. Whenever possible, source all wood from a single location, ensuring it is well-dried and consistent in size.

Second, conduct at least one practice test on each stove type to familiarize yourself with the testing process and the stove's characteristics. This practice will also help determine the amount of fuel needed to bring the specified volume of water to a boil.

Third, utilize the practice tests to ascertain the local boiling point of water, which is the temperature at which water ceases to rise, regardless of the heat applied.

Fourth, a complete WBT requires a minimum of 10 liters of cool water for each pot utilized. In areas where water is limited, water used on one day may be cooled and reused for testing the following day.

Finally, ensure that there is ample space and sufficient time to conduct the tests without interruptions. Testing should ideally take place indoors in a wind-protected room that allows for adequate ventilation to disperse harmful emissions *(WBT- Shell Foundation)*.



(1) *(2)*

Figure 21: Diagram of the standard test sequence for cook stoves with a single power level (1) and Illustrative graph of water temperature versus time for any test phase (2) (ES ISO 19867-1:2018)

Equipment and Measuring Devices for the Water Boiling Test

- Scale

Figure 22: Scale

- Digital Thermometer with thermocouple probe

Figure 23: Digital Thermometer/ Immersed

- Infrared thermometer

Figure 24: Infrared Thermometer

- Moisture meter

Figure 25: Wood Moisture Meter

- Tongs

- Timer
- Pot

Figure 26: Pot

- Char Container

Figure 27: Char Container

- Heat resistant gloves
- At least 20 liters of clean water for each WBT
- 4 to 5 kg of air-dried fuelwood for each test

Figure 28: Fuelwood

- Measuring meter
- Digital Multi meters

Figure 29: Digital Multi meters

Steps for each test

1. Complete the initial page of the Data and Calculations form, which requires details regarding the stove, fuel, and testing conditions. Assign a unique number to each series of tests for future identification.

2. Measure the following parameters, ensuring that each is recorded once for every series of tests. Document these measurements on the first page of the Data and Calculations form: Ambient air temperature, Average dimensions of the wood (length x width x height) to provide an approximate indication of the fuel size utilized in the test, Wood moisture content (% - wet basis) as determined by the wood moisture meter, Dry weight of the standard pot provided, excluding the lid, Weight of the container designated for charcoal, Local boiling point of water, ascertained using the same digital thermometer and sensor intended for use during testing, Utilize a tape measure to capture the stove's dimensions and provide a description in the designated area.

3. Prepare the fuel wood, ensuring it is pre-weighed for one of the tests. The fuel should exhibit relative uniformity in size and shape.

4. After measuring and recording these parameters and preparing the fuel, proceed with the testing phase *(WBT- Shell Foundation)*.

4. DESIGN, MANUFACTURING AND TESTING

4.1 Design

4.1.1 Basic Dimension and Sizes

The basic sizes of a wood burning stoves are the diameter of fire bed (d), the height by the bottom of the pot and the fire bed, the amount of air required, area of air Inlet and area of chimney.

The initial dimension to be set in the basic sizes is the diameter of the pot (which is *Injera Mitad* in our case). The average *Mitad* has a diameter of 60cm and a thickness of 2mm (Adem & Ambie, 2017) and this value is practically measured from commercially available *Injera Mitads*. So, the diameter of the *Mitad* will be 60cm.

$$D_{mitad} = 60cm$$

From different literature, through extensive research and trials, the diameter of the fire bed (d) and the height (h) b/n the bottom of the pot (*Mitad*) and the fire bed can be taken from the below equation (GTZ).

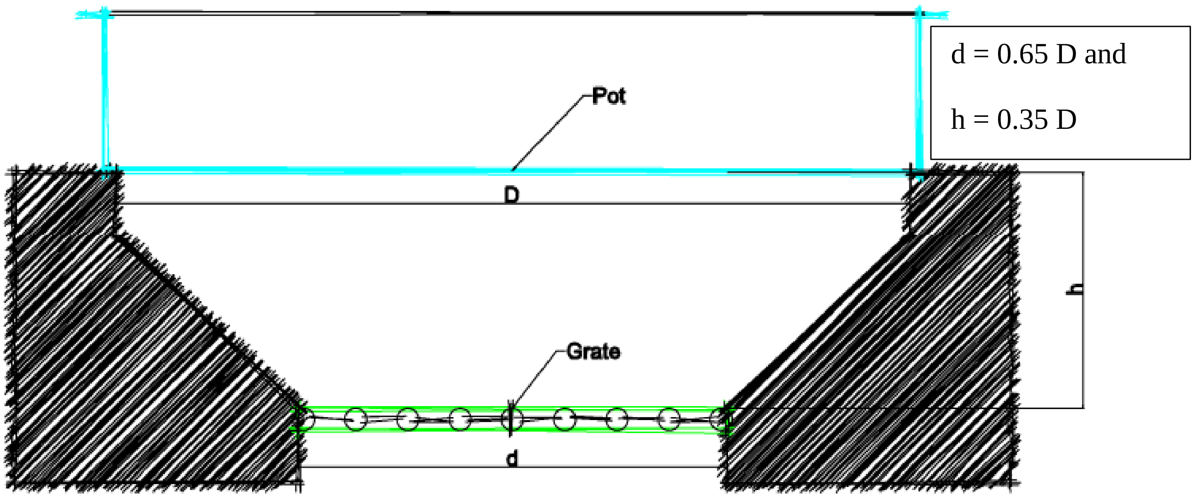


Figure 30: Basic dimension of a stove

Therefore, we have:- $D_{mitad} = 60cm$

$$d = 0.65*60cm = 39cm$$

$$h = 0.35*60cm = 21cm$$

As can be seen the diameter of the fire bed (grate) is smaller than the diameter of the pot (*Mitad*). Which has the advantage of having more time and room for the combustible gases at the top and the fuel is made to keep the central position in order to have uniform heat distribution in the stove.

The other basic dimension of the stove is the overall height of the stove since the stove is designed to have a stand (since the design is *Yekum* stove). The overall height of the stove will be set to 85cm, as per the standard dimension of *Yekum* stoves. In addition, the stove will have two main body parts which are the top part that contains the main body of the stove and the bottom part that contains the stand for the top part.

4.1.2 Fuel Consumption and Fire power of the stove

Since the new stove is a forced draft and has different addition features that can improve the performance, a minimum of 60% reduction of fuel compared to three stove open fire is expected. Therefore, the SFC of our new stove (SFC_{NS}) will be:

$$SFC_{NS} = SFC_{TSOF} \text{ x } (1 - 0.6)$$

$$SFC_{NS} = 929 \text{ g wood /Kg injera x } 0.4$$

$$SFC_{NS} = \underline{371.6} \text{ g wood / Kg injera}$$

On average 25-30 injera will be baked at a time for more households. So, taking 30 injera at a time and an average weight of injera 310g.

Weight of fuel consumed (W_{FC}) by the new stove will be;

$$W_{Fuel\ consumed} = SFC_{NS} \text{ x No injera x } 0.31\text{kg}$$

$$W_{Fuel\ consumed} = 0.3716 \text{ kg wood/ Kg injera x 30 injera } * 0.31 \text{ kg injera}$$

$$W_{Fuel\ consumed} = \underline{3.456 \text{ kg wood}}$$

The total baking time to bake 25-30 injera is ranged from 100min to 129min from different type of stoves. For our case, we can take 102 min baking time which is similar to the time taken for yekum mirt stove (Adem & Ambie, 2017). And the heating value of the fuel (HV_{Fuel} of *Eucalyptus wood*) can be taken as 18,640 kJ/kg considering the same fuel as reference (Dino Adem *et al.*, 2019). So, the fire power (FP) of the new stove will be;

$$FP = \frac{W_{Fuel\ consumed} \text{ x } HV_{Fuel}}{\text{Time (s)}}$$

$$FP = \frac{3.456kg * 18,640kJ/kg}{102min * 60sec}$$

$$FP = 10.5\ kw$$

So, the expected fire power of the new stove is 10.5 kw.

4.1.3 Inlet and Exhaust Air Requirement

Considering a wood is composed of 50% carbon, 43% oxygen 6% hydrogen and 1% Ash by mass, a theoretical or minimum air requirement ($M_{Theoretical\ Air}$) for complete combustion of 1kg of fuel can be give as ("Theoretical or Minimum Air Required for Complete Combustion,").

$$M_{Theoretical\ Air} = 100/23 \times [(8/3c + 8H_2 + S) - O_2]\ kg\ of\ air/\ kg\ Fuel$$

$$M_{Theoretical\ Air} = 100/23 \times [(8/3 \times 0.5 + 8 \times 0.06 + 0) - 0.43]\ kg\ Air/\ kg\ Fuel$$

$$M_{Theoretical\ Air} = 6\ kg\ Air/\ Kg\ Fuel$$

Taking average air density of Ethiopia to be 1kg /m^3 at an average altitude of 1500m, the volume of the theoretical air ($V_{Theoretical\ air}$) required will be:

$$V_{Theoretical\ air} = M_{Theoretical\ Air} / Density\ of\ Air$$

$$V_{Theoretical\ air} = 6kg / 1\ kg/m^3$$

$$V_{Theoretical\ air} = 6\ m^3\ Air/\ Kg\ Fuel$$

The total volume of air ($V_{Total\ Theo.\ Air}$) required to bake 30 *Injera* will be:

$$V_{Total\ Theo.\ Air} = V_{Theoretical\ air} \times W_{Fuel\ consumed}$$

$$V_{Total\ Theo.\ Air} = 6\ m^3\ Air/\ Kg\ Fuel \times 3.456\ kg\ fuel$$

$$V_{Total\ Theo.\ Air} = 20.736\ m^3\ Air$$

Considering 30% extra air for complete combustion of the fuel the total required volume of air ($V_{Total\ Required\ Air}$) will be:

$$V_{Total\ Required\ Air} = V_{Total\ Theo.\ Air} \times 1.3$$

$$V_{Total\ Required\ Air} = 20.736\ m^3\ Air * 1.3$$

$$V_{Total\ Required\ Air} = 27\ m^3\ Air$$

Finally, the volume flow rate ($V_{flow\ rate}$) of Air supply will be:

$$V_{flow\ rate} = V_{Total\ Required\ Air} / BakingTime$$

$$V_{flow\ rate} = 27m^3 / 102min$$

$$V_{flow\ rate} = 0.27m^3/min$$

So, the total amount of air required for combustion will be 0.27 m^3/min.

