EEP
ENERGY AND ENVIRONMENT PARTNERSHIP / SOUTHERN AND EAST AFRICA

The Energy and Environment Partnership Programme Southern and East Africa
PHASE II

30 MARCH 2017

TECHNICAL BRIEF
COOKSTOVES & ENERGY EFFICIENCY

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INTRODUCTION

Energy efficiency is a major goal of improved cookstove programmes. In the countries where EEP S&EA projects are being implemented, cooking forms the single main daily use of energy by households, and therefore also has the highest energy savings potential through efficient technologies.

Biomass is the only source of fuel for 2.7 billion people worldwide.[1] In many developing countries, approximately 50% of energy consumption is specifically for cooking food. In these countries, between 70-90% of the energy is derived from direct burning of biomass such as wood or charcoal,[2] which has serious implications for the health and environment.

[1] pg 1; A rough guide to clean cookstoves; Differ Group; 23 March 2012; http://cleancookstoves.org/resources_files/a-rough-guide-to-clean.pdf

[2] pg 1; Wood-Based Biomass Energy Development for Sub-Saharan Africa; World Bank; http://siteresources.worldbank.org/EXTAFRREGTOPENERGY/Resources/717305-1266613906108/BiomassEnergyPaper_WEB_Zoomed75.pdf

An average rural family in sub-Saharan Africa can spend 20% or more of its income on purchasing wood or charcoal for cooking, and in many other cases, women and children use exorbitant amounts of time to collect biomass for cooking. Furthermore, significant health ailments result from the indoor air pollution caused by charcoal and wood fires. [4]

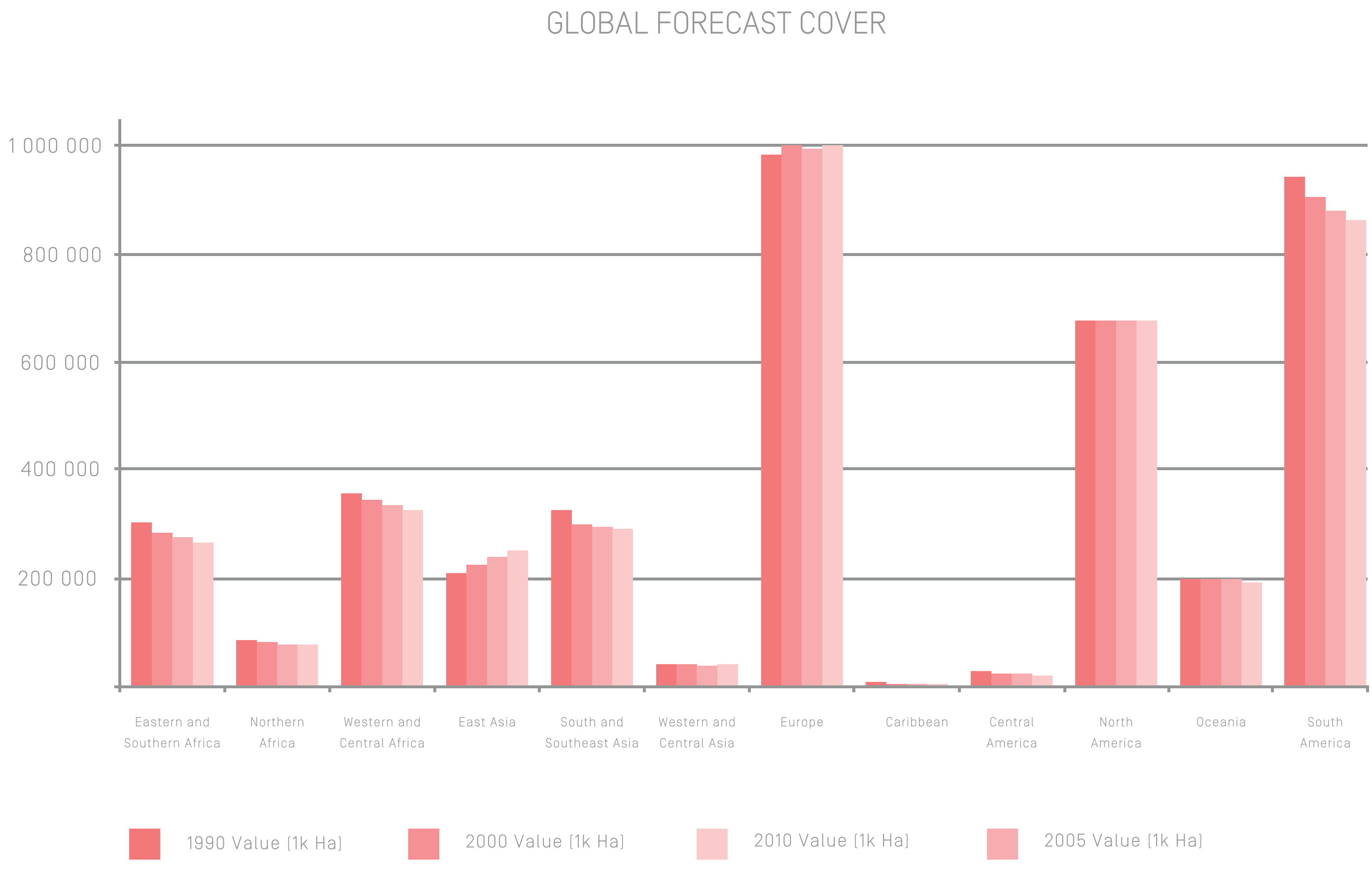

Figure 1: Global forest cover from 1990 to 2010.[3]

