# Bakeries cooking on biomass in Ethiopia: a matter of climate and indoor air pollution

## An observational study investigating the climate and health related issues of indoor open fire cooking in Ethiopian bakeries

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Background picture by: Leon Simons (2015)

# Abstract

This study set out to assess the impact of preparation of the number one staple food of Ethiopia, the Injera. As many of the Injera stoves (also called mitads) are fired using solid biomass fuel, low efficiency and indoor air pollution are common. Previous literature has focused on household stoves and indoor air pollution only, whereas this paper investigates the issue in commercial bakeries in the city of Addis Abeba. To assess indoor air pollution, Particulate matter smaller than 2.5µm ($PM_{2.5}$) has been measured using personal exposure measurements and ambient indoor air pollution in bakeries. Climate impact is assessed using a Material Flow analysis of the stoves, coupled with fuel or energy use of different stove types. Data was collected from bakeries in different sub-cities of the city of Addis Abeba between December 2015 and May 2016, where 15 bakeries were using biomass and 15 were using electricity as heating source. In this research the benefits of a transition to electric cooking are quantified, and barriers for implementation were identified. The energy use of stoves can potentially be reduced by up to 95% when switching to efficient electric stoves, reducing lifetime climate impact per stove by up to 98%. The reduction in indoor air pollution that is accompanied by a switch to electric cooking leads to an almost threefold reduction in $PM_{2.5}$ concentrations in bakeries (geometric mean level biomass: 394 $\mu g/m^3$, electric: 134 $\mu g/m^3$), and an almost twofold reduction in personal $PM_{2.5}$ exposure among bakery employees (geometric mean level biomass: 415 $\mu g/m^3$, electric: 216 $\mu g/m^3$). This research shows the importance of a transition to electric cooking in Ethiopia and could be used in the future to assess economic and occupational health impact of a transition as well.

# Contents

# 1 Introduction

## 1.1 General background

Nearly half of the world's population is either cooking or heating their home with open fires or simple stoves using biomass (WHO, 2014). In many developing countries, especially in Africa, over 90% of household energy consumption comes from these biomass-fired cooking practices (IEA, 2006). Biomass-fired cooking stoves have several issues: the stoves are resource inefficient (Ballard-Tremeer, 1997) and they are a major source of both ambient and indoor air pollution. Especially indoor air pollution is problematic, as this is a known cause of respiratory disease and detrimental to public health (Bruce, Perez-Padilla, & Albalak, 2000; Smith & Mehta, 2003). The issue of indoor air pollution mainly occurs in developing countries and low-income areas in urban environments (Gordon et al., 2014; Ni et al., 2016; Wangchuk, He, Knibbs, Mazaheri, & Morawska, 2016). Lastly, there is also an increased risk of injury and death by direct smoke inhalation and burns (Peck, Kruger, van der Merwe, Godakumbura, & Ahuja, 2008).

One of the countries where indoor open fire cooking stoves are still highly prevalent is Ethiopia. Ethiopia is a country in Sub-Saharan Africa with an estimated population of 100 million people (CIA, 2015) of which most rely on biomass for their daily energy needs. In fact, 99% of residential energy consumption in Ethiopia is from biofuel and waste, which in turn is 92% of total end-user energy consumption (Guta & Börner, 2015). Switching from low-efficiency biomass stoves to an alternative with higher efficiency, could reduce the country's energy and material use, as well as reduce climate impact and improve the health of their inhabitants.

In Ethiopia, the main staple food is Injera, Injera is a large, pancake-like bread and it is part of almost every meal. It requires a specialized stove called a Mitad to prepare, which used to be part of almost every household. Education and increased investments in the micro- and small enterprise sector have led to a shift from household cooking to more centralized, larger bakeries serving more than just one family (Chacko & Gebre, 2012). This shift leads to changes in the impact of biomass cooking, as centralization of baking leads to more intense use of stoves, which allows fewer people to be exposed to the indoor air pollution the traditional biomass stoves cause.

Furthermore, the shift from households to bakeries is an opportunity to professionalize the process of baking Injera. Because of this, it is a relevant subject to study in relation to the possible improvement of working conditions and the impact on environment and efficiency. Bakeries differ from households in terms of the times the stoves are operated, how they are furnished, their arrangement/size and their ventilation characteristics. It is expected that even though bakeries usually have some measures to reduce indoor air pollution, the longer duration of exposure and extra stoves lead to higher pollution levels than in households (Rollin, Mathee, Bruce, Levin, & von Schirnding, 2004).

In comparison to electrical stoves, stoves that use biomass are low-efficiency sources of heat and they are also producers of airborne pollutants (Ballard-Tremeer, 1997; Danas Electrical Engineering, 2015).

This means that a large-scale transition away from biofuel could lead to a vast improvement in energy and material efficiency, provided that the electricity production is efficient as well. Replacing biomass fuels by clean technology significantly reduces the use of biomass fuels such as wood or charcoal and leads to less deforestation(Fullerton, Bruce, & Gordon, 2008; Miah, Al Rashid, & Shin, 2009).

However, electric stoves have their own issues. Many areas in Ethiopia are not connected to the grid (yet) but are dependent on local micro grids, so total electric capacity is often very limited and sometimes even entirely absent (Gärtner & Stamps, 2014). Because of this, electricity consumption should be as efficient as possible. Also, since electricity generation in Ethiopia is generated for more than 99% from renewable sources (IEA, 2014b), the climate impact reduction when switching to efficient electric stoves is highly significant. This is why the Dutch start-up company Magic Ventures© has developed a new electric Injera cooking plate, making use of different materials and an altered design compared to the current electrical stoves, to optimize the efficiency of Injera baking. This efficiency is an essential difference, as electric stoves have been around for a long time, but due to their low efficiency they have high operational costs, use more energy than necessary, and prevent fast, large-scale implementation (Alem, Hassen, & Köhlin, 2013).

## 1.2 Research aim

The aim of this research is to compare three types of mitads (biomass-fired, traditional electric and high-efficiency electric) on the:

1) Impact on a national level (in Ethiopia), in terms of primary energy use and greenhouse gas emissions

2) Implications for the national electricity generation sector

3) Barriers to implementation of a large-scale electrification in the cooking sector

4) Impact on exposure to indoor air pollution in bakery employees

## 1.3 Research Questions

The following research questions are addressed in this study:

### 1.3.1 Main Research question

*What is the possible impact of the implementation of efficient electric stoves on the Ethiopian climate impact and on indoor air pollution inside bakeries?*

### 1.3.2 Sub-questions

1. *What are the realized savings on energy and materials compared to current cooking methods when a switch to efficient electric cooking is made?*

2. *What is the renewable electricity potential of Ethiopia, and what would a large scale transition to electric cooking mean for the power sector?*

3. *To what extent is electric Injera cooking an alternative to current cooking stoves in practice?*

4. *To what extent is the type of Injera stove used in Ethiopian bakeries associated with the concentration of indoor air pollutants?*

## 1.4 Scientific relevance

This research contributes to uncovering the unknown impacts on indoor air pollution, energy use and related greenhouse gas emissions of the different cooking methods used to prepare Injera in Ethiopia. Results of this study can improve maternal and child health[1] (public health) and reduce the use of solid fuels (environmental sustainability). Even though there have been research projects concerning biomass fuel and indoor air pollution in households (Akhtar, Ullah, Khan, & Nazli, 2007; Po, FitzGerald, & Carlsten, 2011; Saud et al., 2012), to the best of the author's knowledge there is no previous research conducted on indoor air pollution and climate impact of bakeries utilizing biomass. Due to the high prevalence of biomass cooking in Ethiopia and the shift from household cooking to bakeries, the total impact on the country's climate impact and respiratory health is expected to be significant. Among the main knowledge gaps that need to be filled according to literature are intervention studies to test the effect of technological and behavioural interventions and exposure assessment in different settings to aid epidemiological study (Fullerton et al., 2008), making this research highly relevant.

This study also doubles as a preliminary study to conduct a larger scale study in this setting. In such a study not only in the capital city of Addis Ababa, but also the rural areas and other regions of Ethiopia would be investigated. This can form a more coherent and complete view of the situation in Ethiopian bakeries spread across the country. Moreover, the pilot study will be used to set up collaboration between occupational and environmental health groups in Utrecht and Addis Ababa, and an innovative start-up that wants to introduce a new, fuel-efficient mitad ("Magic Mitad") in Ethiopia. This study builds a foundation to be able to investigate acute and long-term health effects of bakery workers and accompanying children in Ethiopia.

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[1] Young children are often taken care of by the mothers and are often in the same room as the mother while preparing the Injera

# 2 Theory

## 2.1 Energy and Material theory

In Africa, the consumption of bioenergy is higher than that of all other energy sources combined. However, because of their low efficiency and emission of airborne pollutants, and also because of the increasing supply of appliances relying on electricity, electrification is rapidly accelerating (See section 1.1). Almost one billion people are projected to gain access to electricity in sub-Saharan Africa in 2040 (IEA, 2014a). Shaping this rapid electrification is a relevant issue, as there are worldwide debates on the long term sustainability of the use of fossil fuels. Combining the electrification of sub-Saharan Africa with generation of renewable electricity could make a major difference in the use of fossil fuels and Africa's $CO_2$ emissions in the coming years and the effect on both local- and global climate.

In Ethiopia there is large potential for renewable energy sources. Even though total energy consumption comes largely from biomass, the small part that is currently electric, is produced for over 99% from hydropower and wind (IEA, 2014b). The trend in installed renewable electric capacity is also strongly upwards, as can be seen in Figure 1. This high share of renewable electricity generation means that any appliance using electricity instead of other energy sources (e.g. Kerosene, charcoal and even biomass) is often better for the environment than non-electric alternatives. Therefore compared to electrification in other countries, transitioning to electric cooking in Ethiopia could have the strongest positive impact. As cooking is the largest contributor to total energy use in Ethiopia (IEA, 2006a), this is the most important sector when it comes to research on energy use and efficiency.