4.1.4 Air intake, Fuel intake and exhaust chimney size

Supply Air

Taking the velocity of air intake to be 1 m/s as recommended in natural draft air supply, we can have the area of air supply ($A_{Air\ Intake}$).

$$A_{Air\ Intake} = V_{flow\ rate}\ /\ \text{Air Intake Velocity}$$

$$A_{Air\ Intake} = 0.27\ (m^3/min) \times (1min/60s)\ /\ 1m/s$$

$$A_{Air\ Intake} = \underline{\underline{0.0045m^2}} = \underline{\underline{45cm^2}}$$

Now, since the air supply is designed to have eight (8) holes in order to have a uniformly distributed supply air, the area for the one air supply hole will be:

$$A_{Air\ Intake\ Hole} = 45cm^2/8$$

$$A_{Air\ Intake\ Hole} = \underline{\underline{5.625cm^2}}$$

Then, having a circular hole, the diameter of the air supply hole ($d_{Air\ Intake\ Hole}$) will be:

$$d_{Air\ Intake\ Hole} = \sqrt{4}\ A_{Air\ Intake\ Hole}/\pi$$

$$d_{Air\ Intake\ Hole} = \underline{\underline{2.7cm}}$$

So, the eight air supply holes diameter will be around 2.7cm.

Fuel Intake

From air to fuel intake area for fuel and air intake with common opening can be approximated with *("Theoretical or Minimum Air Required for Complete Combustion,")*:

$$A_{Air\ Intake} = 0.3 \times A_{Air\ \&\ Fuel\ Intake} \text{ and } A_{Fuel\ Intake} = 0.7 \times A_{Air\ \&\ Fuel\ Intake}$$

In our case, since the fuel intake area and air intake area differ,

$$A_{Air\ \&\ Fuel\ Intake} = A_{Air\ Intake}/0.3 = 45cm^2/0.3$$

$$A_{Air\ \&\ Fuel\ Intake} = 150\ cm^2 \quad \text{and}$$

$$A_{Fuel\ Intake} = 0.7 \times A_{Air\ \&\ Fuel\ Intake} = 150cm^2 \times 0.7$$

$$A_{Fuel\ Intake} = \underline{\underline{105cm^2}}$$

So, the minimum amount of fuel intake area will be 105cm^2. But, since we use common type of wood with an average diameter of 5cm and to use a maximum of four (4) wood sticks at a time the width of the fuel gate should be greater than 20cm. In addition, since the design incorporates a sight glass to check the combustion at the fuel gate door, the height of the fuel gate should be greater than 5cm. By considering the above issues, the area of fuel gate will be 288cm^2 with **24cm** width and **12cm** height.

Exhaust Air and Chimney

The area which the exhaust air leaves the stove should be higher than that of the area of the intake air because additional to the supply air other combustion gases will leave the stove with the exhaust air.

Taking the recommended value of area increment which is 30%, we can have:

$$A_{Exhaust\ Air} = A_{Air\ Intake} \times 1.3$$

$$A_{Exhaust\ Air} = 45cm^2 \times 1.3$$

$$A_{Exhaust\ Air} = \underline{\underline{58.5cm^2}}$$

Now, since the exhaust air is designed to have four (4) holes which can be collected in the chimney in order to have a uniformly distributed exhaust air, the area for the one air exhaust opening ($A_{Air\ Exhaust\ Opening}$) will be:

$$A_{Air\ Exhaust\ Opening} = 58.5cm^2 / 4$$

$$A_{Air\ Exhaust\ Opening} = \underline{\underline{14.6cm^2}}$$

Then, having a rectangular opening , the width and height of one of the four exhaust air openings can be taken as **8cm** and **2cm** respectively considering effective area.

The area of the chimney ($A_{Chimney}$) is equivalent to the area of exhaust air ($A_{Exhaust\ Air}$).

$$A_{Chimney} = \underline{\underline{58.5cm^2}}$$

Then, having a circular chimney, the diameter of the chimney ($d_{chimney}$) will be:

$$d_{Chimney} = \sqrt{4}\ A_{Chimney}/\pi$$

$$d_{Chimney} = \underline{\underline{8.6cm}}$$

Here, the diameter of the chimney can be taken as **10cm** considering any clogging generated from the flue gas and allowing a safe clearance for the exhaust air.

In addition, the design will use the flue gas to make cooking in order to utilize the heat that will leave the stove with the flue gas. But, while putting a pot on the top of the flue gas, the calculated chimney area will be affected. For this case, we can make the diameter of the flue gas outlet to be **15cm** by which we can gate the required exhaust area between the pot and the skirt that will be put in order to increase the contact of the flue gas and the pot.

In the case where cooking is not necessary, we can construct a circular reducer that can minimize the diameter of the flue gas top (15cm) to the chimney diameter (10cm).

4.1.5 Thermoelectric Generator Sizing

Forced draft needs a blower or fan to deliver the required amount of air for the stove. Here, a blower or fan needs an electricity to function the motor. For our case we use a thermoelectric generator (TEG) which uses a heat from the combustion chamber of the stove. The TEG that was supposed to be used for the project was a packaged module that contains all necessary units including cooling fan, hot and cold side heat sink plates, electronic circuit, output ports and battery charging cable.

Figure 31: Packaged TEG module ("Stove Top TEG,")

But considering the cost of the package use, the less effort that needs and the availability, the TEG components that will sized and prepared will to be done with available materials by collecting each items like copper hot side heat sink (heat collector) and hot side plate, cold side aluminum plates, TEG module, cold side heat sink including fan and fins and other electrical components that can complete the system like DC-DC convertors, Lithium ion batteries, capacitor, LED lights, switches and USB ports.

The idea of collecting effective heat at the center of the combustion chamber with the help of heat sink plate is found to be better. So, the position of the TEG hot side heat sink will be located at the center of the combustion chamber in order to collect as much as possible heat from the fire.

The specification of thermoelectric module used for this research is shown below as *table 7* as per manufacturer of the module.

Speciation of Used Thermoelectric Module	
Parameters	Values
Module size (mm)	55 x 55
Hot side temperature (^{0}C)	220
Cold side temperature (^{0}C)	30
Open circuit voltage (V)	15
Matched load resistance (Ω)	7.8
Matched load output voltage (V)	7.5
Matched load output current (A)	0.96
Matched load output power (W)	7.2

Table 7: Specification of Thermoelectric Module Used (Data sheet)

So, four 7.2 w thermoelectric modules with total of 28.8 w are used considering the cost and size of the package with the minimum power requirement of a household to charge a cellphone and to light up an LED Light in addition to give power for the fan motor.

In addition, the air that blows through the cold heat sink will leave gaining some heat the temperature of the will be raised. So, since this air is used for the combustion air of the stove, pre-heated air will be introduce to our combustion chamber which provides an additional efficiency improvement of the stove.

But, in the case if the TEG system fails to work, a natural draft can be used by introducing the required combustion air through the fuel intake by opening the door of the fuel gate. In addition, if a distributed air is needed, the design allows an opening in front of the air intake holes that can be opened when the blower fails to work.

Multi-Functionality

As can be seen in the introduction, *Injera* is baked for only 2 to 3 times a week for more households. The design believes that having the additional features, materials and assumptions to use the stove 2 to 3 times a week will influence the payback period and customer satisfaction. So, in order to use the stove daily, the stove is designed for both *Injera* baking and cooking interchangeably using additional cooking combustion chamber with top plate. The hinges attached to both *Mitad* and cooking plates will allow the changing process easier.

In addition to the one time baking or cooking, the design allocates a proper position (a pot seat) to cook or boil water using the flue gas exhausted from the stove while baking *Injera*. So, the above additional features will make the stove to be a multifunctional stove.

Ash Collector

The other additional feature of the stove is that it has an ash collector below the grate and air supply holes. This feature also participates its own role in the efficiency of the stove by allowing a free space for the contact of air and fuel. In addition, since ash is a good insulator, the collected ash below the grate can be used as an insulator to resist the heat loss through the bottom of the stove.

4.1.6 Preliminary Design

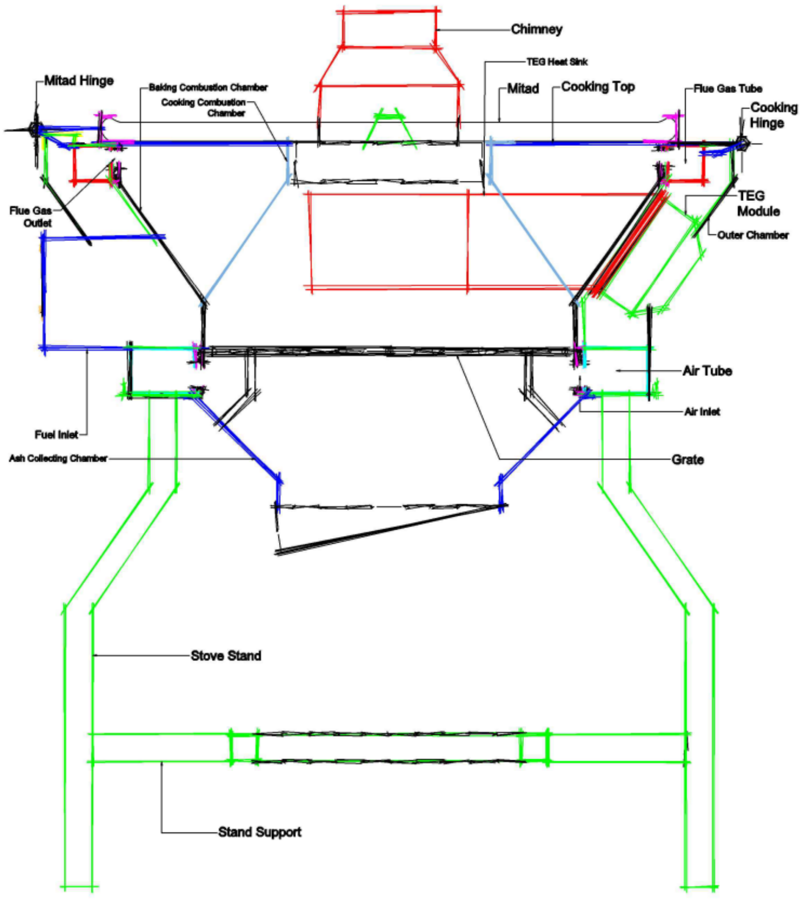


Figure 32: Preliminary Design

4.2 Manufacturing

4.2.1 Manufacturing Drawing (Part Drawing)

The part drawings of this project are done using Solid work commercial modeling software and they attached in the Appendix E of this paper.