[3] FAO – Global Forest Resources Assessment 2010 at www.fao.org/docrep/013/i1757e/i1757e.pdf

[4] Chapter 15; Energy For Cooking In Developing Countries; World Energy Outlook 2006

1. HEAT ENERGY FROM BIOMASS

1.1. COMBUSTION

Combustion is a commonly used process for cooking which liberates heat and creates waste products. Combustion is a complex chemical reaction: the amount of heat and byproducts that are released by the reaction depend on the amount of oxygen that is present and on the fuel that is burnt. Ambient air (approximately 79% nitrogen and 21% oxygen) is the typical source of oxygen for combustion. Combustion releases a large amount of heat in the presence of a slightly excess amount of oxygen due to the complete oxidation of the fuel. It is the most widespread energy conversion process for cooking.

1.2. PYROLYSIS

Pyrolysis is the thermal decomposition of material without the addition of air or oxygen. It requires low heat to break down biomass molecules (around 400 - 700deg C). Many pyrolysis reactions occur in sequence or at once, depending on the organic molecule. Pyrolysis is endothermic, which means that it requires constant heat to maintain the reaction. Pyrolysis is the process used for making charcoal from wood. The gas produced contains long chained hydrocarbons that are condensable and can be separated as oil at room temperature and that can form dangerous aerosols when condensed in the air. The remaining gas is a medium heating value gas. In normal fires, certain sections within the bulk combustion process are anoxic due to localized availability of air and therefore in a state of pyrolysis. The pyrolysis products are burnt almost instantaneously to form CO2, H2O and other minor pollutants.

1.3. GASIFICATION

Gasification requires the addition of a small amount of oxygen and more heat, not enough to combust but enough to lead to the formation of partially oxidized gas products such as carbon monoxide, methane, hydrogen and volatile organic carbons (VOC's). These VOC's can be burnt for further energy release. If air is added to the gasification process, the byproduct gas is a low heating value gas called producer gas. All three reactions occur in a simple fire with the major overall reaction being combustion. Good management of these reaction stages can optimize the heat generation process for cooking.

1.4. ACTUAL PROCESS

Thermal conversions of biomass do not occur in isolation, and a mixture of the three processes is often present in a flame. The diagram below indicates the complex process of combustion in wood:

Complete combustion seldom occurs inside an incinerator. Products of incomplete combustion, such as carbon monoxide, are produced. The flue gas can also contain non-combustible substances and compounds that contain chlorine and fluorine - these toxic byproducts are emitted into the air. Modern technologies have been developed to clean these toxins out of flue gas streams on industrial plants, but this remains unchecked on many smaller installations. One of the benefits of clean cookstoves is that harmful emissions are significantly reduced.

Smoke is an unwanted byproduct of fires. Its chemical constituency depends on the process. Fires with high availability of oxygen burn at a high temperature and with small amount of smoke produced; oxygen and hydrogen are almost completely oxidized to form carbon dioxide and water for instance. However, the lower the temperature and the worse the mixing of fuel and secondary fuel gasses with the combustion zones of the flame and oxidizing air, the more un-combusted pollutants are released and the lower the efficiency of the combustion process.