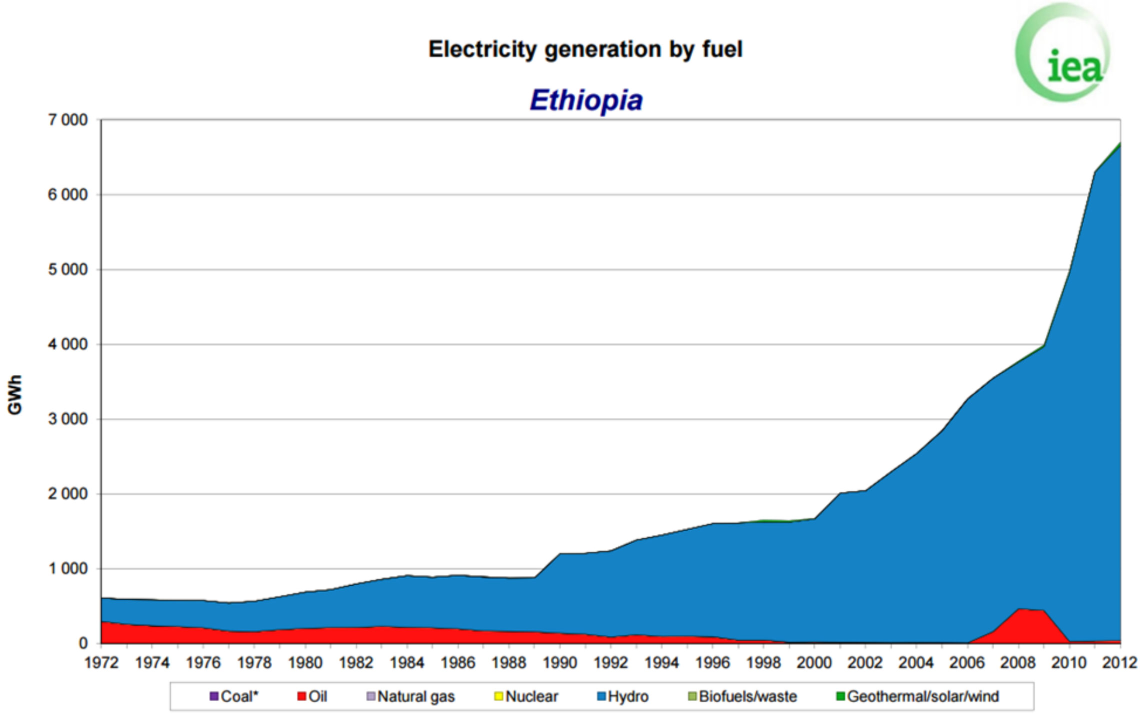

**FIGURE 1 ETHIOPIAN ELECTRICITY GENERATION BY FUEL** (IEA, 2014b)

If an insight into the Ethiopian electricity network of the future is to be obtained, examining the cooking sector more closely can provide a better understanding into what the current developments are and how they might be shaped in the future. A trend in Ethiopia is the rise in the number of small manufacturing plants and other small businesses (Nyagah, 2013). A consequence of this is also the increase in centralization of baking Injeras, shifting from decentralized production in households to a more centralized system where production takes place in bakeries. Production in bakeries can also be done more efficiently, for example because they require less warm-up time per Injera due to their higher production volume. Because of this, Injera can be produced at lower costs than they can be produced at home, this is a possible reason for this transition to more centralized production.

Bakeries have several characteristics which make them a relevant topic to study, especially regarding the possibilities to improve efficiency on a larger scale, with smaller relative investments. Bakeries can have multiple stoves in one room, stoves are operated more intensively, operating times are different and experienced staff is making use of the equipment. An example of a large electric bakery and a small biomass bakery are shown in Figure 2 and Figure 3. Durability and efficiency can have a major impact on their lifetime costs, as well as on climate and health impacts caused by the total amount and type of fuel used to operate the stoves.

FIGURE 2 LARGE ELECTRIC BAKERY, ALSO SHOWING $PM_{2.5}$ MEASURING EQUIPMENT BACKPACKS (OWN PICTURE)

FIGURE 3 SMALL BIOMASS BAKERY (LEON SIMONS 2015)

In Figure 4 a simple calculation of one of the savings made by centralizing the Injera production is depicted. Because the mitads need a high temperature before they can be used for baking Injera, the warm-up time can be around half an hour as in conventional mitads, both electric and for other types of fuel, a big clay plate needs to be heated. This example is chosen as this characteristic is directly related to energy use. It shows that for producing thousand Injeras, centralized production requires 75% less energy for warming up the plate and also 90% less mitads are needed. This greatly reduces the energy use, material use and climate impact of the Injera production chain.

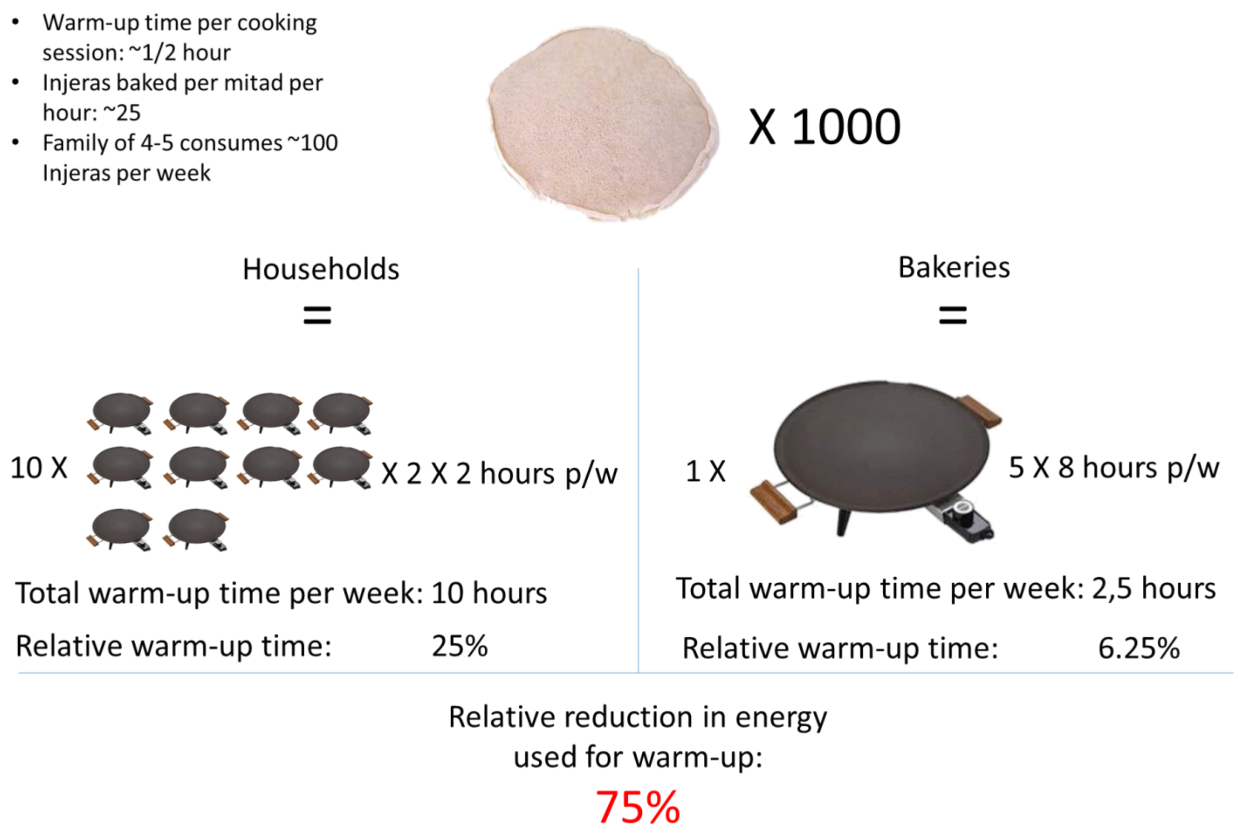

FIGURE 4 COMPARISON OF HOUSEHOLD INJERA PRODUCTION AND CENTRALIZED INJERA PRODUCTION

In this example working days of 8 hours are assumed for the commercial bakeries, but there are even examples of bakeries that use the mitads for 24 hours per day, thus almost completely eliminating the warm-up time.

Earlier studies have shown that switching from solid fuel stoves or open fire cooking to electric stoves could greatly improve energy efficiency and reduce pollutants in many developing countries (Danas Electrical Engineering, 2015). Looking at fuel use, wood stoves have a conversion efficiency of 15%, and charcoal stoves have an efficiency of around 30% whereas Electric stoves with can have a conversion efficiency of 70% or even more when an efficient design is used (Danas Electrical Engineering, 2015; Jones, 2015). The potential savings when using electric stoves could therefore be significant.

In order to assess the energy and material impact of different cooking stoves mass balances need to be calculated. This theory is based on the law of conservation of energy, from which the law of conservation of mass was derived. By taking into account the materials flowing in and out of a system, mass flows can be identified which provide insight into the use of materials and energy in for example the production and lifetime of a specific product (Himmelblau, 1967).

The equation depicting the mass balance of a system is as follows (Equation 1):

$$Input = Output + Accumulation$$

**EQUATION 1 MASS BALANCE EQUATION** (Himmelblau, 1967)

For the production and lifecycle of Injera stoves the mass balance can be divided into different steps or activities. Every activity requires energy and produces waste, minimizing how often the steps are taken and reducing the flows for each step leads to higher life cycle efficiencies. The first activity is material acquisition, which includes mining and refinement of raw materials. The second activity is material manufacturing, where the raw materials are turned into the materials necessary for production such as plastics and steel sheets. Then the third activity is product assembly, where the processed materials are combined to make the finished product. When the product is finished, the fourth activity is the use-phase, in this phase the intended purpose of the product is utilized, until it breaks or becomes obsolete for the intended purpose. The last activity is the disposal phase. In this phase the product is no longer used in its current form. In this phase there are four possibilities, or sometimes a combination of these possibilities:

1. The product can be re-used: no or minor changes to the product are made
2. The product can be recycled: some parts are re-used and re-assembled into a similar product
3. The materials will be recycled: No parts are re-used, but instead materials are collected from the product and used again in other products
4. Parts end up as waste and are no longer part of the material cycle

A graphic representation of what the mass balance looks like is shown in Figure 5, the green boxes represent activities, yellow arrows represent a flow of energy and grey arrows a flow of both energy and material:

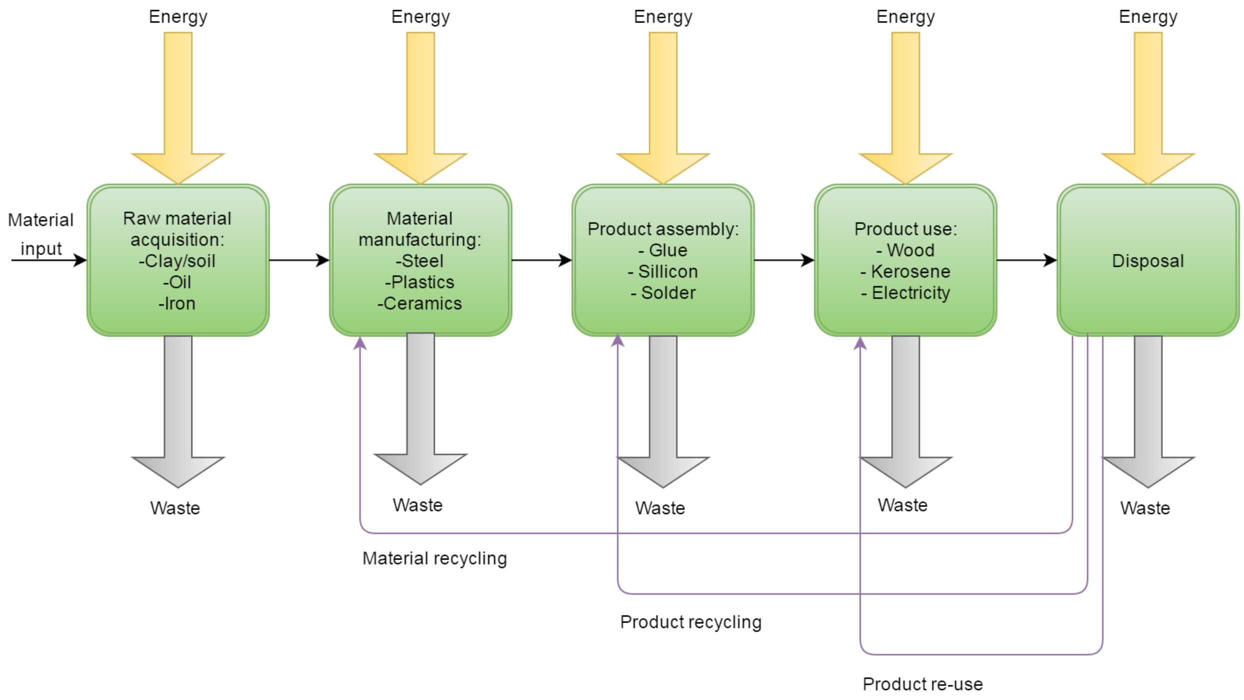

**FIGURE 5 THEORETICAL MASS BALANCE FLOWCHART FOR INJERA STOVES**

Assessing all the flows in this diagram creates an insight into the type of materials that are used in every step of the life cycle. More importantly, it can also show the total emission equivalents at each step along the way by deriving this from the energy use and its associated direct emissions. By assessing the type of energy used in each step of the life cycle, related $CO_2$ emissions can be calculated using their emission factors (Equation 2):

$$Emission = Emission\ factor * Activity$$

**EQUATION 2 EMISSIONS FROM ENERGY USE** (Department for Environment, n.d.)

Adding up all the emission equivalents from the different steps leads to a cradle-to-cradle or cradle-to-grave analysis. Data on the end-of-life/disposal phase in the case of the stoves is not available as there is no standard disposal/repair/recycling system in place in Ethiopia, therefore only known recycling rates are used in the study. The analysis provides a measure to compare different stoves on their lifetime impact in terms of total $CO_2$ emissions, which leads to the potential climate impact improvements on a national scale for different levels of penetration per stove type.

## 2.2 Pollution and Exposure theory

The use of biomass as cooking (and heating) fuel and the related pollution is a major issue in Africa (Staton & Harding, 1998). Using solid fuels in stoves leads to many types of pollution, particulate matter 2.5µm or smaller in size ($PM_{2.5}$) being the most significant when it comes to health implications (Atkinson, Kang, Anderson, Mills, & Walton, 2014). $PM_{2.5}$ forms via numerous combustion side-reactions. Particulate matter becomes more dangerous as the particles get smaller, as they increase in potential to cause adverse health effects as they travel further into the respiratory system (Harrison & Yin, 2000). The deposition potential for the different sizes of PM is displayed in Figure 6.

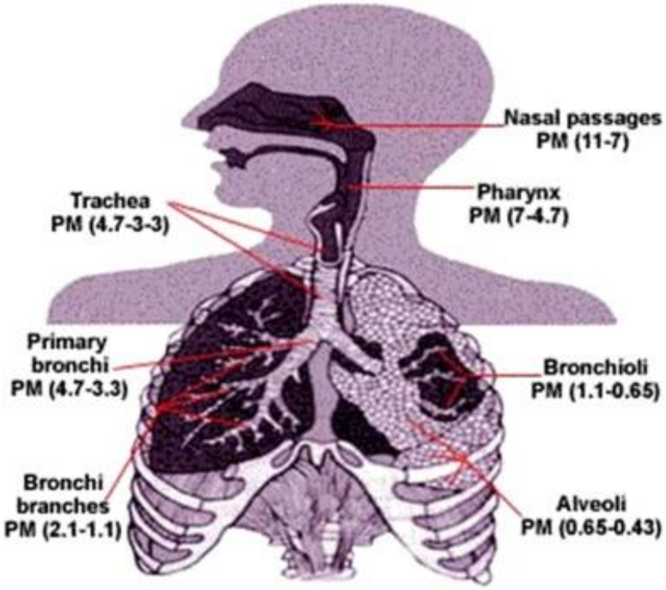

**Figure 6 Deposition potential for different PM particle sizes** (Kim, Kabir, & Kabir, 2015)

Exposure to PM is known to cause several harmful health effects, this includes an increase in the severity of chronic respiratory and cardiovascular disease, decrease in lung function and premature mortality (Kim et al., 2015). For this reason it has been under scrutiny in many studies, focusing on long- or short-term exposures (Kloog, Ridgway, Koutrakis, Coull, & Schwartz, 2013; Po et al., 2011). In the meta-analysis by Po et al., exposure to short term high-concentrations of PM exhibits increased odds of developing acute respiratory infection in children by a factor of 3.43 (also known as an odds ratio of 3.43). In women, an increase in prevalence of chronic bronchitis and COPD by a factor of 2.52 and 2.40 respectively is reported.

In the study conducted by Kloog et al. (2013) the effects of short- and long-term exposure are reported. Short-term exposure leads to an increase in mortality of 2.8% for every $10 \mu g/m^3$ increase in $PM_{2.5}$ concentration. For long-term exposure, the odds of developing particulate matter related diseases increased by a factor of 1.4 for every $10 \mu g/m^3$ increase.

In a study specifically focused on households in Ethiopia using biomass fuels for cooking, the geometric mean of $PM_{2.5}$ concentration has been measured to be $818 \mu g/m^3$ (Sanbata, Asfaw, & Kumie, 2014). At these high concentrations, $PM_{2.5}$ is known to cause a multitude of respiratory diseases and other health issues. There does not appear to be a reduction in $PM_{2.5}$ concentration when improved biomass stoves are used, compared to traditional biomass-fired stoves (ibid.). So this means that even improved, more efficient stoves using solid biomass cause hazardous indoor air pollution in the form of $PM_{2.5}$. This is also a reason to skip the transition to "cleaner" biomass stoves, and directly investigate the switch to electric stoves.

It is to be expected that the order of magnitude of $PM_{2.5}$ concentrations in bakeries using biomass fuels for cooking is the same as that in households. However, actual concentrations might be higher or lower than in households, due to the more intensive use of the cooking plates or because of a better design of bakeries regarding ventilation.

When biomass is burned in an open fire or in a non-optimal stove, the conditions for burning, also lead to incomplete combustion. This in turn leads to the emission of other gases than $CO_2$ due to the chemical process displayed in Equation 3:

$$C_xH_y + zO_2 \rightarrow aCO_2 + bCO + cH_2O + dH_2$$

EQUATION 3 INCOMPLETE BURNING OF HYDROCARBONS

Carbon monoxide (CO) poisoning is a well-known risk when short-term high doses of CO are inhaled, which is more likely at high concentrations. The first serious symptoms start occurring at 200ppm, causing a slight headache and possible loss of judgment (Goldstein et al., 2008). As CO is an odourless, tasteless and colourless gas, its effects are usually only discovered when it is already too late, and lead to permanent brain damage or even death (Harvard Health Publications, 2015). Chronic exposure to low concentrations of the gas can lead to vague symptoms which are easily mistaken for other common illnesses (Knobeloch & Jackson, 1999). Reducing CO concentrations to a minimum should therefore be a priority to bakeries and other environments where exposure to the gas can be expected.

The WHO recommends that the following exposure levels of CO are not exceeded:

- 87.1PPM for 15 minutes
- 52.3PPM for 30 minutes
- 26.1PPM for 1 hour
- 8.7PPM for 8 hours

At these concentrations and timespans, the biological marker (blood COHb levels) does not exceed 2.5%, which is the lowest measured concentration in the blood where effects on human subjects have been measured (WHO, 2004).

# 3 Methods

A pilot study targeting energy and material efficiency and indoor air pollution from different cooking methods in Ethiopian Injera bakeries was conducted. A combination of an observational field study measuring material use and energy use, air quality inside and outside the bakeries and a cross-sectional survey on bakery characteristics and health in Addis Ababa was used. The methods used are graphically represented in Figure 7.