4.2.2 Manufacturing Drawing (Assembly Drawing)

The assembly drawing of this project is also done using Solid work commercial modeling software and is shown below. The detail is attached in the Appendix E of this paper.

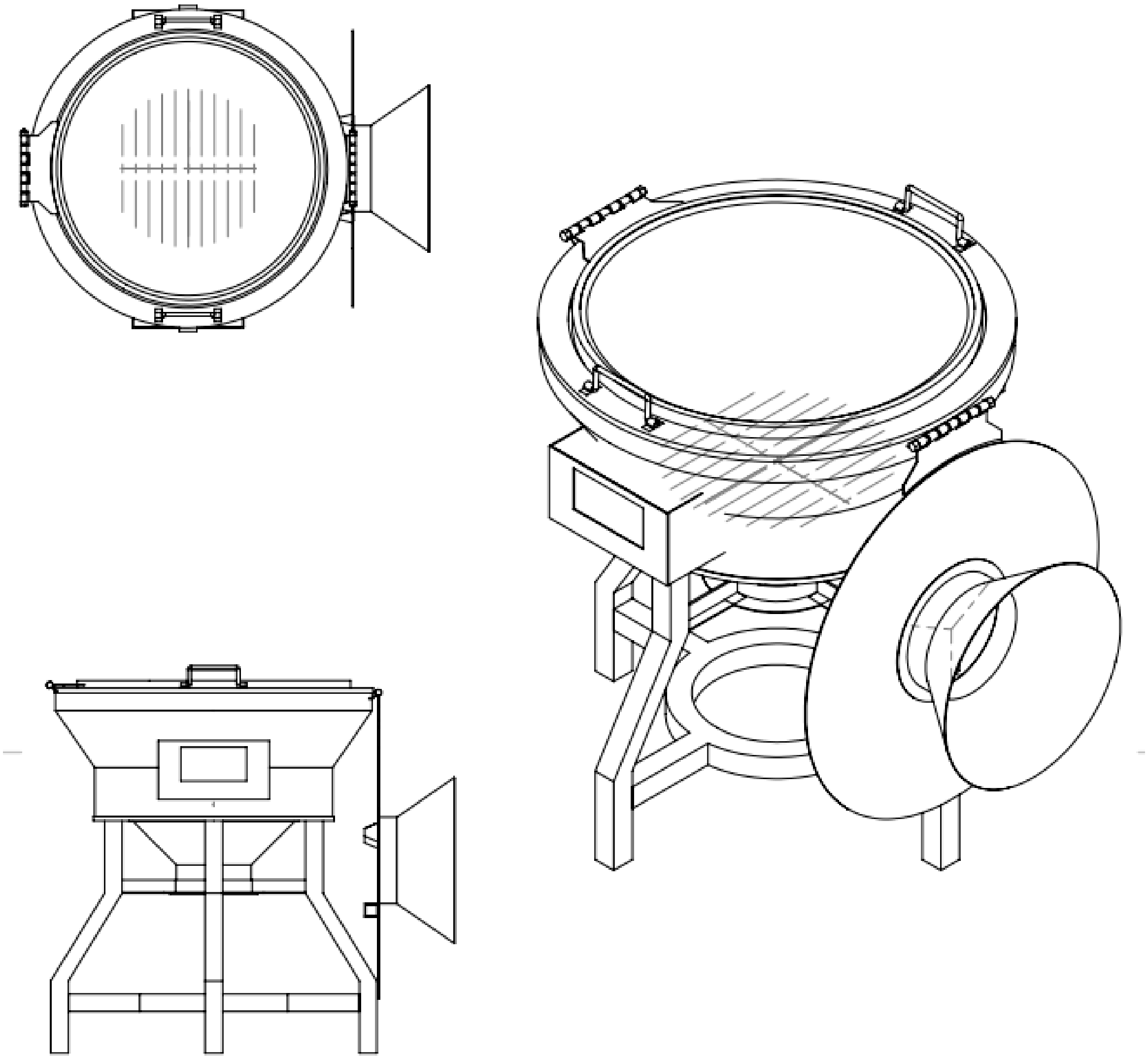


Figure 33: Assembly Drawing

4.2.3 Part List

Part List		
Partial Parts	Part No	Part Name
Top Baking Part	1	Baking combustion chamber
	2	Side support plate
	3	Top support plate
	4	Outer chamber
	5	Grate
	6	Air transfer duct
	7	Air Nozzel
	8	Wood feeding enclosure
	9	Wood feeding door
	10	Flue gas collector
	11	Flue gas cooking pot seat
	12	Flue gas collector support
	13	Top part handle
	14	Chimney reducer
	15	Chimney
Top Cooking Part	1	Cooking combustion chamber
	2	Cooking top plate
	3	Cooking pot seat
Bottom Part	1	Stand legs
	2	Stand Bottom support
	3	Stand top support
	4	Ash collecting chamber
	5	Ash Access door
	6	Ash collecor support
TEG Part	1	Hot side heat collector
	2	Thermoelectric module
	3	Cold side heat sink
	4	DC Fan
	5	Air duct to air tube
	6	Bolt and nut

Table 8: Part List

4.2.4 Main Parts Manufacturing Process with Pictures

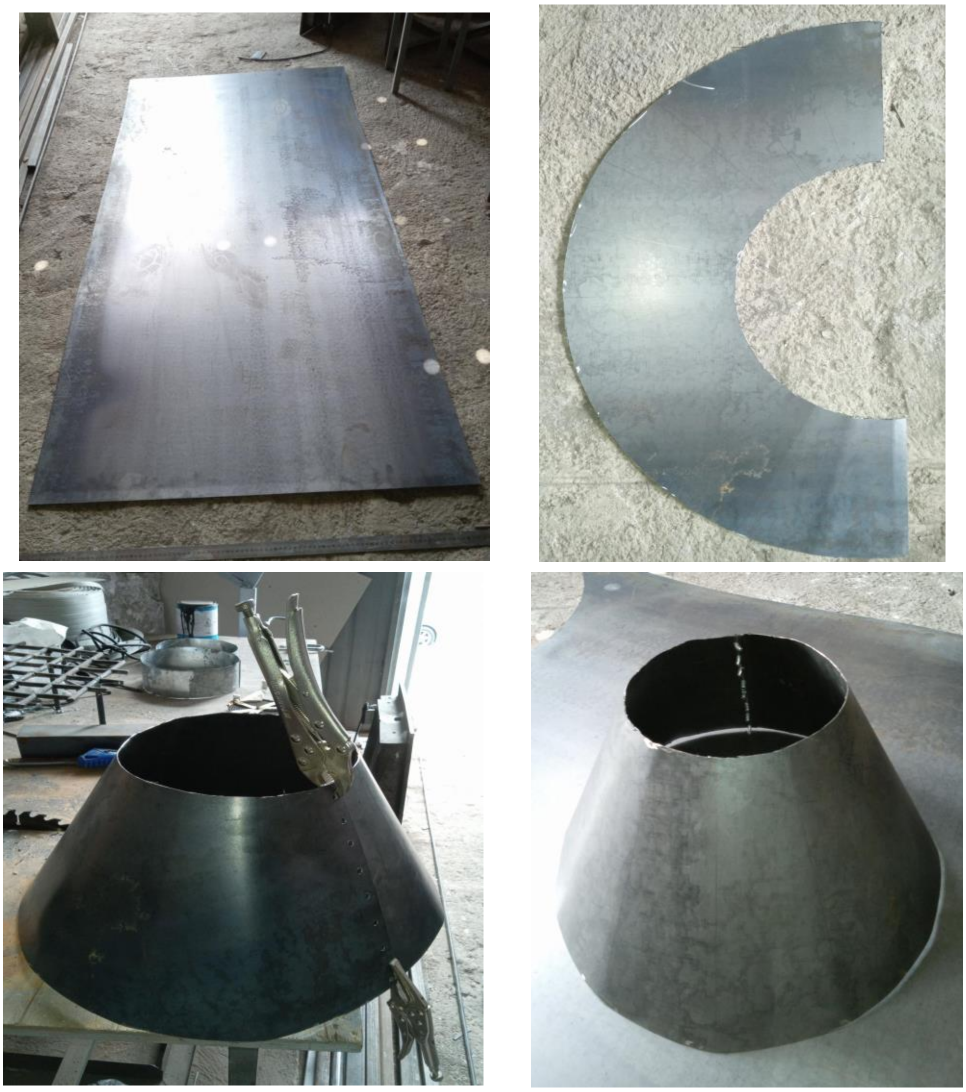


Figure 34: Manufacturing Process of combustion chambers

Figure 35: Manufacturing of cooking combustion chamber assembly

Figure 36: Top and Bottom part Manufacturing

Figure 37: Applying Fiber Glass Insulation

Figure 38: Preparation and Applying Gypsum

Figure 39: TEG Integration setup

Figure 40: Final Picture of Assembled Product

4.3 Testing

4.3.1 Test Procedure

After having the required materials and testing devices stated in chapter three, data recorded will be done for each tests and will be filled in Data and Calculation form. The procedure of the test is done as follow:

1. Set up the timer, ensuring it remains inactive until the fire is ignited.

2. Each pot should be filled with 16 kg (16 liters) of clean water at room temperature. To determine the correct amount, place the pot on a scale and add water accordingly. Document the combined weight of the pot and water in the Data and Calculations Sheet.

3. Utilize wooden fixtures to position a thermometer in each pot, ensuring it measures the water temperature at the center, 5 cm from the bottom. Record the initial temperature of the water in each pot, verifying that it is consistent with the ambient temperature.

4. Ensure the stove is at room temperature. Ignite the fire in a consistent manner, adhering to local practices. Document any additional materials used to start the fire, aside from the wood from the initial pre-measured bundle (for instance, paper or kerosene).

5. Upon the fire catching, note the starting time. During the subsequent "high power" phase of the experiment, manage the fire using local methods to bring the first pot to a boil quickly while minimizing fuel consumption.