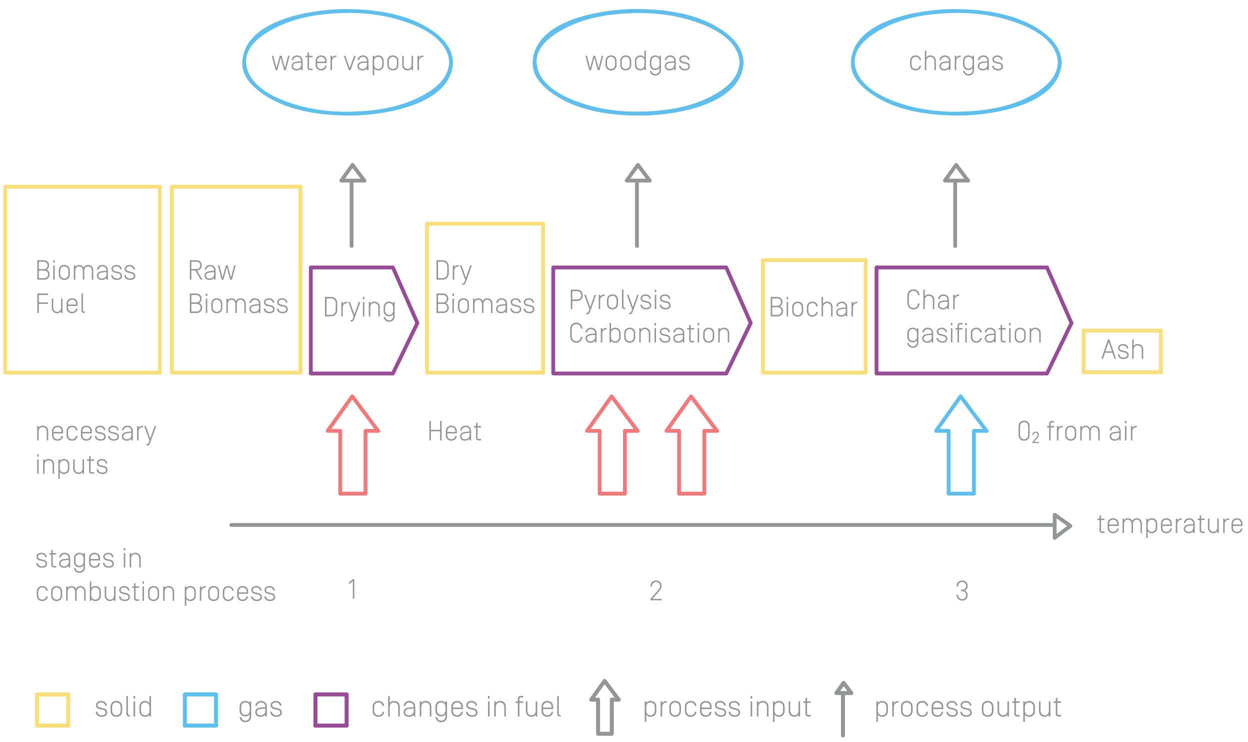

Figure 2: Changes in solid fuel that is combusted [5]

[5] pg 8; Micro-gasification: Cooking with gas from dry biomass; C Roth; 2014

2. FUEL TYPES

2.1. COMBUSTION

Biofuels consist of the following major chemical components:

- Combustible component: Lignin, cellulose or other organic hydrocarbon molecules.
- Water: in the form of free moisture and fixed water.
- Ash: The incombustible component mainly containing calcium silicon, magnesium and iron oxides and salts.

The amount of thermal energy contained in the combustible component of the biomass fuel is called the calorific value. Table 1 from the Biomass Energy Centre shows a comparison of relative calorific values for biomass fuel types.

The calorific value of a biomass fuel can be increased by driving off the water or VOC components, which leads to a purer form of carbon which contains higher amounts of energy per unit mass. The calorific value of charcoal is approximately 1.5 times higher than that of wood it originates from, due to the water and other products that have been driven off during the charcoal making (pyrolysis) process (Table 1).

Energy is transported more effectively for fuels with higher calorific value. These fuels also release more heat, which give them attractive properties for cooking.

Fuel	Net Calorific Value (CV) by Mass GJ/tonne	Net Calorific Value (CV) by Mass kWh/kg	Bulk Density kg /m^3	Energy Density by Volume MJ/m^3	Energy Density by Volume kWh/m^3
Wood Chips (30% MC)	12.5	3.5	250	3,100	870
Log Wood (stacked air-dry (20% MC)	14.7	4.1	350 - 500	5,200 - 7,400	1,400 - 2,000
Wood (solid - oven dry)	19	5.3	400 - 600	7,600 - 11,400	2,100 - 3,200
Wood Pellets	17	4.8	650	11,000	3,100
Miscanthus (bale - 25% MC)	13	3.6	140 - 180	1,800 - 2,300	500 - 650
House Coal	27 - 31	7.5 - 8.6	850	23,000 - 25,000	6,400 - 7,300
Anthracite	33	9.2	1,100	36,300	10,100
Heating Oil	42.5	11.8	845	36,000	10,000
Natural Gas (NTP)	38.1	10.6	0.9	35.2	9.8
LPG	46.3	12.9	510	23,600	6,600

Table 1: Comparison of calorific values for different fuel types [6]

[6] http://www.biomassenergycentre.org.uk/

3. BURNING METHODS

The EEP portfolio contains several technologies which employ different burning methods for generating heat efficiently for cooking at household level. By means of comparison, the main methods for burning biomass will be discussed below:

3.1. THREE STONE FIRE

A standard biomass fire is surrounded by three large stones, which are used to balance a cooking pot. Three stone fires are inherently inefficient due to the thermal losses towards the sides of the fire.