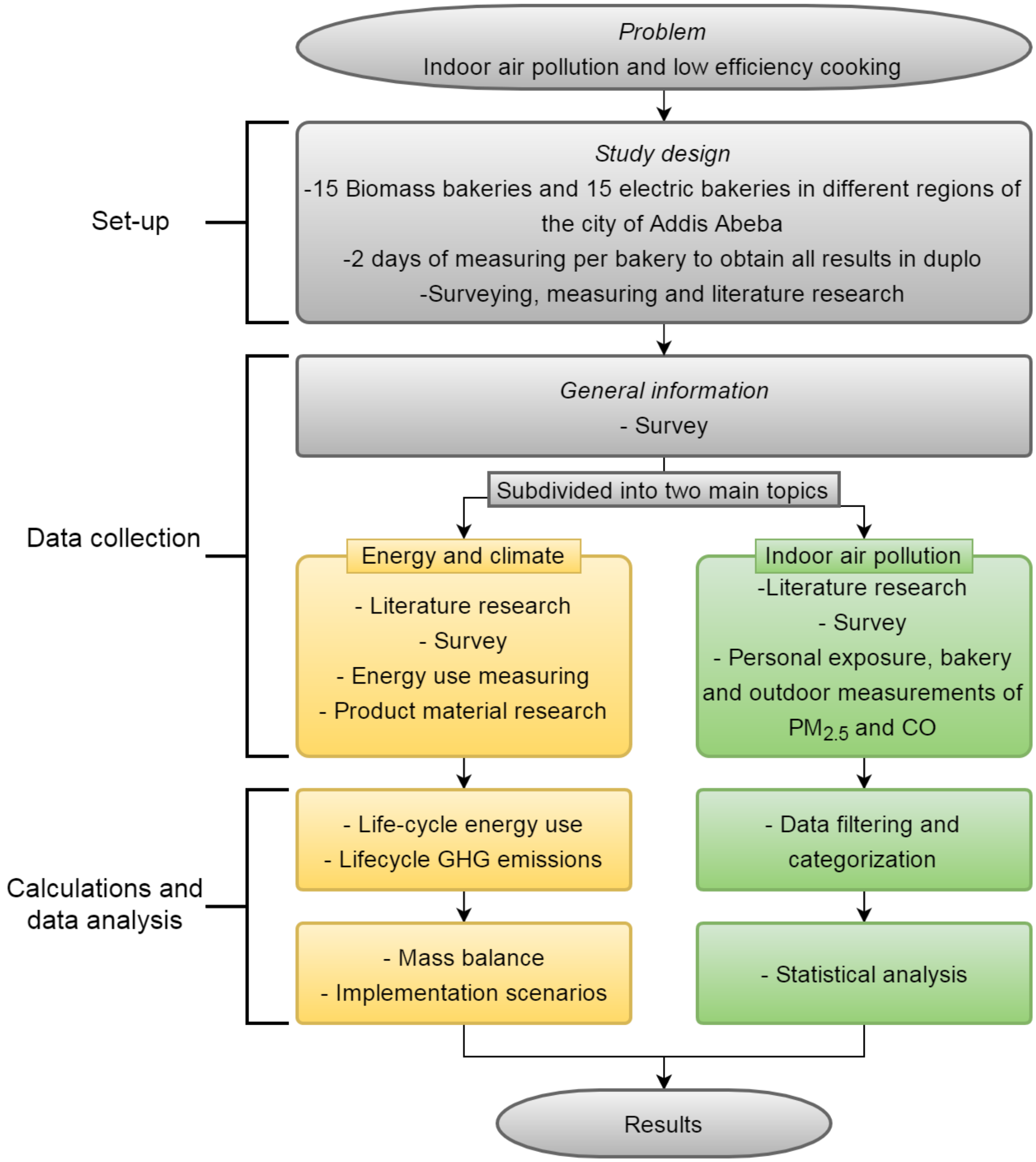

FIGURE 7 FLOW-CHART SUMMARIZING THE METHODS USED IN THIS STUDY

The grey shapes indicate similar steps for both parts of the research, where the yellow and green indicate a different approach for respectively energy and indoor air pollution related steps. This figure shows the chronological sequence of the methods. This report follows the same sequence with the exception of the “Calculations and data analysis” chapter, as the calculation steps are sometimes also performed during the analysis.

## 3.1 Set-up

During the research in Addis Ababa, a survey (Appendix I) was conducted among the women who work in the bakeries to gather general demographics, information on bakery characteristics, on working conditions and obtain health/respiratory system related data. This data was used to identify whether the bakeries were fitting to be part of the research.

To determine the energy and material use of the bakeries, a mass balance analysis of stove production was conducted. This leads to the total lifetime greenhouse gas (GHG) emissions ($CO_2$eq) of the production of different stove types, also known as embodied energy. This was then added to their fuel/energy use over their expected lifetime to determine the total climate impact per stove. This in turn is used again to determine the impact of more efficient stoves on a national scale in different scenarios of penetration of newer, more efficient cooking technologies. Using this mass balance analysis to assess where materials and energy are used in the lifecycle of the Injera stoves, the total lifetime $CO_2$ emissions are determined.

This research entailed measuring fuel inputs in the use phase, as well as collecting data on the material composition of different stoves used in practice and where possible their manufacturing process emissions. This lead to values for the following phases:

1. Emissions from material production
2. Emissions from assembly and manufacturing
3. Emissions in the use phase
4. Emissions in the end-of-life phase[2]

Combining these data, the total environmental impact in terms of $CO_2$ emissions of the different types of cooking stove was determined.

On the indoor air pollution data, measurements on both stationary and personal exposure are important to assess whether the concentration of pollutants is uniformly distributed, or whether the bakery workers are exposed to a greater or lesser extent depending on their location in the bakery. Air quality is measured in and around the Injera bakeries to determine the difference in concentration of air pollutants between bakeries using biomass-fired and electricity-powered mitads. If there were other

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[2] Data on the end-of-life phase of the stoves is incorporated in the recycling values mentioned later in Table 4

known sources of $PM_{2.5}$ or CO in the bakery (e.g. open fire, other biomass stoves and coffee on charcoal), this was registered so this can be accounted for in the data analysis.

### 3.1.1 Subjects

Bakeries that were identified had to meet the following requirements that were set to fit the definition of bakery and be eligible for the study:

- They have to sell Injera to people outside their family on a daily basis
- They use either biomass or electric stoves
- They are willing to cooperate on all aspects of the research

Subjects that met the requirements for this study were obtained in five different ways:

1. Lists from governmental (sub-city) offices (only licensed, and in general larger bakeries)
2. Asking shops and restaurants that sell Injera who they buy from and grinding mills who they sell to
3. Asking the bakeries if they have relatives and acquaintances active in Injera bakeries.
4. Asking around on the street
5. For biomass bakeries only: Checking out places in the street that have smoke coming out of the building (usually out of chimneys) if they are Injera bakeries

The different methods were chosen to make sure not only the official, registered bakeries would be part of the research. Another reason the different methods were used is because not all administration offices were willing to cooperate, so it was a necessity to be able obtain bakeries in the different sub-cities in the city. For more information on how cooperation from the subjects was obtained, refer to Appendix IV.

All measurements were completed *in duplo*, where the second measurement was always within one week of the first measurement. A summary of the collected samples is given in Table 1. As selecting the study sample of local bakeries was not possible from a long distance, this was arranged *in situ*. This research is also used as preliminary study for future research on a larger scale, thus the selection was based on obtaining a diverse sample with different types of Injera stoves as selection criterion, being electric or biomass-fired. The sample size was chosen because this sample size was sufficient to discover statistically significant results according to a power analysis based on initially expected results.

TABLE 1 BAKERIES ASSESSED, SUBJECTS SURVEYED AND $PM_{2.5}$ SAMPLES TAKEN DURING THE RESEARCH

|  | **Amount** |
|---|---|
| **Bakeries assessed** |  |
| **Biomass (Lakech)** | 15 |
| **Electric** | 15 |
| **Total** | 30 |
| **Subjects surveyed** |  |
| **Exposure measured** | 39 |
| **No exposure measured** | 4 |
| **Total** | 43 |
| **$PM_{2.5}$ Samples taken** |  |
| **Personal** | 64 |
| **Bakery** | 56 |
| **Outdoor** | 38 |
| **Other**[3] | 30 |
| **Total** | 188 |

## 3.2 Data collection

To answer the research questions, different measures and metrics have been used to assess the performance of the three different stoves and bakeries in terms of indoor air pollution, energy and material use and climate impact. Details on the tools, measures and metrics used can be found in Appendix II

### 3.2.1 Use of instruments

*Survey*

The first tool that was used is the survey. This survey has passed criteria for ethical clearance from the Addis Abeba University and was approved. Informed consent was obtained from all subjects, after which the survey questions were asked as they are posed in the survey (Appendix I). The questions were asked while the women were baking, so they did not use extra time to answer the questions. The survey's questions were divided into four categories:

1. Demographical information
2. Personal working conditions
3. Bakery characteristics

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[3] Blancs, Duplicates and failed measurements

4. Respiratory symptoms and health[4]

The questions in category 1 were used to determine the demographics of the employees, questions in category 2 were mainly used to assess personal impact of working in a bakery and the questions in category 3 were used to obtain more detail on the differences and similarities between bakeries.

*kWh meter and clamp meter*

When the bakeries made use of electricity to power their mitads, the electricity was measured using a kWh meter wherever possible, and if this was not possible the clamp meter was used. The direct kWh meter is preferred because this is the most accurate and reliable way of measuring kWh consumed over a period of time. However, due to limitations in the bakery, such as a lack of plugs for the mitads or unsafe conditions, this method is not always possible.

When the kWh meter was used, it was plugged into the wall socket, and the mitad was then in turn plugged into the kWh meter. Then for the duration of the baking session, the amount of Injera baked was counted, and the weight of the Injera was also determined using a scale in the bakery or the portable scale. With this information the amount of kWh per Injera and per kg of Injera was obtained.

When the kWh meter could be used, the clamp meter was used instead. The clamp meter measures current using the magnetic field that a flowing current causes. This means that the current could be measured without having to touch the wires connected to the mitad, greatly enhancing safety and usability. The potential was then measured directly after by plugging the measuring wires into a wall-socket in the same building. The current and potential were measured at the beginning of the baking session, and also when the baking session nears an end. If the baking session was expected to be longer than 4 hours, an extra measurement in the middle was done to enhance accuracy. Taking the average of the measured power, multiplied by the baking time lead to an estimate of the consumed electricity for that baking session.

*Weighing scale*

When a bakery was not operating electric mitads, but used biomass, the mass input and type was measured where possible. Only when bakery was using measurable units with a clear reference (i.e. ‘2 sacks per day’ ‘100kg per 200 Injera’) then the fuel was weighed using the digital scale and fuel type was noted. If there was no unit with clear reference available, the amount could not be reliably obtained, and only fuel type was noted. The scale was calibrated to 0 for every measurement, then the sack/stack/box of fuel was weighed by pulling up the scale until the fuel lifts, then the value on display was read and written down. When the weight was beyond 40kg, or was not measurable using a hanging scale, a locally available scale was used.

*PM2.5 Measurement backpacks and CO dositubes*

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[4] The questions in category 4 are not within the scope of this research and are therefore not elaborated on further in this paper, they will be assessed in a follow-up study.