6. When the water in the first pot reaches the designated boiling time (1 hour), promptly execute the following actions: Record the temperature at the specified time, remove all wood from the stove, extinguish the flames, and dislodge any loose charcoal from the ends of the wood into the combustion chamber. Weigh the unburned wood taken from the stove along with the remaining wood from the pre-weighed bundle, and document the result on the Data and Calculation form. Wait until the water temperature decreases by 5 °C or after 5 minutes, then weigh each pot with its water and record these weights on the Data and Calculation form.

Finally, extract all remaining charcoal from the stove, combine it with the charcoal that was dislodged from the sticks, weigh the total, and record the weight of the charcoal along with the container on the Data and Calculation Form.

4.3.2 Test Place and Setup

The test is done in EREDPC stove testing laboratory located at Gurd Shola, Addis Ababa, Ethiopia and most used measuring devices are from this laboratory. The measured value of local boiling point at this test place is found 92.5 ^{0}C.

Figure 41: Test Place

The test is done based on the test protocol as below for two stoves; for the manufactured stove and *Mirt* stove at the same time. This is because having a comparative test at same parameters and conditions will give a better comparative result. So, five tests for each stove was taken to evaluate the performance of each stove. In addition, natural draft of manufactured stove was also tested.

(1) *(2)*

Figure 42: Experimental setup of Mirt (1) and manufactured (2) stoves

4.3.3 Sample Measured Values

Initial water temperature and ambient air temperature readings

(1) *(2)*

Figure 43: Initial Water Temperature (1) and Initial Air Temperature (2)

Moisture content and local boiling temperature readings

(1) *(2)*

Figure 44: Moisture Content (1) and Local Boiling Point (2)

Fire Starting

Figure 45: Fire Starting

Weight of charcoal container and charcoal container + charcoal

(1) *(2)*

Figure 46: Weight of char container (1) and char container + char (2)

Weight of empty pot, initial pot with water and final pot with water

(1) *(2)*

(3)

Figure 47: Weight of empty pot (1), initial pot with water (2) and final pot with water (3)

Weight of initial wood and final remaining wood

(1) *(2)*

Figure 48: Weight of initial wood (1) and final remaining wood (2)

Open circuit voltage produced and rated voltage and current produced while lighting bulb

(1) *(2)*

Figure 49: Open circuit voltage produced (1) Rated voltage and current produced while lighting bulb (2)

5. RESULT AND DISCUSSION

5.1. Result of Performance of Stove

The performance of the manufactured stove will be discussed compared with the existing *Mirt* stove which has currently the highest efficiency of performance among *Injera* baking stoves. So, this research believes having a comparative test at the same environmental conditions will give a better comparative result rather than taking reference efficiency values from different researchers.

Three Setup of stove tests was conducted having five tests for each, test of

- *Mirt* Stove
- Manufactured Stove with Natural Draft and
- Manufactured Stove with Forced Draft

While having the evaluation of the test, the thermal efficiency varied across different tests based on several factors. These include the type of fuel used, the amount of water evaporated, the mass of fuel consumed, leftover char post-test, and additional aspects like the moisture content in the fuel.

The recorded thermal efficiency for Mirt Stove is 34.69% at test 1, 35.06% at test 2, 33.58% at test 3, 33.15% at test 4 and 33.81% at test 5. And the recorded thermal efficiency for manufactured stove in forced draft case is 37.97% at test 1, 36.77% at test 2, 38.49% at test 3, 36.06% at test 4 and 37.29% at test 5. In addition, the recorded thermal efficiency for manufactured stove in natural draft case is 35.77% at test 1, 34.85% at test 2, 36.78% at test 3, 35.42% at test 4 and 36.28% at test 5.

The tests for Mirt Stove revealed that the lowest thermal efficiency recorded is 33.15% at test 4 and the highest observed thermal efficiency reached 35.06% at test 2. The average thermal efficiency across five tests for Mirt Stove is found 34.06%.

The tests for the manufactured stove in forced draft case revealed that the lowest thermal efficiency recorded is 36.06% at test 4 and the highest observed thermal efficiency reached 38.49% at test 3. The average thermal efficiency across five tests for the manufactured stove in forced draft case is found 37.32%.

The tests for the manufactured stove in natural draft case revealed that the lowest thermal efficiency recorded is 34.85% at test 2 and the highest observed thermal efficiency reached 36.78% at test 3. The average thermal efficiency across five tests for the manufactured stove in natural draft case is found 35.82%.

The summary of performance result of stoves is generated by WBT 4.2.3 Excel sheet after inserting the recorded data. The summary of test result of *Mirt* stove is shown in *table 9*, the summary of test result of manufactured stove with forced draft is tabulated in *table 10* and also the IWA Tiers of performance report for the manufactured stove with forced draft is tabulated in *table 11*.

As a result, the average thermal efficiency of *Mirt* stove is 34.06 % of while the thermal efficiency of the manufactures stove with forced draft is 37.32 %. In addition, the thermal efficiency of the manufactures stove with natural draft is 35.82 %.

So, the manufactured stove with forced draft has an efficiency improvement of 3.26% in addition to small scale power generation.

The high-power cold start test is held for all stoves, meaning the stove was at room temperature prior to testing and the local boiling point was set at 92.5°C. The average water temperature changes over the test of one hour is illustrated in *figure 49* below. As shown in the graph, the water will reach its boiling point from 25 to 30 minutes of boiling and will reduce by 3 to 5^0c within 5 minutes of simmering.

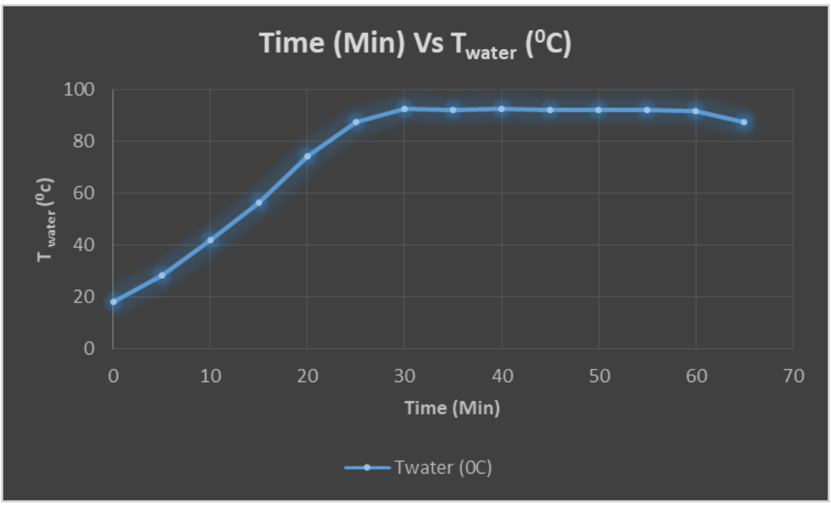


Figure 50: Temperature of water Vs time Graph

Test Result Summary of *Mirt* Stove

WATER BOILING TEST - VERSION 4.2 TEST Results

All cells are linked to data worksheets, no entries are required

Stove type/model	Mirt Stove
Location	MWE/RETDPC Stove Laboratory
Fuel description	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)
Wind conditions	Light Breeze
Ambient temperature	Different

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
Time to boil Pot # 1	min	60	60	60	60	60	60	-	
Temp-corrected time to boil Pot # 1	min	59	61	62	61	58	60	1.3	2.2%
Burning rate	g/min	30	37	37	40	42	37	4.5	12.2%
Thermal efficiency	%	34.69%	35.06%	33.58%	33.15%	33.81%	0.3406	0.79%	2.3%
Specific fuel consumption	g/liter	138	189	187	205	226	189	32.6	17.2%
Temp-corrected specific consumption	g/liter	135	191	192	207	220	189	32.3	17.1%
Temp-corrected specific energy cons.	kJ/liter	2,551	3,599	3,613	3,907	4,140	3562	608.3	17.1%
Firepower	watts	9,413	11,607	11,654	12,482	13,194	11,670.03	1,421.2	12.2%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
High Power Thermal Efficiency	%	34.7%	35.1%	33.6%	33.2%	33.8%	0.3405851	0.79%	2.32%
Low Power Specific Fuel Consumptior	MJ/(min·L)								
High Power CO	g/MJ								
Low Power CO	g/(min·L)								
High Power PM	mg/MJ								
Low Power PM	mg/(min·L)								
Indoor CO Emissions	g/min								
Indoor PM Emissions	mg/min								

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	2
Low Power Specific Fuel Consumptior	NA
High Power CO	NA
Low Power CO	NA
High Power PM	NA
Low Power PM	NA
Indoor CO Emissions	NA
Indoor PM Emissions	NA

NA = Not Applicable; IWA Performance Tiers are not reported if there are fewer than 3 tests conducted.

Table 9: Test Result Summary of Mirt Stove

Test Result Summary of Manufactured Stove

WATER BOILING TEST - VERSION 4.2.	TEST Results
All cells are linked to data worksheets, no entries are required	
Stove type/model	IBIBSITEG Model
Location	MWE/RETDPC Stove Laboratory
Fuel description	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)
Wind conditions	Moderate Wind
Ambient temperature	Different

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
Time to boil Pot # 1	min	60	60	60	60	60	60	0.0	
Temp-corrected time to boil Pot # 1	min	61	58	61	58	58	59	1.8	3.0%
Burning rate	g/min	36	37	41	42	41	39	2.4	6.1%
Thermal efficiency	%	37.97%	36.77%	38.49%	36.06%	37.29%	0.3732	0.96%	2.6%
Specific fuel consumption	g/liter	194	192	236	231	228	216	21.3	9.8%
Temp-corrected specific consumption	g/liter	199	184	239	224	221	213	21.6	10.1%
Temp-corrected specific energy cons.	kJ/liter	3,747	3,474	4,506	4,215	4,157	4020	407.9	10.1%
Firepower	watts	11,445	11,595	12,798	13,061	12,776	12,335.15	754.3	6.1%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
High Power Thermal Efficiency	%	38.0%	36.8%	38.5%	36.1%	37.3%	0.373153	0.96%	2.57%
Low Power Specific Fuel Consumption	MJ/(min·L)								
High Power CO	g/MJ								
Low Power CO	g/(min·L)								
High Power PM	mg/MJ								
Low Power PM	mg/(min·L)								
Indoor CO Emissions	g/min								
Indoor PM Emissions	mg/min								

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	3
Low Power Specific Fuel Consumption	NA
High Power CO	NA
Low Power CO	NA
High Power PM	NA
Low Power PM	NA
Indoor CO Emissions	NA
Indoor PM Emissions	NA

NA = Not Applicable; IWA Performance Tiers are not reported if there are fewer than 3 tests conducted.