3.2. CONSTRUCTED BRICK & MORTAR STOVES

A variety of these stoves exist, whereby the biomass fire is created in an insulated combustion chamber. More intense heat is generated and cleaner combustion results from the more complete burning of the organic compounds in the fuel. The benefit of brick and mortar stoves is that they can be vented with a chimney, which removes indoor cooking smoke. However, these stoves are permanent or semi-permanent installations with the drawbacks of being more expensive and not being portable.

3.3. PORTABLE STOVES

There are a wide variety of prefabricated portable stoves which are designed to burn biomass more effectively than a standard three-stone fire. The main improvements in these stoves are as follows:

1. Insulation of sides: The combustion chamber is insulated with thermally non-conductive materials which improve the stove’s efficiency.
2. Passive control of airflow: Control of airflow is done through smart design of airflow channels and adjustable vents.
3. Active injection of secondary air-flow: a fan is used to blows high velocity, low volume jets of air into the combustion chamber, which when optimized results in more complete combustion of the fuel. This active injection can be effectively employed for gasification: some fuel is lit on top of the stove, forcing combustible products to pass through the flame front before being emitted into the air.

In conventional cooking, any heat applied to the pot after it reaches boiling temperature is merely replacing heat lost to the air by the pot and in some cases driving off moisture from the food in the pot. Since an insulated cooker prevents most of the heat in the food from escaping into the environment, much less additional energy is needed to complete the cooking process.

4. EFFICIENT STOVE TECHNOLOGIES

The main improved stove technologies represented in the EEP S&EA portfolio are described in this section.

4.1. ROCKET STOVE

This simple design allows convective updrafts in the chimney to constantly draw fresh air into the combustion chamber. Most commercial rocket stove designs have a fuel tray which ensures unobstructed airflow under the fuel. VOC's and CO from the fuel are partially burnt in the chimney. The temperature of the flame is controlled by obstructing the bottom entrance of the stove.

Rocket stoves are effective for burning firewood and sticks. These stoves can be constructed from metal drums, bricks or from clay, and are generally a more affordable option than other stoves.

4.2. FORCED-AIR MICRO-GASIFIER STOVE

Forced-air micro-gasifier stoves have a variety of designs, but the principles of operation require gasification to occur in the fuel, and secondary air to be blown into the flame. By increasing the velocity of the secondary airflow, more effective mixing can occur which results in higher efficiency. For the example in Figure 4, fuel is lit at the top, which heats lower layers of fuel and causes gasification reactions in these lower layers. A fan forces air into the flame, which allows for complete combustion of the gasification products. The fan is typically powered by batteries (charged by a small solar panel) or thermoelectric generators (that use waste heat), which also allows these stoves to provide low-power outputs for charging mobile phones or powering LED lights.

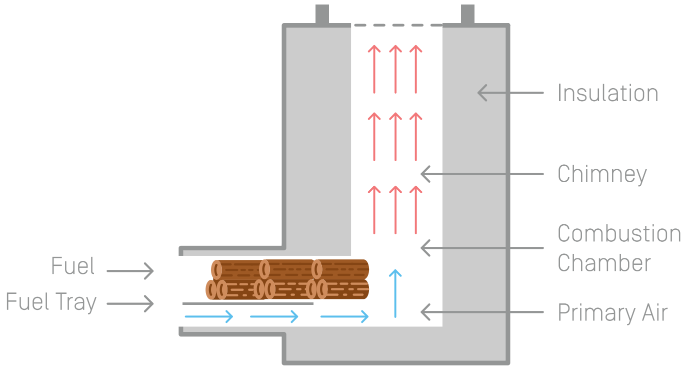

Figure 3: Side view of a typical rocket stove design.

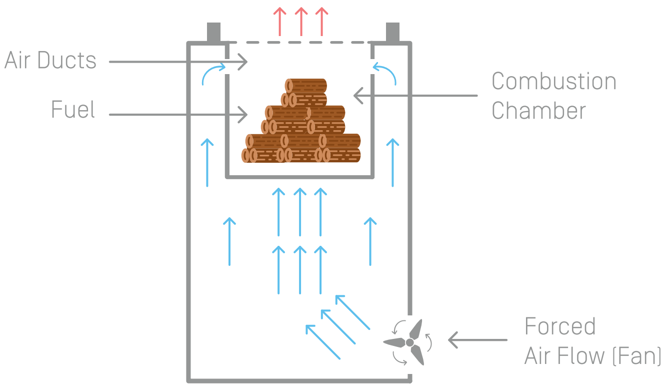

Figure 4: Side view of a typical forced air micro-gasifier stove design

4.3. NATURAL DRAFT GASIFIER STOVE

The natural draft gasifier stove design allows for initial combustion and gasification to occur due to primary airflow that creates an updraft through the heated fuel. As shown in Figure 5, the natural draft gasifier stove is constructed with two cylindrical containers. Secondary airflow occurs due to convective updrafts that form as the inner burning chamber heats the air contained by the outer cylinder. Secondary airflow is injected into the flame to allow for more complete combustion of VOC's and CO that are released from the gasified fuel. When the fuel is lit from the top, it is defined as a TLUD (top-lit updraft) stove.