Before each measuring day, for every required measurement location (personal, bakery, outside) a pump was randomly selected from the pool of working pumps and combined with a battery that held enough charge for the maximum expected runtime. When the pump was assembled it was tested with a calibrated "Sho-Rate Flow-meter" to determine whether the pump was able to pump the right amount of air for the measurements. After this test, the equipment was stocked inside a small backpack. For all types of measurement, the equipment is put inside a backpack, as this was the most convenient way for all types to find a suitable location to put/hang the equipment. Filters with filter canisters can be prepared at any time, as long as they are stored in the same way as the unprepared filters.

On the measuring day, a logbook is filled in with details on pump, battery, backpack and filter number, breaking time of the dositube and flow rate. The dositubes were attached to the backpack, facing away from the nozzle, to obtain a passive sample as instructed in the user manual of the dositubes. The flow rate was measured on-site and adjusted to 72.5 on the Sho-rate meter which corresponds to the 3.5l/min that is required to collect the correct particle size on the filter.

To make sure all circumstances are kept as constant as possible in the different locations, specific procedures for timing and placement were adhered to that can be found in Appendix III

## 3.3 Calculations and data analysis

### 3.3.1 Energy and Materials

#### 3.3.1.1 Mass Balance

With the data that was obtained on the flow of materials used in the production, maintenance and end-of-life, material flows were calculated and a mass balance analysis is conducted for the traditional biomass mitad and a regular electric mitad. All materials were listed and ordered into the right phase of a figure showing the different product phases and Figure 5 was used as a blueprint to create a mass balance. Due to the nature of the data available the raw material acquisition, material production and assembly phases were pooled together as production-phase in the results section, this lead to the new blueprint shown in Figure 8.

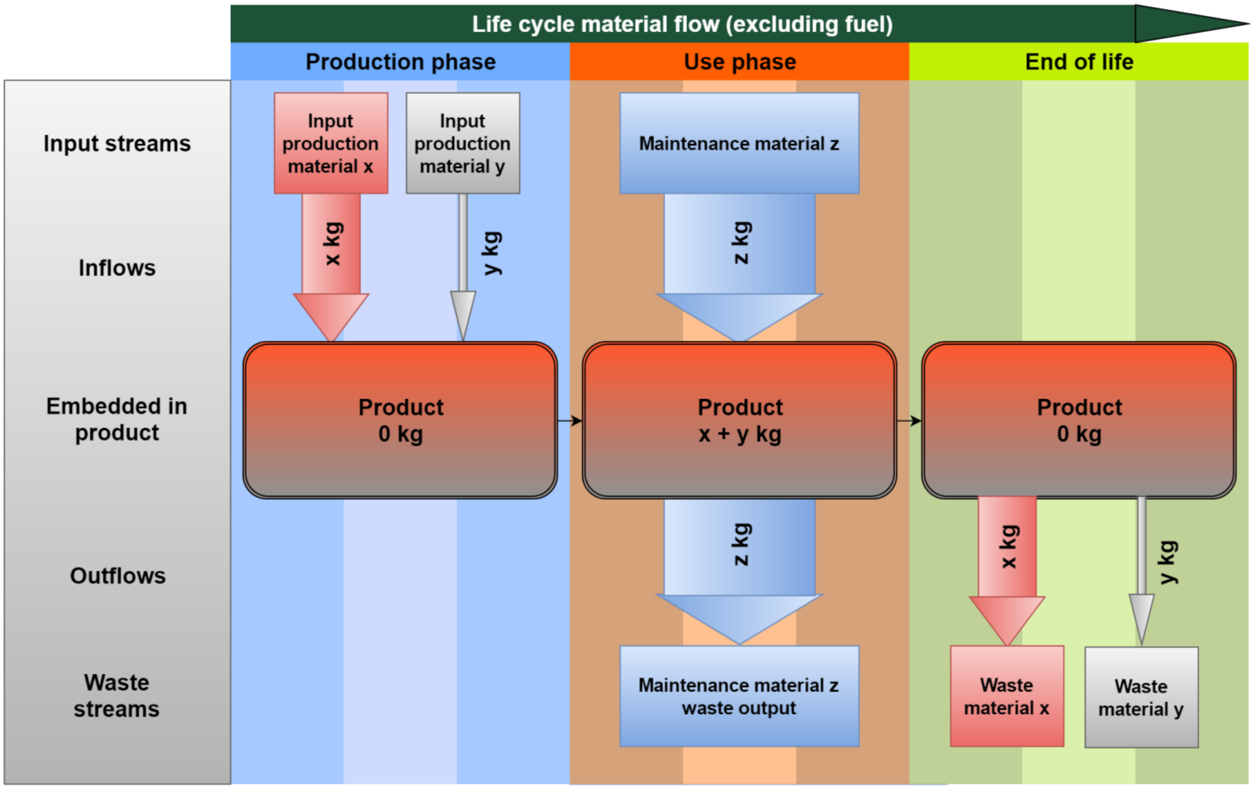

FIGURE 8 GENERALIZED MASS BALANCE EXAMPLE

In this figure, the three lifecycle phases are shown in the 3 coloured columns, and the position in each column indicates what the value means, shown on the left grey column. The 0kg product in the production phase and end of life phase indicates that the loop starts and ends with no products outside of the loop. The product weight in the middle column indicates the weight of the actual product

Equation 1 shows that in a system which is not gaining more mass (Accumulating), output equals input. When the output of the system over the entire life-span is added up, total material use is given. Then in turn using Equation 2 and data from literature (Table 20) were used to determine GHG emissions from the embodied energy of the stoves. For the mass balance analysis in this paper, the consumption of materials in the different phases is separated into two main categories: The physical product and the fuel usage. This separation is necessary as in the use phase (specifically for the biomass stove) so much material was used that none of the other streams would have been visible in a representation.

#### 3.3.1.2 Embodied energy and climate impact per stove

By multiplying the specific energy use of the stoves measured during data collection by the average expected use per year, the yearly production and fuel use were determined. Multiplying this fuel use for each stove with the emission factor (Equation 2) of either biomass or Ethiopia’s electricity grid, total climate impact per stove was calculated.

#### 3.3.1.3 Current power system in Ethiopia

To obtain data on the current Ethiopian power system, literature sources providing information on Energy production, available capacity, amount of connections etc. were consulted to determine what the boundaries for a transition to an electrified cooking system in Ethiopia are. Data from scientific sources was pooled with announcements and news media to obtain an estimate on future capacity increases as well. Calculations using the obtained data allowed for comparison between the different possible scenarios discussed in the following section.

#### 3.3.1.4 Scenarios

To be able to make predictions on the potential national impact on energy use and climate in Ethiopia, 6 scenarios on penetration of stove replacement were examined:

3 of the scenarios focused on 10% penetration, 50% penetration and 100% penetration of a regular electric mitad and 3 scenarios focused on a high-efficiency mitad with the same penetration levels. These values for penetration were chosen because 100% is the maximum theoretically obtainable value, 50% is close to the current electricity availability of 55% in Ethiopia (The Ethiopian Herald, 2015) and the 10% scenario was added as worst-case-scenario where the issue is not prioritized. The main focus here is what the national climate impact would be and whether the national power grid requires improvements in terms of generation capacity. The calculations were performed using Microsoft Excel's *analysis toolpak*, data obtained from the field and literature sources where measured data was not available.

The difference between the stove types in climate impact was then used to calculate the possible improvement in Ethiopia in different scenarios. By starting with the total energy currently used by biomass mitads (100%) and subtracting the energy use and climate impact from the biomass mitads that were replaced in the scenario, emissions from biomass in the scenario were given. By adding the energy use and impact caused by the replacement mitads, a new total impact was calculated. In the new situation, the total required electricity demand was also calculated by multiplying the amount of replaced mitads with their expected annual energy use.

### 3.3.2 Health and indoor air pollution

For the exposure measurements, statistical analysis was performed using several functions from the *analysis toolpak* in the Microsoft Excel software package. First, descriptive analysis was performed to determine how the data was distributed and what further statistical calculations are necessary. Descriptive analysis was stratified by stove type used (main determinant) and where the data were normally distributed, standard descriptive statistics (i.e. means, medians and standard deviations) of exposure levels were calculated. Where data was right-skewed, data was log-transformed, a T-test was conducted on this data and geometric means were calculated in addition to the general descriptive statistics. Lastly, the correlation coefficient of bakery size (amount of mitads) is determined to determine whether this has also influenced the results.

Filters (a total of 12) were excluded from the analysis when they were not providing reliable data; because the filter was damaged *(3x)*, equipment had technical problems during the measurements *(7x)*, or a filter was unusable due to abnormal exposure *(2x)*. The last category was for outdoor measurements where later a fire was started close to the measuring location. After this, the data was split into measurement type (Outdoor, bakery or personal), then this data was split again separately into measurements conducted at a biomass bakery or an electric one. Lastly, analysis on the same data excluding all measurements that contained other known/visible sources of $PM_{2.5}$ was done.

Results and differences between categories were calculated and reported, after which a t-test was conducted to determine the significance of the data.

The null hypothesis used in the t-test analysis was as follows:

H0: $\mu 1 - \mu 2 = 0$

H1: $\mu 1 - \mu 2 \neq 0$

This null hypothesis states that the difference in the mean in the results from two sample categories was not statistically significant. When the null-hypothesis could be rejected, the difference in mean values was considered significant.

# 4 Results

## 4.1 General results

In this section, the general results obtained from the survey and observed during the tests are reported. The survey (Appendix I) was designed to obtain data and create a better understanding of the bakeries and the characteristics of women who work in them. This survey was conducted among 43 participants, all working in one of the 30 bakeries where tests were executed. The general demographics of the bakery employees are displayed in Table 2.