Table 10: Test Result Summary of Manufactured Stove

Tier Level of Manufactured Stove

GLOBAL ALLIANCE FOR CLEAN COOKSTOVES

IWA Tiers of Performance Report

Stove Manufacturer	Saleamlak Abera
Stove Model	IBIBSITEG Model
Testing Center	MWE/RETDPC Stove Laboratory
Test Protocol	Water Boiling Test - Version 4.2.3
Fuel Used	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)
Pot Used	the pot size selected according to stove outer diametre
Test Dates	25 Dec 2023 to 4 Jan 2024

These results w ere obtained in accordance w ith the IWA and the Global Alliance for Clean Cookstoves' reporting requirements[1].
This data and additional supporting data are shared publically through the Clean Cooking Catalog.

Name of Tester(s)	Saleamlak Abera

		Metric	Value	Unit	Sub-Tier
Efficiency / Fuel Use					
Tier	3	High power Thermal Efficiency	0.373153029	%	3
Emissions					
Tier		High power CO			
		Low power CO			
		High power PM 2.5			
		Low power PM 2.5			
Indoor Emissions					
Tier		Indoor emissions CO			
		Indoor emissions PM 2.5			
Safety					
Tier		10 weighted safety parameters			

Tier 0 → Improving Importance → Tier 4

[1] Interim Stove Performance Reporting Requirements:
http://w w w .cleancookstoves.org/our-w ork/standards-and-testing/guidelines-and-standards/guidelines--standards-documents/interim-stove-performance.pdf

Table 11: Tier Level of Manufactured Stove

5.2. Result of TEG Power Generation

The temperatures of the hot and cold sides of the thermoelectric generator were recorded using an infrared thermometer each time. The fan operated directly on the voltage generated by the thermoelectric generator, meaning its speed was directly related to the voltage produced and the temperature difference. The recorded value of maximum temperature is 250°C on the hot side, while the cold side reached 110°C.

The open circuit voltage of the TEG fluctuated between 3V and 14.2V, responding to changes in temperature within the combustion chamber. To ensure a consistent output, a DC-DC step-up converter was connected to the output of the thermoelectric generator, boosting the voltage to a steady 5V. After integrating the DC-DC converter, the TEG system consistently produced a reliable output of 5V. *Figure 50* illustrates the recorded data showing the time versus open circuit voltage and temperature difference. As shown in the graph, a maximum of 14.2 open circuit voltage was found at the stated temperature difference.

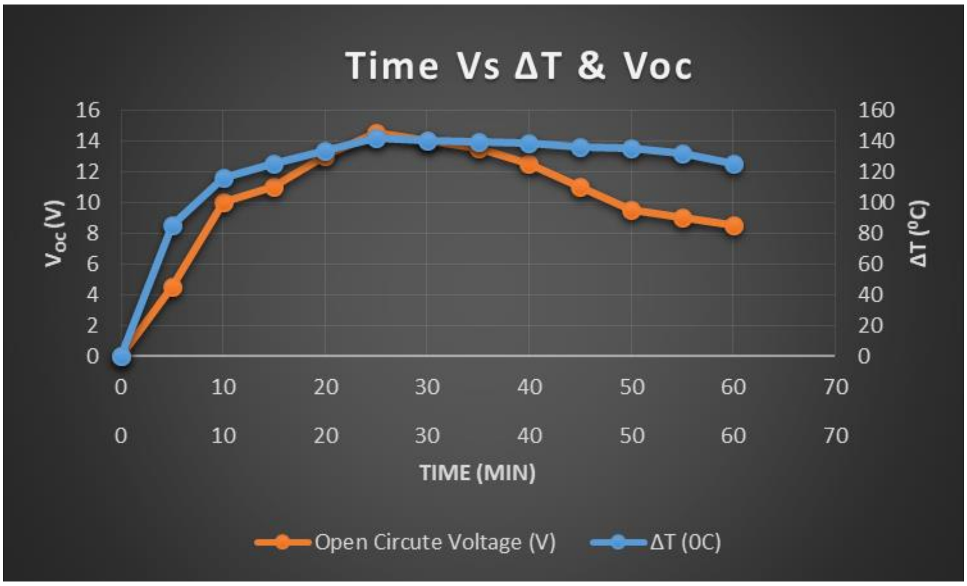


Figure 51: Time Vs Temperature Difference (ΔT) & Open Circuit Voltage (V_{oc})

As per the specification of TE module, the expected power output was 4x7.2w which is 28.4w at a temperature difference of 150^0c. The result of electricity generation of this project obtained is not as per expected. The maximum rated power output gained in the test was 8.6v x 0.16A while lighting bulb and running DC fan which is around 1.4 w at a temperature difference of 140^0c (Hot side 220^0c and Cold side 80^0C).

6. CONCLUSION AND RECOMMONDATION

6.1. Conclusion

An improved biomass *Injera* baking stove integrated with thermoelectric generator was designed, manufactured and its performance was comparatively evaluated with *Mirt* stove according to standard WBT protocol. The test was conducted fifteen times, five tests for *Mirt* stove, five tests for the manufactured stove with natural draft and five test for tests for the manufactured stove with forced draft. And each test is conducted for an hour and the results are generated by WBT 4.2.3 Excel evaluation setup.

The comparative result declared that, the forced draft stove which is designed and manufactured by this research (37.32%) has an average of 3.26% efficiency improvement compared to *Mirt* stove (34.06%) in addition to small scale power generation. In addition, the test of the natural draft stove (35.82%) has a 1.5% efficiency improvement compared to *Mirt* stove.

The Integrated TEG was generating an open circuit voltage of 14.2V and output rated power of 1.4w (8.6 V x 0.16) while running a DC fan and DC LED lamp at an average temperature difference of 140^0C. But the power generation of the TE module was not satisfactory, because the setup has a potential of generating around 28w if it was working as per the specification. So, as it is, the generated power can run the DC fan which helps the process of forced draft and can light up an LED lamp in order to help baking and cooking at night which gives the light for the room.

6.2. Recommendation

As a recommendation, a small scale power storage system should be integrated in the future work in order to start the fan in the first minutes of and to save the power for different purpose.

It is also recommended to conduct the emission performance of the stove in order to evaluate the indoor air pollution by measuring the amount of particulate matter and CO emission.

In addition, the field test or kitchen performance test (KPT) should be conducted in order to know the exact performance of the stove with the actual application including boiling or cooking at the flue gas outlet cooking setup.

7. REFERENCE

Kamil Dino Adem, & Demiss Alemu Ambie. (2017). A review of injera baking technologies in Ethiopia: Challenges and gaps. Energy for Sustainable Development, 41, 69-80. doi:10.1016/j.esd.2017.08.003

Andrew Beahrs. (2013). Three-Stone Fire: Designing Better Stoves for Africa. Retrieved from https://www.vqronline.org/articles/three-stone-fire

Aprovecho Research Center. Test Results of Cook Stove Performance.

Dr. Mark Bryden, Dean Still, Peter Scott, Geoff Hoffa, Damon Ogle, Rob Bailis, & Ken Goyer. (2013). Design Principles for Wood Burning Cook Stoves. Retrieved from https://www.bioenergylists.org/stovesdoc/Pcia/Design%20Principles%20for%20Wood%20Burning%20Cookstoves.pdf

Kamil Dino Adem, Demiss Alemu Ambie, Maria Puig Arnavat, Ulrik Birk Henriksen, Jesper Ahrenfeldt, & Tobias Pape Thomsen. (2019). First injera baking biomass gasifier stove to reduce indoor air pollution, and fuel use. AIMS Energy, 7(2), 227-246. doi:10.3934/energy.2019.2.227

Yosef Assefa Feleke. (2007). Assesing Environmental Benefits of Mirt Stove with Particular Reference to Indoor Air Pollution (Carbon monoxide & Suspended particulate matter) and Energy Conservation. (Msc.), Addis Ababa Retrieved from http://etd.aau.edu.et/bitstream/handle/123456789/7695/Yosef%20Assefa.pdf?sequence=1&isAllowed=y

H. B. Gao, G. H. Huang, H. J. Li, Z. G. Qu, & Y. J. Zhang. (2016). Development of stove-powered thermoelectric generators: A review. Applied Thermal Engineering, 96, 297-310. doi:10.1016/j.applthermaleng.2015.11.032

GTZ. Sustainable Utilization of Natural Resources for Improved Food Security. Energy, 24.

Anteneh Gulilat. (2014). A Report on Controlled Cooking Test of Gonzie Stove: Stove Testing Result. Retrieved from Addis Ababa: https://energypedia.info/images/1/19/Gonzie_Stove_CCtest_report_2014.pdf

Anteneh Gulilat, & Walelign Girma. (2011). A Report on Controlled Cooking Test Results Performed on 'Mirt with integrated chimney' and 'Institutional Mirt' Stoves: Stove Testing Results. Retrieved from https://energypedia.info/images/5/50/Stove_testing_results%2C_A_report_on_controlled_cooking_test_results_performed_on_%E2%80%98Mirt_with_integrated_chimney%E2%80%99_and_%E2%80%98Institutional_mirt%E2%80%99_stoves%2C_Report_by_Anteneh_Gulilat%2C_May_23%2C_2011..pdf

Humanity Development Library. Earthen stove design and soil analysis. Retrieved from http://www.nzdl.org/cgi-bin/library?e=d-00000-00---off-0hdl--00-0----0-10-0---0---0direct-10---4-------0-0l--11-en-50---20-about---00-0-1-00-0-0-11----0-1%20&cl=CL1.9&d=HASH01ae57cff12a68d26e7b409a.14.1&gt=1

IEA. (2017). Energy Access Outlook 2017: World Energy Outlook Special Report. Retrieved from https://www.iea.org/reports/energy-access-outlook-2017

IEA. (2020). Access to electricity. Retrieved from https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity

James J. Jetter, & Peter Kariher. (2009). Solid-fuel household cook stoves: Characterization of performance and emissions. Biomass and Bioenergy, 33(2), 294-305. doi:10.1016/j.biombioe.2008.05.014

James Jetter, Yongxin Zhao, Kirk R. Smith, Bernine Khan, Tiffany Yelverton, Peter DeCarlo, & Michael D. Hays. (2012). Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metric Useful in Setting International Test Standards: Supporting Information. Retrieved from https://ndownloader.figstatic.com/files/4124914/preview/4124914/preview.pdf