4.2. IMPROVED CHARCOAL STOVE

Charcoal is loaded from the top, and lit from the bottom. Once the charcoal starts combusting, convective updrafts draw fresh air into the combustion chamber through the bottom entrance. The bottom entrance is usually equipped with a door or ashtray which can be used to control airflow and consequently also temperature. Some improved charcoal stoves are designed to allow secondary airflow through ventilation holes at the top of the combustion chamber, which also improves combustion. The improved charcoal stove still has CO emission, but very little smoke emission. Improved charcoal cookstove designs use insulation such as ceramics to prevent radiated heat losses from the sides of the device.

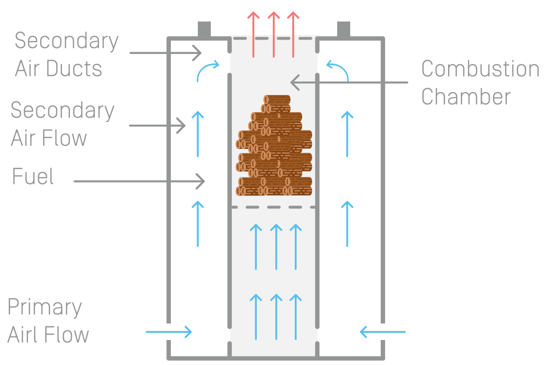

Figure 5: Side view of a typical TLUD stove technology

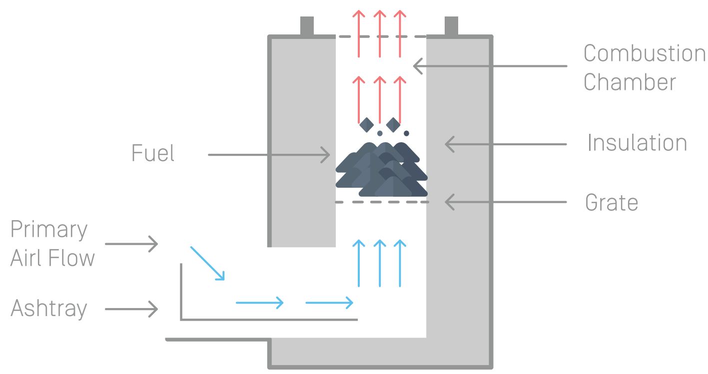

Figure 6: Side view of a typical improved charcoal cookstove

5. EFFICIENCY CONSIDERATIONS

There are various ways of measuring efficiency for cookstoves. The most common practices are the following:

1. Thermal efficiency: Measuring the heat transfer to the cooking vessel as a fraction of the calorific weight of the biomass input. This is commonly done by means of a water-boiling test.
2. Baseline comparison: Measuring the performance of a cookstove technology in relation to a known baseline such as the three-stone fire.
3. Biomass savings: Measuring the performance of cookstove in relation to the amount of fuel that would normally be consumed for the same activity.

It is important to realize that the efficiency of a stove is inherently connected with the function of the device, which is cooking. Consequently, cooking-like operation should be modelled when testing the stove's efficiency and tests cannot only be modelled for the steady state of operation since transient temperature changes that are inherent in the cooking process, as indicated in Figure 7.

Energy losses appear because of three reasons. Firstly, some heat from the cooking fire escapes before it can reach the cooking vessel. Secondly, some heat from the cooking fire is used to heat up the cooking pot, which constantly loses heat to the environment. Thirdly, heat is lost due to evaporation of liquids from the cooking pot.