TABLE 2 BAKERY EMPLOYEE DEMOGRAPHICS FROM THE SUBJECTS QUESTIONED IN THE SURVEY

| | Bakery employees |
|---|---|
| **Gender** | |
| **Male** | 0% |
| **Female** | 100% |
| **Age** | |
| **0-17** | 0% |
| **18-29** | 65% |
| **30-49** | 28% |
| **50+** | 2% |
| **Not disclosed** | 5% |
| **Education** | |
| **No education** | 30% |
| **Primary school** | 53% |
| **High school** | 15% |
| **Technical school or higher** | 2% |

The most notable results obtained from the survey are:

- Injera baking is exclusively done by women
- A single stove produces 120 Injera per day on average
- The largest age group of the women working in the bakeries is 18-29
- The average salary of the employees is 1112 (Median 1000) Birr a month, working 6-7 days a week. At the time of writing this is equal to less than €50 a month[5]
- The average bakery has 4.9 mitads operational, however this is heavily offset by the 35 mitads in the largest bakery that participated in this research, the median value is 3 mitads per bakery

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[5] Exchange rate of €1 to 24.14 Birr, retrieved from http://www.wisselkoers.nl/ethiopie_birr on 25/7/2016

- Electric bakeries are more abundant and spread across the city of Addis Abeba than Lakech bakeries, which are mostly concentrated in the North-West (See Figure 9). This area is also in close vicinity to forest where firewood is collected

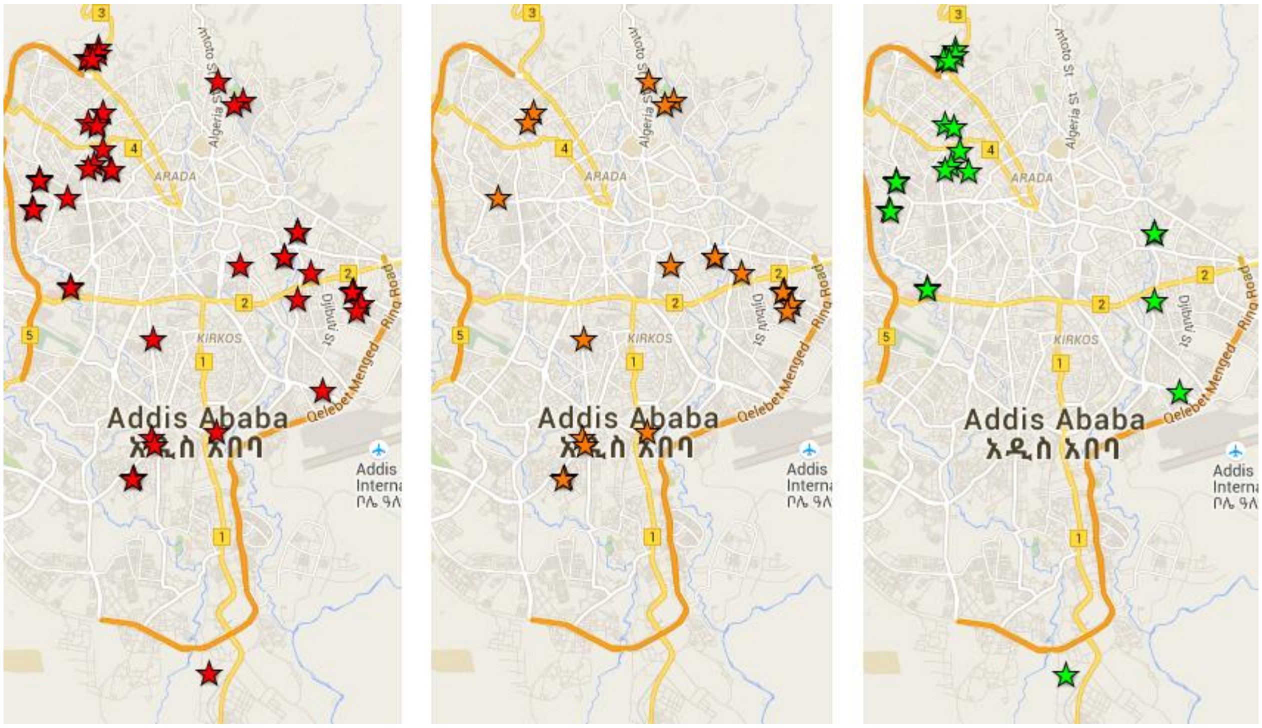

FIGURE 9 A: ALL BAKERIES FOUND B: ELECTRIC BAKERIES ONLY C: LAKECH BAKERIES ONLY (MAPS CREATED USING HTTP://WWW.GPSVISUALIZER.COM/)

## 4.2 Mass Balance

This section shows the results of the mass balance analysis discussed in in Section 3.3.1.1, showing the embodied energy of the biomass mitad versus the electric mitad.

### 4.2.1 Mass flow of product

Summarized results of the materials and mass used in the production of the mitads can be found in Table 3. The results are sorted by material, so that in the next step the total GHG emissions from material production could be calculated. Table 4 shows lifetime and recycling rates, which were necessary to determine how often certain parts need to be replaced in the lifecycle of the product and how much of each raw material is needed to create new plates. A more detailed breakdown of the dimensions and materials of the mitads can be found in Appendix V.

TABLE 3 MASS USED IN PRODUCTION PHASE FOR THREE MITAD TYPES, SORTED BY MATERIAL

| | Clay | Steel/iron | Glasswool | Ceramics/glass/ sillicon | Total weight |
|---|---|---|---|---|---|
| | kg | kg | kg | kg | kg |
| **Lakech mitad** | 46.1 | 6.25 | - | - | 52.3 |
| **Electric mitad**[6] | 9.5 | 3.26 | 1.02 | - | 13.7 |
| **High-efficiency electric mitad**[7] | - | ±3.2 | ±1 | ? | 5-10kg (*estimate!*) |

TABLE 4 LIFETIME AND RECYCLING OF PARTS OF THE MITAD, BASED ON BAKERY OWNERS' ESTIMATES

| Mitad type | Part of the mitad | Estimated lifetime[9] | Recycling[8] |
|---|---|---|---|
| **Lakech** | Plate | 6 months | 0% |
| | Frame | 10 years | 0% |
| **Electric** | Plate | 2 years | 0% |
| | Frame | 10 years | 0% |
| | Isolation | 10 years | 80% |
| | Wire | 2 years | 90% |

---

[6] Mass of the electric switch is not considered, as there is no documentation on the materials used for it

[7] The mass flow for the high-efficiency mitad could not be completed as this product is still in the prototype phase where major changes are still made to the design.

[8] For more detail see Table 15

Based on the theory in section 2.1, the data from Table 3 and Table 4 was used to create the mass flow balances in Figure 10 and Figure 11.

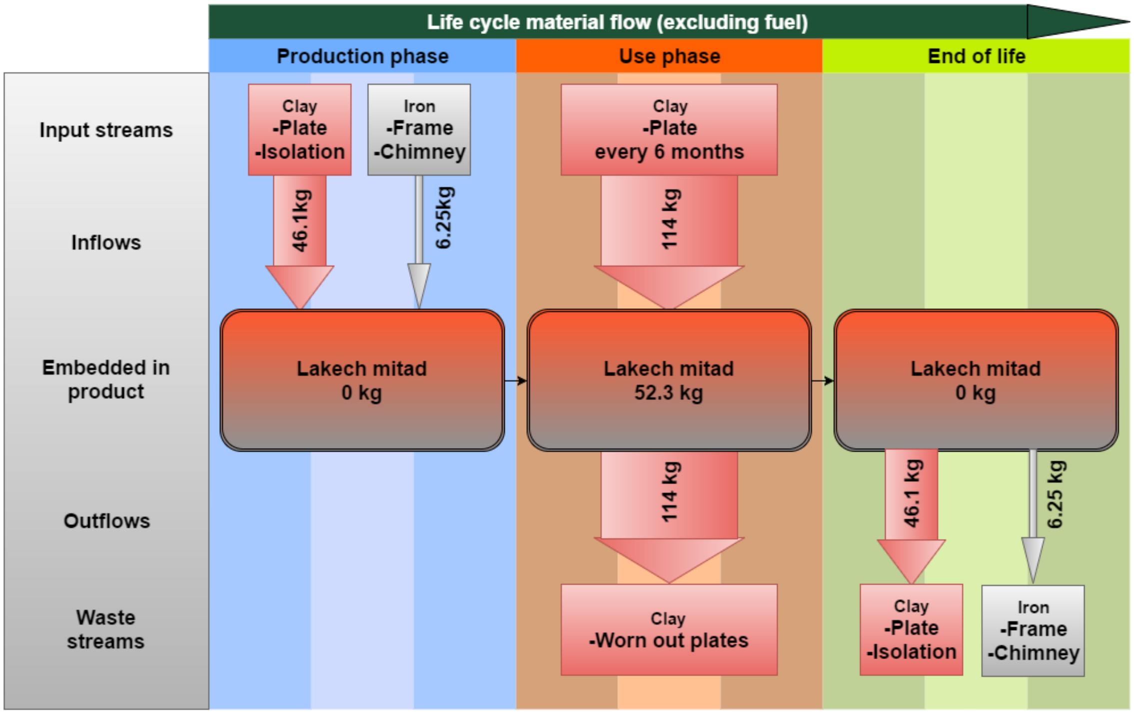

FIGURE 10 MASS BALANCE OF A LAKECH STOVE, EXCLUDING FUEL

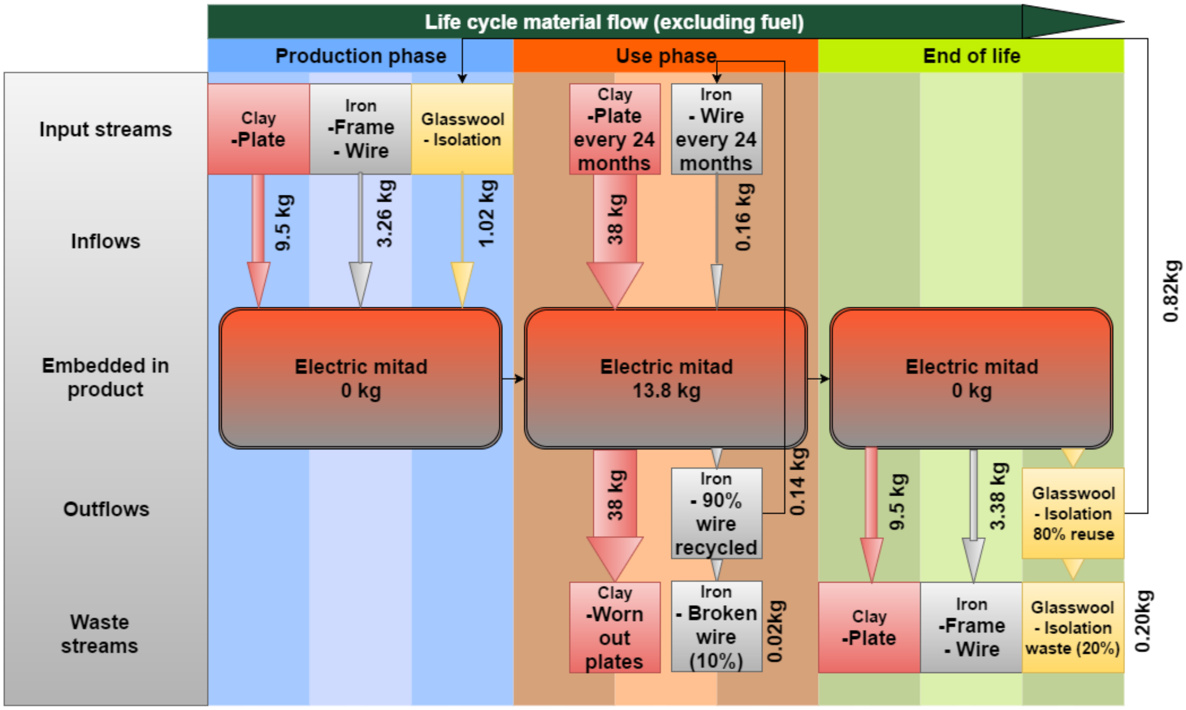

FIGURE 11 MASS BALANCE OF AN ELECTRIC STOVE, EXCLUDING FUEL

In Figure 10 the simplicity of the biomass stove becomes clear, as only two materials are used to produce the mitad and only one in the maintenance phase. The figure does show that in the maintenance phase a large amount of clay is used to replace the plates during its lifetime. Also note that there are no arrows indicating recycling of a material.