Milind P. Kshirsagar, & Vilas R. Kalamkar. (2014). A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. Renewable and Sustainable Energy Reviews, 30, 580-603. doi:10.1016/j.rser.2013.10.039

Samuel Kelbesa Ligdi. (2020). Design, Simulation, Manufacturing and Testing of Forced Draft Microgasifier. (Msc.), Addis Ababa University, Addis Ababa. Retrieved from http://etd.aau.edu.et/bitstream/handle/123456789/24795/Samuel%20Kelbesa.pdf?sequence=1&isAllowed=y

Fikadu Mamuye, Bekele Lemma, & Teshale Woldeamanuel. (2018). Emissions and fuel use performance of two improved stoves and determinants of their adoption in Dodola, southeastern Ethiopia. Sustainable Environment Research, 28(1), 32-38. doi:10.1016/j.serj.2017.09.003

Kumar Manoj, Kumar Sachin, & S. K. Tyagi. (2013). Design, development and technological advancement in the biomass cookstoves: A review. Renewable and Sustainable Energy Reviews, 26, 265-285. doi:10.1016/j.rser.2013.05.010

O. Mazzoni, & H. Isaac. (2003). Fuel Substitution Impacts: An Assessment Matrix Analysis. Retrieved from https://assets.publishing.service.gov.uk/media/57a08d17ed915d3cfd0017ee/R8019FR.pdf

Sonam A. Mehetre, N. L. Panwar, Deepak Sharma, & Himanshu Kumar. (2017). Improved biomass cookstoves for sustainable development: A review. Renewable and Sustainable Energy Reviews, 73, 672-687. doi:10.1016/j.rser.2017.01.150

Emmanuel Ochima. (JUNE, 2017). Investigation of the Thermal Properties of Wood Ash and Clay-Sawdust Mixture for Use as Insulation Materials in a Rocket Stove.

Perumal Raman, Narasimhan K. Ram, & Ruchi Gupta. (2014). Development, design and performance analysis of a forced draft clean combustion cookstove powered by a thermo electric generator with multi-utility options. Energy, 69, 813-825. doi:10.1016/j.energy.2014.03.077

Mohammadreza Sedighi, & Hesamoddin Salarian. (2017). A comprehensive review of technical aspects of biomass cookstoves. Renewable and Sustainable Energy Reviews, 70, 656-665. doi:10.1016/j.rser.2016.11.175

Donna M. Staton, & Marcus H. Harding. (2002) Health and Environmental Effects of Cooking Stove Use in Developing Countries

Retrieved from http://lists.bioenergylists.org/stovesdoc/Environment/staton.pdf

Stove Top TEG.

Kailasnath B. Sutar, Sangeeta Kohli, M. R. Ravi, & Anjan Ray. (2015). Biomass cookstoves: A review of technical aspects. Renewable and Sustainable Energy Reviews, 41, 1128-1166. doi:10.1016/j.rser.2014.09.003

Mulugeta Tadesse. (2020). The Developmental Patterns of Injera Baking Stoves: Review on the Efficiency, and Energy Consumption in Ethiopia. International Journal of Mechanical Engineering, 7(1), 7-16. doi:10.14445/23488360/ijme-v7i1p102

TEG-BS-5W-5V-1. Biomass Stove with a 5 Watts Thermoelectric Power Generator: Commercial Catalog.

Theoretical or Minimum Air Required for Complete Combustion.

U.S. Department of Energy. (2011). Biomass Cookstove Technical Meeting: Summary Report: Energy Efficiency and Renewable Energy: Biomass Program. Retrieved from https://www1.eere.energy.gov/bioenergy/pdfs/cookstove_meeting_summary.pdf

The Water Boiling Test (WBT) Prepared by Rob Bailis, Damon Ogle, Nordica MacCarty, and Dean Still with input from Kirk R. Smith and Rufus Edwards - For the Household Energy and Health Program, Shell Foundation

Report on Thermal Performance of mirt stove, EREDPC - Adonay Asirat and Lake Belete, July 2021, Addis Ababa, Ethiopia

ES ISO 19867-1:2018 Ethiopian Standard "Clean cook stoves and clean cooking solutions — Harmonized laboratory test protocols —Part 1: Standard test sequence for emissions and performance, safety and durability" published by International Organization for Standardization

ES 6085:2019 Ethiopian Standard Clean cook stoves and clean cooking solutions - Performance Requirements and Test Methods

Water Boiling Test, WBT 4.2.3 Excel Sheet

WHO. (2018). Household air pollution and health. Retrieved from https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Wikipedia. (2021). Injera. Retrieved from https://en.wikipedia.org/wiki/Injera

Wikipedia. (2021). Kitchen stove. Retrieved from https://en.wikipedia.org/wiki/Kitchen_stove

Ortega Arriaga, Paloma & Babacan, Oytun & Nelson, J. & Gambhir, Ajay. (2021). Grid versus off-grid electricity access options: A review on the economic and environmental impacts. Renewable and Sustainable Energy Reviews. 143. 110864. 10.1016/j.rser.2021.110864.

Ofosu, Eric & Gyamfi, Samuel & Diawuo, Felix & Ayodele, Harold & Kallon, Patrick. (2022). Technical Considerations for the Design and Selection of Improved Cook stoves: A Review.

Tigist Elias Haile, Kamil Dino Adem, Experimental evaluation of low-cost thermoelectric integrated rocket stove, Cleaner Energy Systems, Volume 7, 2024, 100112, ISSN 2772-7831, https://doi.org/10.1016/j.cles.2024.100112. (https://www.sciencedirect.com/science/article/pii/S2772783124000062)

Wikipedia, https://en.wikipedia.org/wiki/Thermoelectric_generator

Thermoelectric Generators: Design, Operation, and Applications, 2023, https://www.intechopen.com/ chapters/1148098

Applied Thermoelectric Solutions, How Thermoelectric Generators Work,

https://thermoelectricsolutions .com/how-thermoelectric-generators-work/

Encyclopedia, Scholarly Community Encyclopedia, Thermoelectric Generators: Progress and Applications, https://encyclopedia.pub/entry/1682

ES-6085-2019 Standard Test for Energy Performance and Safety for Clean Cook stoves in Ethiopia. Summary report of Ethiopian standard test results for twenty-six solid biomass cook stoves, published by EnDav Ethiopia (Sep, 2024).

APPENDIX

Appendix – A: Data Recording Sheets

Data Recording Sheet

Data Recording Sheet						
Time (Min)	Water Temperature (^{0}C)	Cold Side Temperature (^{0}C)	Hot Side Temperature (^{0}C)	Produced Open Circut Voltage (V)	Produced Rated Voltage (V)	Produced Current Voltage (V)

Fuel Moisture Content Sheet

If you are determining fuel moisture with the Delmhorst J-2000 or similar handheld moisture meter, take 3 pieces of fuel at random from the stock used for each test and measure each in three places along its length. Enter the results in the gray spaces below. The worksheet will automatically calculate average moisture content on a dry and wet basis.
If you are using another means to determine fuel moisture, ignore this worksheet and enter the moisture in the proper space on each Test's data form.

Test-1 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-2 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Method used to obtain wood moisture:

The Delmhorst J-2000 moisture analyzer measures fuel moisture on a dry basis. To find moisture on a wet basis, use the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1+MC_{dry}}$$

This spreadsheet does this calculation automatically if a value is entered in the dry-basis space. Output requires moisture content on a wet basis, so the

Test-3 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-4 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-5 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-6 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-7 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-8 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-9 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Test-10 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ____ wet-basis ____

Fuel moisture content worksheet

Water Boiling Test – Test Entry Form

Water Boiling Test - Test Entry Form

These values are not linked to the Test sheets. This sheet is provided so you can print an easy data entry form. You will have to enter these values in each Test sheet to obtain the calculations.

Air Temperature		Name of Testers	____________
Wind Conditions		Date	____________
		Stove Type/Model	____________
Fuel Dimensions		Test Number	____________
Moisture Content (wet basis)		Location	____________
		Fuel Type	____________
Dry Weight Pot 1		Notes	
Weight Container for Char			
Local Boiling Point * * enter on General Information			
Background CO2 (ppm)**			
Background CO (ppm)**			
Background PM (ug/m3)**			

** For emission testing only

Cold Start

	Start	End
Time		
Weight of Fuel		
Water Temperature, Pot 1		
Water Temperature, Pot 2		
Water Temperature, Pot 3		
Water Temperature, Pot 4		
Weight of Pot 1 with water		
Weight of Pot 2 with water		
Weight of Pot 3 with water		
Weight of Pot 4 with water		
Fire Starting Materials		

Water Boiling Test – General Information

Water Boiling Test - General Information Version 4.2.3

Test & stove description		*Fuel description*	
Name of Tester(s)		Your general description	
Test Number or Code		Fuel type	
Test Dates		Fuel description	
Test Year		Average length (cm)	
Test Location		Cross-sectional dimensions (cm x cm)	
Replicate Test Number		*Default values (looked up)*	
Altitude/Elevation (m)		Gross calorific value	HHV, kJ/kg
Stove Type/Model		Net calorific value	LHV,kJ/kg
Manufactured by		Char calorific value	LHV,kJ/kg
Description and Notes		Char carbon content	by mass
		If possible, enter a calorific value from measurements of local fuel below.	
		☐ Check box if you have a measured calorific value	
Description of Pot(s)			
		Measured gross calorific value	HHV measured, kJ/kg
Ambient conditions		Measured net calorific value	LHV, kJ/kg
Air relative humidity (%)		Assumed net calorific value	LHV, kJ/kg
Local boiling point (C)		*Values to be used for tests*	
Emission testing		Gross calorific value	- HHV, kJ/kg
Atmospheric P (kPa)		Net calorific value	- LHV, kJ/kg
Pitot delta-P		Fuel carbon content	by mass
Hood flow rate (m3/hr)		*Description of firestarter (e.g. paper, fluid) and small wood or kindling*	
		(note: Kindling should be weighed and reported with wood)	
Notes or description about stove or operation not incluc			

Description of operation during the high-power test		*Description of operation during the simmering test*	
How is fire started?		How is fire started?	
When do you add new fuel to the fire?		When do you add new fuel to the fire?	
How much fuel do you add at one time?		How much fuel do you add at one time?	
How often do you feed the fire without adding fuel (e.g. push sticks)?		How often do you feed the fire without adding fuel (e.g. push sticks)?	
Do you control the air above or below the fire? If so, what do you do?		Do you control the air above or below the fire? If so, what do you do?	