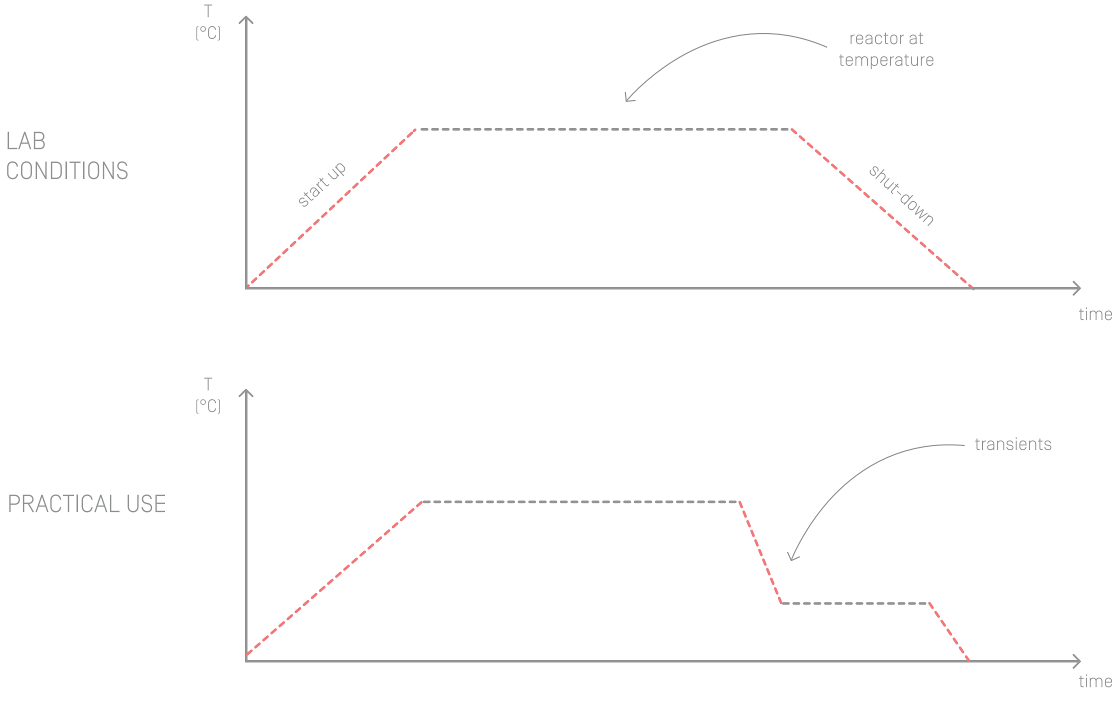

Figure 7: The top graph shows a simplified case where a stove is fired up, attains a stable temperature, and switched off after a set time period. The practical case could include various boil, simmering and refuelling phases, which leads to inefficient heating and cooling transients.

Figure 8 indicates typical primary fuel to applied heat efficiencies for various cooking appliances in first and third-world contexts. For first-world appliances, the efficiencies are calculated by accounting for losses in electrical generation, transmission and distribution losses:

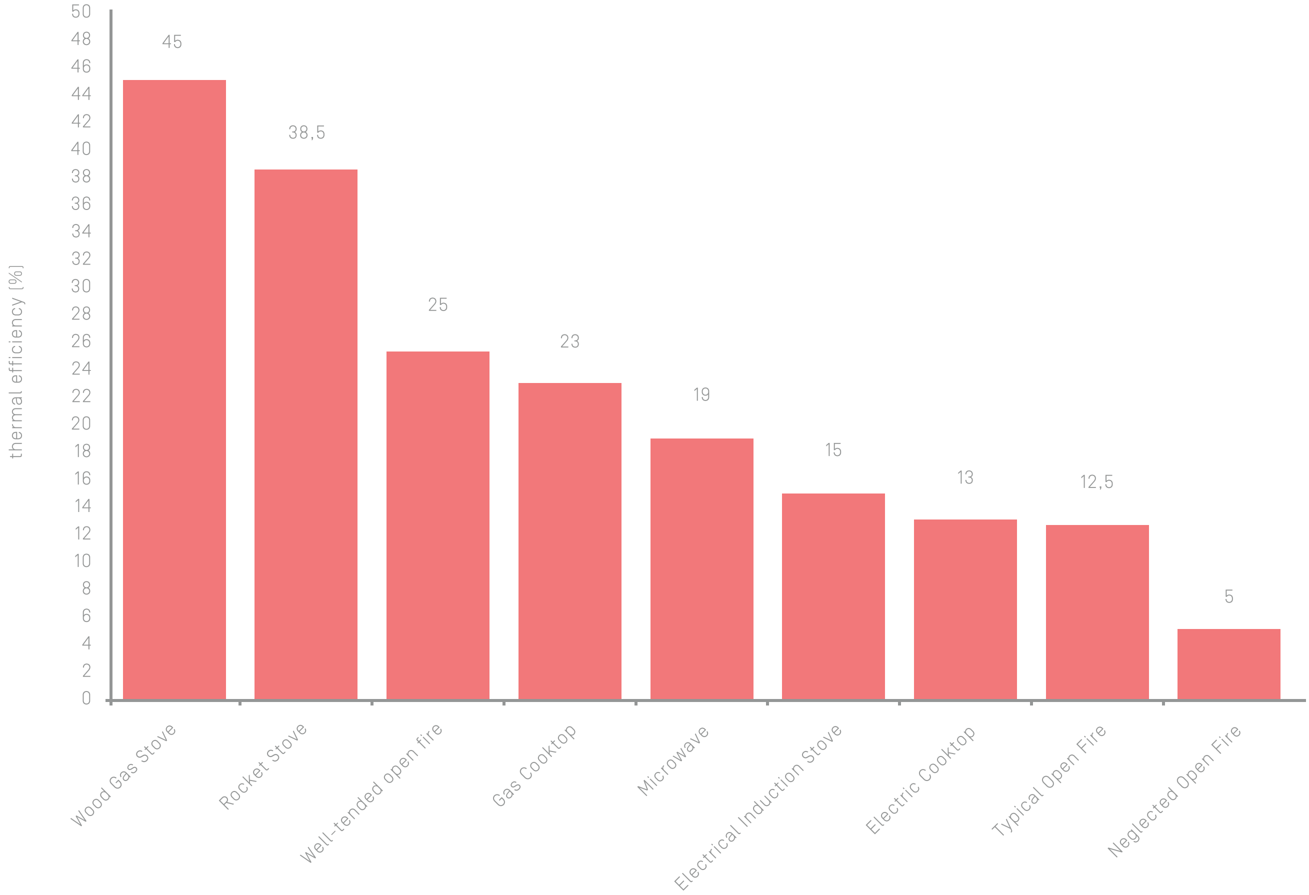

Figure 8: Comparison of thermal conversion efficiencies for various appliances from primary fuel source to final heat conversion [7, 8]

[7] http://www.lowtechmagazine.com/2014/06/thermal-efficiency-cooking-stoves.html

[8] pg 7; Energy-efficient cooking: What users can save with energy efficient cooking stoves and ovens; Wuppertal Institute for Climate, Environment and Energy; 2013

6. EFFICIENCY MEASUREMENTS

6.1. EFFICIENCY CLAIMS

EE measures are expressed as a percentage, which is calculated according to one of the following baselines:

Empirical:

- Measured useful output energy measured against a baseline input energy.
- For cookstoves, the calorific value of input fuel is calculated and the useful energy output is measured by means of standardized cooking tests.
- Typical correct statement: “The product’s thermal efficiency is X%”.
- Baseline for comparison is implied as the input energy of the system.

Comparative technology:

- Amount of energy consumed by new system compared to a baseline consumption of another verified system.
- For cookstoves, an unverified product’s consumption is compared to the statistically verified performance of another product.
- Typical correct statement: “Product A is X% more efficient than Product B”, where the thermal efficiency of B has been verified.
- Baseline for comparison must be clearly stated.

Comparative fuel use (similar to 2):

- Amount of fuel consumed by new system compared to the fuel used by a less efficient baseline system.
- For cookstoves, an unverified product’s fuel consumption is compared to the statistical baselines of another product’s fuel consumption for the same task or activity.
- Typical correct statement: “Product A uses X% less fuel than Product B”, where the fuel consumption of B has been verified.
- Baseline for comparison must be clearly stated.

6.2. EFFICIENCY TESTS

Due to a variety of efficiency claims in the cookstove industry, several standardized efficiency tests and protocols have been developed in order to compare cookstove performance. The Global Alliance for Clean Cookstoves [9] has created widely accepted efficiency tests and tools [10] which define the industry standard for efficiency claims. The water boiling test (WBT) is useful to determine the stove's thermal efficiency, and controlled cooking test does test the stove's performance for typical region-specific operations. Apart from these rigorous testing and validation methods, the alliance has also outlined less complicated water boiling tests that can be performed by low-skilled technicians to provide acceptably consistent efficiency results. [11]

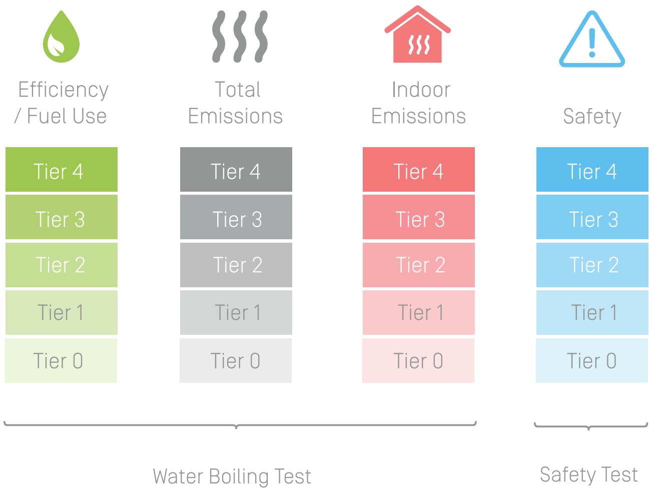

Figure 9: Efficiency evaluation criteria as set forth by the Global Alliance of Clean Cookstoves [12]

	High Power	Low Power
	Thermal Efficiency [%]	Specific Consumption [MJ/min/L]
Tier 0	< 15	> 0.050
Tier 1	≥ 15	≤ 0.050
Tier 2	≥ 25	≤ 0.039
Tier 3	≥ 35	≤ 0.028
Tier 4	≥ 45	≤ 0.017

Table 2: Efficiency evaluation criteria as set forth by the Global Alliance of Clean Cookstoves [13]

It is essential to realize that human behaviour directly influences the performance of the multi-variable cooking operation. [14] The energy efficiency of a clean cookstove is not only device dependent, but is significantly influenced by the user's fuel measurements and operation. This fact is demonstrated in Figure 8, which indicates the significant efficiency difference between a well-tended open fire (25% efficient) compared to a neglected three-stone fire (5% efficient).