In Figure 11 the mass balance for the electric stove is shown. This type requires three materials in the production phase and two during maintenance, but the production and maintenance weight inputs are lower than those in the biomass stove, leading to a lower weight product. This figure also shows some recycling flows, which lead to a lower waste output and therefore lower raw material input as well.

Using the material flows from Figure 10 and Figure 11 and the methods described in section 3.3.1.2 the embodied energy and material related climate impact are calculated. These values are displayed in Table 5.

TABLE 5 LIFECYCLE EMBODIED ENERGY AND PRODUCTION RELATED $CO_2$ EMISSIONS

| | **Total lifecycle embodied energy (ex. Fuel)** | **Total material related climate impact ($CO_2$e emissions, ex. Fuel)** |
|---|---|---|
| | MJ | kg |
| **Lakech mitad** | 606 | 47.0 |
| **Electric mitad** | 214 | 16.2 |

The results show the total energy used to build, maintain and dispose of the product. Embodied energy shows how much energy was necessary to create the parts of the stove, where climate impact shows how much $CO_2$ equivalents were emitted in the production of the materials used in the lifetime of the stove. The table shows that even though the electric plate uses more different materials, this is compensated by the lower weights, leading to lower lifecycle embodied energy and climate impact.

As the high-efficiency mitad is still in the prototype phase, it is not yet possible to conduct a material flow analysis on the materials used to construct it, as the components that are to be used in the stove, and in what ratios are not finalized yet.

### 4.2.2 Mass balance of fuel and electricity

In the mass flow analysis figures, fuel was excluded, as electricity is not directly comparable to the direct biomass input used in the Lakech stoves. The flow of electricity and biomass in terms of emissions was significantly higher than those in the rest of the lifecycle. A comparison between the different stove types is made based on estimated lifecycle $CO_2$ emissions using the most recent available energy mix data of Ethiopia for electricity, and lifecycle greenhouse gas emissions for biomass energy acquired from forestry. The results of these calculations are shown in Table 6.

TABLE 6 SAVINGS PER UNIT OF PRODUCTION

| | Energy per Injera | Injera weight | Fuel per kg of food | | Energy per kg of food | Energy used per stove per year | Savings relative to biomass | Savings relative to regular electric |
|---|---|---|---|---|---|---|---|---|
| | MJ | kg | Kg fuel | kWh | MJ | GJ | Percentage | Percentage |
| **Average lakech** | 8.11 | 0.31 | 1.4 | | 26 | 340.5 | - | - |
| **Average electric** | 0.79 | 0.29 | | 0.80 | 2.9 | 33.0 | 89% | - |
| **Efficient mitad** | 0.42 | 0.35 | | 0.33 | 1.2 | 17.4 | 95% | 59% |

The values in the “Fuel per category of food” column are split in two, as the stoves used a different type of fuel (biomass or electricity). The most important values are marked in green, these are the relative savings compared to the Lakech/biomass stove, and the relative savings comparing the high-efficiency stove to the regular electric stove.

## 4.3 Ethiopian power sector and impact of stove improvement

Using the methods in section 3.3.1.3, the situation of the current power sector in Ethiopia was retrieved. The Ethiopian sector relies mainly on Wind- and Hydropower for its installed capacity as can be seen in Table 7. Together they make up 96.1% of the total installed capacity in Ethiopia, where the other 3.9% is supplied by geothermal installation and Oil/Gas turbines. Future plans are mainly in expansion of Geothermal and hydropower, therefore Ethiopia’s climate impact for electricity is relatively low (USAID, 2015).

The lifecycle greenhouse gas emissions for biomass acquired from forestry converted to electricity has a median value of 36 $gCO_2eq/kWh$, based on electric conversion efficiencies of 27%-50% (IPCC, 2012). As the biomass is not actually converted into electricity, but burned instead, the efficiency was already taken into account in the calculated value of total energy used. This means that the emissions per unit of energy had to be lowered by 61.5% (100% minus the average of 27% and 50%, 38.5%) to 14 $gCO_2eq/kWh$ or 50 $kgCO_2eq/GJ$. Recent data on the energy mix of Ethiopia was difficult to obtain, the latest reliable data available being from 2014 on the year 2013 (IEA, 2014b). The medians for hydropower, geothermal energy, wind power and oil respectively are 3.8, 45, 4.6 and 840 $gCO_2eq/kWh$.

Using the data from Table 8, an average Carbon intensity of the Ethiopian power grid in 2013 was calculated to be 4.8 $gCO_2eq/kWh$ or 17.1 $kgCO_2eq/GJ$.

TABLE 7 INSTALLED CAPACITY IN ETHIOPIA (USAID, 2015)

| **Source of power generation** | | **Installed capacity (2014)** | |
|---|---|---|---|
| | | MWs | Percentage of total |
| **Renewable Energy** | Hydropower | 1890 | 88.1% |
| | Geothermal | 5 | 0.2% |
| | Wind | 171 | 8.0% |
| | **Total** | **2066** | **96.3%** |
| **Fossil Fuels** | Oil/Gas turbines | 79 | 3.7% |
| | **Total** | **79** | **3.7%** |
| **Total generation capacity** | | **2145 MWs** | |

TABLE 8 ELECTRICITY GENERATED IN ETHIOPIA FOR 2013 (IEA, 2014b)

| **Source of power generation** | | **Generated electricity (2013)** | |
|---|---|---|---|
| | | TJ | Percentage of total |
| **Renewable Energy** | Hydropower | 30.017 | 95.6% |
| | Geothermal | 61 | 0.2% |
| | Wind | 1.282 | 4.1% |
| | **Total** | **31.360** | **99.9%** |
| **Fossil Fuels** | Oil | 29 | 0.1% |
| | **Total** | **29** | **0.1%** |
| **Total generated electricity** | | **31.389 TJ/8719GWh** | |

Table 7 and Table 8 show that Ethiopia's installed capacity mainly relies on renewable energy sources, and that of the installed capacity, the non-renewable energy sources are barely utilized (0.1%).

This data concerned the current situation in Ethiopia, but for a transition to happen, more generation capacity is needed to supply in the extra created demand of electricity. Therefore literature research was also conducted to examine future possible renewable energy capacity, the results of this are shown in Table 9.

TABLE 9 RENEWABLE ENERGY POTENTIAL IN ETHIOPIA (REEEP, 2013)

| Source of renewable power generation | Estimated total technical capacity | Capacity currently utilized | |
|---|---|---|---|
| | MWs (economic potential) | MWs | Percentage |
| **Hydro** | 45.000 (30.000) | 2.066 | 4.6% (6.9%) |
| **Wind** | 10.000 | 171 | 1.7% |
| **Geothermal** | 10.000 | 5 | <0.1% |

As shown in the last column of the table shaded in green, even if only the economic Hydropower capacity is considered, less than 10% of the available generation capacity is currently in use.

The following table (Table 10) displays the lifetime emissions of the different stove types and also how material related $CO_2$ emissions from embodied energy relate to the total lifetime emissions.

TABLE 10 LIFETIME $CO_2$EQ EMISSIONS OF DIFFERENT STOVE TYPES

| | Energy used per stove in 10 years | Life cycle emission intensity | Lifetime emissions (10 yr) per stove | Material related $CO_2$ emissions |
|---|---|---|---|---|
| | GJ | kg$CO_2$eq/GJ | *t*CO2eq | *t*$CO_2$eq |
| **Average Lakech** | 3,405 | 50 | 170 | 0.047 |
| **Average electric** | 330 | 17.1 | 5.64 (-96.7%) | 0.0162 |
| **Efficient mitad** | 174 | 17.1 | 2.98 (-98.3%) | **?** |

Table 10 provides the most notable results in the last two columns: Embodied energy only causes a fraction of total emissions even though the fuel and electricity used is sourced from renewable energy sources. And that the savings in emissions from a transition can be above 96%, and even above 98%.

## 4.4 Available capacity

Using literature research as described in section 3.3.1.3, the situation regarding available capacity was examined and is reported in this section. Ethiopia has a planned expansion of the transmission line network through the country, the planned lines can be found in Figure 12. This figure also shows what type of grid is recommended in different areas of the country. Because the Ethiopian energy companies and government have not provided recent data on their energy supply, it is difficult to make estimates on the progress. There is however, a major dam (The Grand Ethiopian Renaissance Dam) under construction that is expected to be operational in 2017 that will add 6000MW of hydropower capacity to the grid, essentially quadrupling the available power of Ethiopia (Kable Intelligence Limited, 2015).

Assuming it has operating hours and efficiency similar to the current installations, it theoretically generates 95.3PJ per year.