Appendix – B: WBT Tier Level

Water Boiling Test - Tier Level and List Values

List Values

	wind conditions	fuel description	emissions calculations	version# 4.2.3
1	(Select from list)	(Select from list)	Carbon Balance	
2	No wind	Manufactured	Total Capture	
3	Light breeze	Cut to size	Custom: Entered Above	
4	Moderate wind	Natural		
5	Strong wind	Briquettes		
6	Very strong wind	Charcoal		
		Gel		
		Liquid		

IWA VITA WBT Tiers	units		Tier 0		Tier 1		Tier 2		Tier 3		Tier 4
High Power Thermal Efficiency	%	<	0.15	≥	0.15	≥	0.25	≥	0.35	≥	0.45
Low Power Specific Consumption	MJ/min/L	>	0.05	≤	0.05	≤	0.039	≤	0.028	≤	0.017
High Power CO	g/MJd	>	16	≤	16	≤	11	≤	9	≤	8
Low Power CO	g/min/L	>	0.2	≤	0.2	≤	0.13	≤	0.1	≤	0.09
High Power PM	mg/MJd	>	979	≤	979	≤	386	≤	168	≤	41
Low Power PM	mg/min/L	>	8	≤	8	≤	4	≤	2	≤	1
Indoor Emissions CO	g/min	>	0.97	≤	0.97	≤	0.62	≤	0.49	≤	0.42
Indoor Emissions PM	mg/min	>	40	≤	40	≤	17	≤	8	≤	2
Safety	Johnsons	<	45	≥	45	≥	75	≥	88	≥	95

Appendix – C: Test Results of Manufactured Stove

Water Boiling Test – Measured Moisture Content for the five tests of Manufactured Stove

Fuel moisture content worksheet for IBIBSITEG Model

If you are determining fuel moisture with the Delmhorst J-2000 or similar handheld moisture meter, take 3 pieces of fuel at random from the stock used for each test and measure each in three places along its length. Enter the results in the gray spaces below. The worksheet will automatically calculate average moisture content on a dry and wet basis.

If you are using another means to determine fuel moisture, ignore this worksheet and enter the moisture in the proper space on each Test's data form.

Test-1 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.6%	8.5%	9.3%
Piece 2	9.8%	10.2%	10.5%
Piece 3	10.9%	10.7%	10.4%

Average moisture content (%): dry-basis 10.10% wet-basis 9.17%

Test-2 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.5%	9.7%	9.6%
Piece 2	9.9%	10.1%	10.7%
Piece 3	10.9%	10.3%	10.4%

Average moisture content (%): dry-basis 10.23% wet-basis 9.28%

Test-3 — Instrument reading (% dry basis)

	1	2	3
Piece 1	8.4%	9.6%	8.5%
Piece 2	10.5%	9.2%	9.1%
Piece 3	8.2%	8.1%	8.3%

Average moisture content (%): dry-basis 8.88% wet-basis 8.15%

Test-4 — Instrument reading (% dry basis)

	1	2	3
Piece 1	9.6%	9.2%	10.6%
Piece 2	8.2%	8.6%	8.8%
Piece 3	9.8%	10.6%	10.9%

Average moisture content (%): dry-basis 9.59% wet-basis 8.75%

Test-5 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.3%	9.8%	9.4%
Piece 2	9.9%	9.6%	9.1%
Piece 3	10.2%	10.8%	10.5%

Average moisture content (%): dry-basis 9.96% wet-basis 9.05%

Test-6 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%): dry-basis

Method used to obtain wood moisture:

The Delmhorst J-2000 moisture analyzer measures fuel moisture on a dry basis. To find moisture on a wet basis, use the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1+MC_{dry}}$$

This spreadsheet does this calculation automatically if a value is entered in the dry-basis space. Output requires moisture content on a wet basis, so the conversion is very important.

Fuel moisture content worksheet for IBIBSITEG Model

Water Boiling Test – Basic Test Data of Manufactured Stove Sample

WATER BOILING TEST - VERSION 4.2.3 - TEST #3

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Saleamlak Abera	gray: efficiency
Test Number	3	blue: emissions
Date	1/2/2024	pink: error, missing input
Location	MWE/RETDPC Stove Laboratory	
Stove type/model	IBIBSITEG Model - Forced Draft	
Type of fuel	Eucalyptus	

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	20.4	ºC		Dry weight of Pot # 1 (grams)	7,610	g	P1
Wind conditions	Moderate wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	50*3*3 cm			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	8.15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,160	kJ/kg	HHV	Weight of container for char (grams)	1,380	g	k
Net calorific value (dry fuel)	18,840	kJ/kg	LHV	Local boiling point	92.5	ºC	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	17,095	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b

Notes about this test:

BASIC TEST DATA

Water Boiling Test – Calculations/Results of Manufactured Stove Test #1

TEST #1 1		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	11:50	t_{ci}	12:50	t_{cf}
Weight of fuel	g	3315	f_{ci}	485	f_{cf}
Water temperature, Pot # 1	ºC	19.2	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23625	$P1_{ci}$	18875	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1605	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2.c}$
Total CO (if available)	g			#	$m_{CO.c}$
Total PM (if available)	g				$m_{PM.c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	2,830	f_{cm}	-	f_{hm}
Net change in char during test	g	225	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2187	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,750	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,250	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	61	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	37.97%	h_c		h_h
Burning rate	g/min	36.4	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	194	SC_c		SC_h
Temp-corr sp consumption	g/liter	198.896579	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	3,747	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	11445	FP_c		FP_h

Water Boiling Test – Calculations/Results of Manufactured Stove Test #2

TEST #1 2		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	9:30	t_{ci}	10:30	t_{cf}
Weight of fuel	g	3430	f_{ci}	535	f_{cf}
Water temperature, Pot # 1	ºC	14.3	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23605	$P1_{ci}$	19130	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1630	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	2,895	f_{cm}	-	f_{hm}
Net change in char during test	g	250	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2216	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,475	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,525	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	58	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	36.77%	h_c		h_h
Burning rate	g/min	36.9	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	192	SC_c		SC_h
Temp-corr sp consumption	g/liter	184.3843736	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	3,474	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	11595	FP_c		FP_h

Water Boiling Test – Calculations/Results of Manufactured Stove Test #3

TEST #1 3		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	9:30	t_{ci}	10:30	t_{cf}
Weight of fuel	g	3375	f_{ci}	490	f_{cf}
Water temperature, Pot # 1	ºC	18.4	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23610	$P1_{ci}$	17960	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1490	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm		#		CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g		#		$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START		
Calculations/Results	Units	data	label	
Fuel consumed (moist)	g	2,885	f_{cm}	
Net change in char during test	g	110	Δc_c	
Equivalent dry fuel consumed	g	2446	f_{cd}	
Water vaporized from all pots	g	5,650	w_{cv}	
Effective mass of water boiled	g	10,350	w_{cr}	
Time to boil Pot # 1	min	60	Δt_c	
Temp-corr time to boil Pot # 1	min	61	$\Delta t^T{}_c$	
Thermal efficiency	%	38.49%	h_c	
Burning rate	g/min	40.8	r_{cb}	
Specific fuel consumption	g/liter boiled	236	SC_c	
Temp-corr sp consumption	g/liter	239.1568845	$SC^T{}_c$	
Temp-corr sp energy consumpt.	kJ/liter	4,506	$SE^T{}_C$	
Firepower	watts	12798	FP_c	

Water Boiling Test – Calculations/Results of Manufactured Stove Test #4

TEST #1 4		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	9:50	t_{ci}	10:50	t_{cf}
Weight of fuel	g	3345	f_{ci}	240	f_{cf}
Water temperature, Pot # 1	ºC	15.0	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23610	$P1_{ci}$	18405	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1560	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	3,105	f_{cm}	-	f_{hm}
Net change in char during test	g	180	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2496	f_{cd}		f_{hd}
Water vaporized from all pots	g	5,205	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	10,795	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	58	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	36.06%	h_c		h_h
Burning rate	g/min	41.6	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	231	SC_c		SC_h
Temp-corr sp consumption	g/liter	223.7318908	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	4,215	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	13061	FP_c		FP_h

Water Boiling Test – Calculations/Results of Manufactured Stove Test #5

TEST #1 5		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	10:00	t_{ci}	11:00	t_{cf}
Weight of fuel	g	3365	f_{ci}	360	f_{cf}
Water temperature, Pot # 1	ºC	15.0	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23610	$P1_{ci}$	18318	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1540	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm		#		CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g		#		$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	3,005	f_{cm}	-	f_{hm}
Net change in char during test	g	160	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2441	f_{cd}		f_{hd}
Water vaporized from all pots	g	5,292	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	10,708	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	58	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	37.29%	h_c		h_h
Burning rate	g/min	40.7	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	228	SC_c		SC_h
Temp-corr sp consumption	g/liter	220.6382757	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	4,157	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	12776	FP_c		FP_h

Water Boiling Test – Summary of Calculations/Results of Manufactured Stove

WATER BOILING TEST - VERSION 4.2.	TEST Results								
All cells are linked to data worksheets, no entries are required									
Stove type/model	IBIBSITEG Model								
Location	MWE/RETDPC Stove Laboratory								
Fuel description	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)								
Wind conditions	Moderate Wind								
Ambient temperature	Different								

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
Time to boil Pot # 1	min	60	60	60	60	60	60	0.0	
Temp-corrected time to boil Pot # 1	min	61	58	61	58	58	59	1.8	3.0%
Burning rate	g/min	36	37	41	42	41	39	2.4	6.1%
Thermal efficiency	%	37.97%	36.77%	38.49%	36.06%	37.29%	0.3732	0.96%	2.6%
Specific fuel consumption	g/liter	194	192	236	231	228	216	21.3	9.8%
Temp-corrected specific consumption	g/liter	199	184	239	224	221	213	21.6	10.1%
Temp-corrected specific energy cons.	kJ/liter	3,747	3,474	4,506	4,215	4,157	4020	407.9	10.1%
Firepower	watts	11,445	11,595	12,798	13,061	12,776	12,335.15	754.3	6.1%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
High Power Thermal Efficiency	%	38.0%	36.8%	38.5%	36.1%	37.3%	0.373153	0.96%	2.57%
Low Power Specific Fuel Consumption	MJ/(min·L)								
High Power CO	g/MJ								
Low Power CO	g/(min·L)								
High Power PM	mg/MJ								
Low Power PM	mg/(min·L)								
Indoor CO Emissions	g/min								
Indoor PM Emissions	mg/min								

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	3
Low Power Specific Fuel Consumption	NA
High Power CO	NA
Low Power CO	NA
High Power PM	NA
Low Power PM	NA
Indoor CO Emissions	NA
Indoor PM Emissions	NA

NA = Not Applicable; IWA Performance Tiers are not reported if there are fewer than 3 tests conducted.