Given that cookstove efficiency is usage-dependent, some tests advocate efficiency measures for cooking typical dishes. Heterogeneous Testing Protocols [15] refer to testing a device at all the power levels with different sized pots of water. These protocols are modelled on culturally appropriate cooking practices.

9 http://cleancookstoves.org/technology-and-fuels/testing/protocols.html
10 Global Alliance for Clean Cookstoves, The Water Boiling Test, Version 4.2.3, 19 March 2013, Source: http://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/399-1.pdf
11 GERES Research and Development Unit, Adapted Water Boiling Test (Awbt), Code AWBT v2.0; https://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/75-1.pdf
12 http://cleancookstoves.org/technology-and-fuels/standards/iwa-tiers-of-performance.html
13 Section 4.2; http://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/6-1.pdf
14 pg 9, Figure 1.5, Micro-gasification: cooking with gas from dry biomass; An introduction to concepts and applications of wood-gas burning technologies for cooking; 2nd edition; Released by GIZ
15 www.setarstoves.org

7. FURTHER CONSIDERATIONS FOR CURRENT COOKING METHODS

7.1. FUEL WASTE

Due to the inherent variability in the grade and mass of the foodstuff to be prepared, the grade and mass of the fuel, and the human control of the cooking process, there is an inherent risk of miscalculating the amount of fuel that is required for a specific cooking activity. Even if a cookstove is highly efficient, waste is often inevitable. [16]

This waste is typically avoided through trial and error optimization, whereby a household will know exactly how much foodstuff has to be prepared, and will be familiar with the exact amount of fuel and cooking time that is required to prepare the specific amount of food. For new users, training and education is essential for cookstove use.

7.2. EE CLEAN COOKSTOVE APPLIANCES

Several clean cookstove manufacturers offer appliances that aid with cooking efficiency. The most common of these appliances is a pot skirt, which ensures that convective heat from the fire is directly channelled onto the pot, instead of being lost to the environment. [17] Pot skirts also shield unwanted drafts and wind, which further improves the thermal efficiency of a stove. [18]

7.3. HEAT RETENTION COOKING

Heat-retention cooking is a concept which compliments energy-efficient cookstoves. As soon as a pot comes to the boil, all further energy that is applied to the pot during the simmering phase is equivalent to the amount of energy that is lost from the pot due to thermal radiation, convection and steam. Heat-retention cooking saves significant amounts of energy and water. [19]

Figure 11 shows the energy improvements that are achievable by employing heat retention cookers in combination with normal low-cost cooking methods.

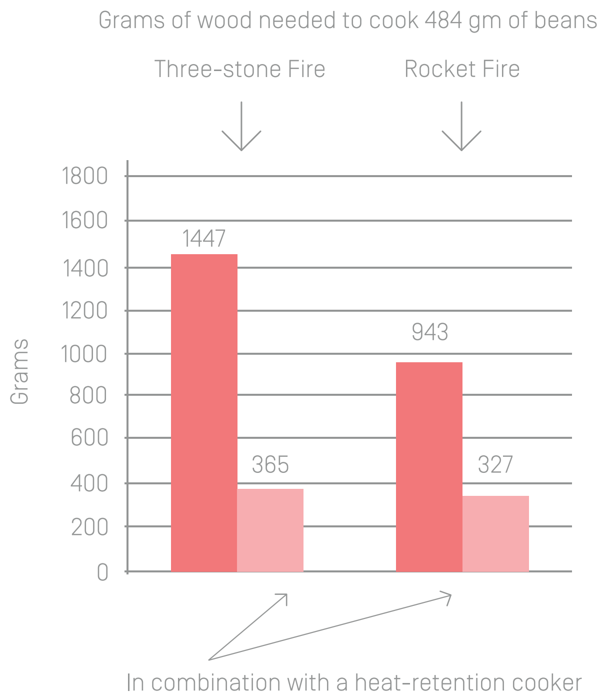

Figure 11: Fuel/Energy savings due to heat-retention cooking. [20]

[16] pg 2, Chapter 3; A report of laboratory test results of the FIVE STAR® stove; SeTAR Centre, University of Johannesburg; 2014

[17] pg 13; http://envirofit.org/wp-content/uploads/2016/07/Envirofit_2016_Product_Catalog_web.pdf

[18] pg 21; Clean Burning Biomass Cookstoves; D Still et all; Aprovecho Research Center; CleanBurningBiomassCookstoves_2016.pdf

[19] pg 2; https://energypedia.info/images/0/0b/HIHK-EU_2011_en_manual_how_to_make_a_heat_retention_bag_tjk_pak.pdf

[20] D Still et all; Aprovecho Research Center: Fuel-efficient Woodstoves and Hayboxes

This material has been funded by the Governments of Finland, the UK, and Austria. The views expressed do not necessarily reflect the donor governments' official policies.