Appendix – D: Test Results of Mirt Stove

Water Boiling Test – Measured Moisture Content for the five tests of Mirt Stove

Fuel moisture content worksheet for IBIBSITEG Model

If you are determining fuel moisture with the Delmhorst J-2000 or similar handheld moisture meter, take 3 pieces of fuel at random from the stock used for each test and measure each in three places along its length. Enter the results in the gray spaces below. The worksheet will automatically calculate average moisture content on a dry and wet basis.
If you are using another means to determine fuel moisture, ignore this worksheet and enter the moisture in the proper space on each Test's data form.

Test-1 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.6%	8.5%	9.3%
Piece 2	9.8%	10.2%	10.5%
Piece 3	10.9%	10.7%	10.4%

Average moisture content (%)
dry-basis 10.10% wet-basis 9.17%

Test-2 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.5%	9.7%	9.6%
Piece 2	9.9%	10.1%	10.7%
Piece 3	10.9%	10.3%	10.4%

Average moisture content (%)
dry-basis 10.23% wet-basis 9.28%

Method used to obtain wood moisture:

The Delmhorst J-2000 moisture analyzer measures fuel moisture on a dry basis. To find moisture on a wet basis, use the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1+MC_{dry}}$$

This spreadsheet does this calculation automatically if a value is entered in the dry-basis space. Output requires moisture content on a wet basis, so the conversion is very important.

Test-3 — Instrument reading (% dry basis)

	1	2	3
Piece 1	8.4%	9.6%	8.5%
Piece 2	10.5%	9.2%	9.1%
Piece 3	8.2%	8.1%	8.3%

Average moisture content (%)
dry-basis 8.88% wet-basis 8.15%

Test-4 — Instrument reading (% dry basis)

	1	2	3
Piece 1	9.6%	9.2%	10.6%
Piece 2	8.2%	8.6%	8.8%
Piece 3	9.8%	10.6%	10.9%

Average moisture content (%)
dry-basis 9.59% wet-basis 8.75%

Test-5 — Instrument reading (% dry basis)

	1	2	3
Piece 1	10.3%	9.8%	9.4%
Piece 2	9.9%	9.6%	9.1%
Piece 3	10.2%	10.8%	10.5%

Average moisture content (%)
dry-basis 9.96% wet-basis 9.05%

Test-6 — Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis

Fuel moisture content worksheet for IBIBSITEG Model

Water Boiling Test – Basic Test Data of Mirt Stove Sample

WATER BOILING TEST - VERSION 4.2.3 - TEST #1

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Saleamlak Abera	gray: efficiency
Test Number	3	blue: emissions
Date	1/2/2024	pink: error, missing input
Location	MWE/RETDPC Stove Laboratory	
Stove type/model	Mirt Stove	
Type of fuel	Eucalyptus	

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	22.5	ºC		Dry weight of Pot # 1 (grams)	7,610	g	P1
Wind conditions	Light breeze			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	65*3*3cm			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	8.15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,160	kJ/kg	HHV	Weight of container for char (grams)	1,380	g	k
Net calorific value (dry fuel)	18,840	kJ/kg	LHV	Local boiling point	92.5	ºC	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	17,096	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b

Notes about this test:

BASIC TEST DATA

Water Boiling Test – Calculations/Results of Mirt Stove Test #1

TEST #1 1		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	15:30	t_{ci}	16:30	t_{cf}
Weight of fuel	g	3540	f_{ci}	1125	f_{cf}
Water temperature, Pot # 1	ºC	16.2	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23625	$P1_{ci}$	20685	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1615	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	2,415	f_{cm}	-	f_{hm}
Net change in char during test	g	235	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	1799	f_{cd}		f_{hd}
Water vaporized from all pots	g	2,940	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	13,060	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	59	Δt^T_c		Δt^T_h
Thermal efficiency	%	34.69%	h_c		h_h
Burning rate	g/min	30.0	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	138	SC_c		SC_h
Temp-corr sp consumption	g/liter	135.3812444	SC^T_c		SC^T_h
Temp-corr sp energy consumpt.	kJ/liter	2,551	SE^T_C		SE^T_H
Firepower	watts	9413	FP_c		FP_h

Water Boiling Test – Calculations/Results of Mirt Stove Test #2

TEST #1 2		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	15:30	t_{ci}	16:30	t_{cf}
Weight of fuel	g	3500	f_{ci}	455	f_{cf}
Water temperature, Pot # 1	ºC	18.2	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23605	$P1_{ci}$	19325	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1715	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	3,045	f_{cm}	-	f_{hm}
Net change in char during test	g	335	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2218	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,280	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,720	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	61	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	35.06%	h_c		h_h
Burning rate	g/min	37.0	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	189	SC_c		SC_h
Temp-corr sp consumption	g/liter	191.0165421	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	3,599	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	11607	FP_c		FP_h

Water Boiling Test – Calculations/Results of Mirt Stove Test #3

TEST #1 3		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	15:30	t_{ci}	16:30	t_{cf}
Weight of fuel	g	3600	f_{ci}	680	f_{cf}
Water temperature, Pot # 1	ºC	19.5	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23610	$P1_{ci}$	19540	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1650	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm		#		CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g		#		$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	2,920	f_{cm}	-	f_{hm}
Net change in char during test	g	270	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2227	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,070	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,930	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	62	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	33.58%	h_c		h_h
Burning rate	g/min	37.1	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	187	SC_c		SC_h
Temp-corr sp consumption	g/liter	191.7787529	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	3,613	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	11654	FP_c		FP_h

Water Boiling Test – Calculations/Results of Mirt Stove Test #4

TEST #1 4		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	15:10	t_{ci}	16:10	t_{cf}
Weight of fuel	g	3750	f_{ci}	550	f_{cf}
Water temperature, Pot # 1	ºC	18.2	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23610	$P1_{ci}$	19220	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1685	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	3,200	f_{cm}	-	f_{hm}
Net change in char during test	g	305	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2385	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,390	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,610	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	61	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	33.15%	h_c		h_h
Burning rate	g/min	39.8	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	205	SC_c		SC_h
Temp-corr sp consumption	g/liter	207.3650583	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	3,907	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	12482	FP_c		FP_h

Water Boiling Test – Calculations/Results of Mirt Stove Test #5

TEST #1 5		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	15:00	t_{ci}	16:00	t_{cf}
Weight of fuel	g	3990	f_{ci}	485	f_{cf}
Water temperature, Pot # 1	ºC	15.5	$T1_{ci}$	92.5	$T1_{cf}$
Water temperature, Pot # 2	ºC		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	ºC		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	ºC		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	23605	$P1_{ci}$	18780	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1775	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm			#	CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	ºC				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g			#	$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label	HOT START data	label
Fuel consumed (moist)	g	3,505	f_{cm}	-	f_{hm}
Net change in char during test	g	395	Δc_c	-	Δc_h
Equivalent dry fuel consumed	g	2521	f_{cd}		f_{hd}
Water vaporized from all pots	g	4,825	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	11,175	w_{cr}	-	w_{hr}
Time to boil Pot # 1	min	60	Δt_c	-	Δt_h
Temp-corr time to boil Pot # 1	min	58	$\Delta t^T{}_c$		$\Delta t^T{}_h$
Thermal efficiency	%	33.81%	h_c		h_h
Burning rate	g/min	42.0	r_{cb}		r_{hb}
Specific fuel consumption	g/liter boiled	226	SC_c		SC_h
Temp-corr sp consumption	g/liter	219.7521448	$SC^T{}_c$		$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	4,140	$SE^T{}_C$		$SE^T{}_H$
Firepower	watts	13194	FP_c		FP_h

Water Boiling Test – Summary of Calculations/Results of Mirt Stove

WATER BOILING TEST - VERSION 4.2 TEST Results

All cells are linked to data worksheets, no entries are required

Stove type/model	Mirt Stove
Location	MWE/RETDPC Stove Laboratory
Fuel description	Eucalyptus Globulus (Southern Blue Gum, Fever Tree)
Wind conditions	Light Breeze
Ambient temperature	Different

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
Time to boil Pot # 1	min	60	60	60	60	60	60	-	
Temp-corrected time to boil Pot # 1	min	59	61	62	61	58	60	1.3	2.2%
Burning rate	g/min	30	37	37	40	42	37	4.5	12.2%
Thermal efficiency	%	34.69%	35.06%	33.58%	33.15%	33.81%	0.3406	0.79%	2.3%
Specific fuel consumption	g/liter	138	189	187	205	226	189	32.6	17.2%
Temp-corrected specific consumption	g/liter	135	191	192	207	220	189	32.3	17.1%
Temp-corrected specific energy cons.	kJ/liter	2,551	3,599	3,613	3,907	4,140	3562	608.3	17.1%
Firepower	watts	9,413	11,607	11,654	12,482	13,194	11,670.03	1,421.2	12.2%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Test 4	Test 5	Average	St Dev	COV
High Power Thermal Efficiency	%	34.7%	35.1%	33.6%	33.2%	33.8%	0.3405851	0.79%	2.32%
Low Power Specific Fuel Consumptior	MJ/(min·L)								
High Power CO	g/MJ								
Low Power CO	g/(min·L)								
High Power PM	mg/MJ								
Low Power PM	mg/(min·L)								
Indoor CO Emissions	g/min								
Indoor PM Emissions	mg/min								

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	2
Low Power Specific Fuel Consumptio	NA
High Power CO	NA
Low Power CO	NA
High Power PM	NA
Low Power PM	NA
Indoor CO Emissions	NA
Indoor PM Emissions	NA

NA = Not Applicable; IWA Performance Tiers are not reported if there are fewer than 3 tests conducted.

Appendix – E: Manufacturing Drawing

Manufacturing Drawing