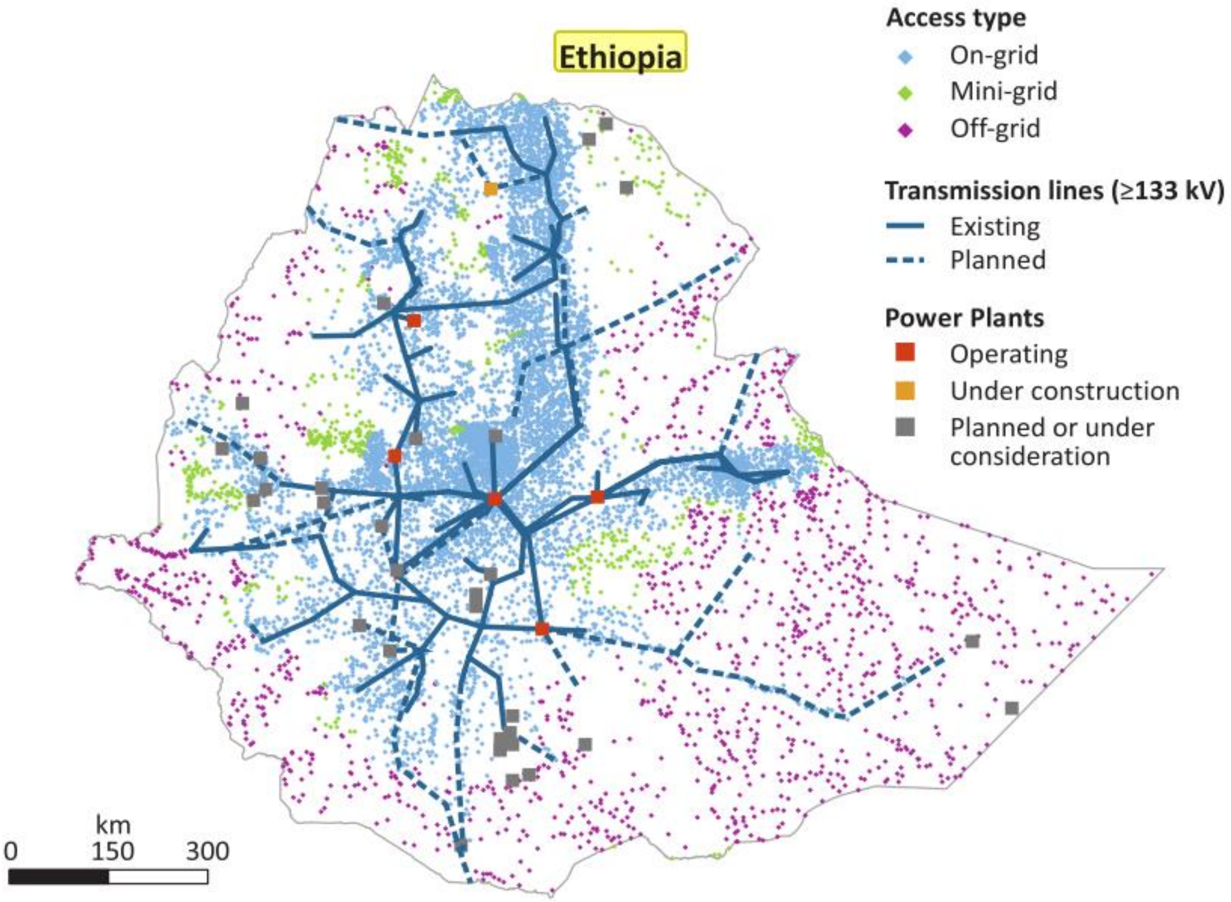

**FIGURE 12 OPTIMAL SPLIT BY GRID TYPE IN ETHIOPIA, BASED ON CURRENT SITUATION AND EXPECTED TRANSMISSION LINE EXPANSION**(IEA, 2014a)

Currently, in the total energy use 91.5% (334TWh) comes from biomass (Tucho, Weesie, & Nonhebel, 2014), of which (more than) 50% (167TWh) is used for Injera preparation each year (Tesfay, Kahsay, & Nydal, 2014)

### 4.4.1 Stove replacement scenarios

Using the scenarios as described in the section 3.3.1.4, six scenarios on improvement of the cooking system in Ethiopia were set-up and assessed:

1. 10% of current biomass mitads is replaced by regular electric mitads
2. 50% of current biomass mitads is replaced by regular electric mitads
3. 100% of current biomass mitads is replaced by regular electric mitads
4. 10% of current biomass mitads is replaced by High-efficiency electric mitads
5. 50% of current biomass mitads is replaced by High-efficiency electric mitads
6. 100% of current biomass mitads is replaced by High efficiency electric mitads

These scenarios have a few implications, in relation to the research questions, the most important ones are:

1. Amount of stoves that have to be produced
2. Savings in primary energy use
3. Savings in GHG emissions
4. Extra electricity supply required

Implication 1 is related to question 3 (*To what extent is electric Injera cooking an alternative to current cooking stoves in practice?)* as a production line needs to be set up. Implication 2 and 3 are directly related to sub-question 1 (*What are the realized savings on energy and materials compared to current cooking methods when a switch to efficient electric cooking is made?)* lastly, implication 4 is directly related to sub-question 2 (*What is the renewable electricity potential of Ethiopia, and what would a large scale transition to electric cooking mean for the power sector?*). The effect on implication 1 through 4 is displayed in Table 11, and the higher the value for penetration is, the bigger the impact of all 4 implications is. In the high-efficiency vs regular electric plate scenarios, the main difference is in the last column “extra electricity required”. Implementing a high-efficiency transition would put less stress on the electricity supply, but producing the same amount of stoves in a more complex process might raise issues.

TABLE 11 NUMERICAL IMPLICATIONS OF THE SIX SCENARIOS

| | Amount of stoves | Savings in primary energy use | | Savings in GHG emissions per year | Extra electricity required |
|---|---|---|---|---|---|
| | | PJ | % | MtCO2eq | PJ |
| **Scenario 1: 10% R-EL**[9] | 1.77*10^5 | 54.3 | 9.03 | 2.90 | 5.82 |
| **Scenario 2: 50% R-EL** | 8.83*10^5 | 271 | 45.2 | 14.5 | 29.1 |
| **Scenario 3: 100% R-EL** | 1.77*10^6 | 543 | 90.3 | 29.0 | 58.2 |
| **Scenario 4: 10% HE-EL**[10] | 1.77*10^5 | 57.0 | 9.49 | 2.95 | 3.07 |
| **Scenario 5: 50% HE-EL** | 8.83*10^5 | 285 | 47.4 | 14.7 | 15.4 |
| **Scenario 6: 100% HE-EL** | 1.77*10^6 | 570 | 94.9 | 29.5 | 30.7 |

Table 11 shows that from an emissions point of view, any increase in replacement with either regular electric plates or high-efficiency plates can lead to a major improvement in GHG emission savings, where the difference between the regular and efficient plate is minor. This can be explained by the very inefficient design of the biomass stoves compared to electric stoves as a whole, but also because of the fact that electricity in Ethiopia is largely generated using hydropower, which has very low lifetime GHG emissions per unit of energy.

## 4.5 Indoor air pollution

### 4.5.1 $PM_{2.5}$ results

This chapter shows the results from the $PM_{2.5}$ measurements. All results were gathered and summarized in Table 12, with the most important results marked in green. The measurements are divided into three categories: outdoor, personal or stationary, and is also split to show the measurements only considering bakeries without other visible sources of pm in the second half. It shows the amount of samples, means, geometric means and range of the measurements for each measured category and also the t-test p-value to show whether the difference between Lakech and electric bakeries is significant.

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[9] R-EL: Regular electric cooking plates/mitads

[10] HE-EL: High-efficiency electric cooking plates/mitads

TABLE 12 RESULTS FROM PM2.5 MEASUREMENTS[11]

| | *Lakech bakeries* | | | | *Electric bakeries* | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean (SD) | GM | Range | n | Mean (SD) | GM | range | t-test p-value |
| **Outdoor air $PM_{2.5}$ (µg/m$^3$)** | 17 | 76(22) | 72 | 41-121 | 17 | 50 (33) | 36 | 4-122 | <0.05 |
| **Personal $PM_{2.5}$ exposure (µg/m$^3$)** | 30 | 521(398) | 415 | 120-1942 | 34 | 299(277) | 216 | 30-1114 | <0.001 |
| **Stationary $PM_{2.5}$ exposure (µg/m$^3$)** | 31 | 591(671) | 394 | 102-3117 | 33 | 184 (145) | 134 | 19-539 | <0.001 |
| | ***Lakech bakeries, no other sources of PM*** | | | | ***Electric bakeries, no other sources of PM*** | | | | |
| **Personal $PM_{2.5}$ exposure (µg/m$^3$)** | 22 | 377(201) | 326 | 120-777 | 15 | 208(123) | 175 | 30-482 | <0.01 |
| **Stationary $PM_{2.5}$ exposure (µg/m$^3$)** | 24 | 332(199) | 279 | 102-772 | 14 | 140(91) | 114 | 19-383 | <0.001 |

The values for the outdoor measurements in the first row of values show that the air outside of the Lakech bakeries has a higher concentration of $PM_{2.5}$ than the outdoor air around electric bakeries. A t-test on the data confirms the difference is statistically significant ($p<0.05$). This difference is either caused by emissions from the bakery polluting the outdoor air, or the Lakech bakeries are located in more polluted areas of the city.

According to the WHO, $PM_{2.5}$ concentration in the ambient air in Africa ranges from 20-75, assuming a $PM_{2.5}$:$PM_{10}$ ratio of 0.5 (World Health Organization, 2006). With this in mind, the values obtained in the study (means of 76 and 50, and geometric means of 72 and 36) are within the expected range considering the outdoor air near Lakech bakeries may have been influenced by the stoves from inside.

---

[11] The following abbreviations are used in the table:
n: amount of samples taken
Mean (SD): mean value of the measurements (Standard deviation)
GM: geometric mean
Range: minimum and maximum values obtained
t-test p-value: p-value obtained from t-test performed on the data when the data was normally distributed, p-value obtained from ln-transformed data when the data was not normally distributed.

After determining the outdoor air pollution, the personal exposure difference and bakery average PM2.5 concentration between Lakech and Electric bakeries is assessed. The results from this are shown in the second and third row of values in Table 12.

A difference in mean and geometric mean of 222 and 199 respectively are found for the personal exposure measurements. For the average stationary bakery concentration even bigger differences are discovered (407 mean and 260 geometric mean). This means that for the women working as Injera cook in the bakery and also other people who are regularly present at these bakeries, a switch to electric cooking can reduce the exposure to $PM_{2.5}$ during their daily work by 48% considering the geometric mean of personal exposure, or by 66% when the geometric mean of the stationary exposure is considered.

Next, data were excluded from bakeries where other visible sources of PM were present. According to the p-value, the difference between the data is still highly significant, but the observed differences in mean and geometric mean are smaller. This shows that even though the mitads are not the only significant source of $PM_{2.5}$, the biomass/Lakech mitads directly contribute to indoor air pollution in the form of $PM_{2.5}$.

Lastly, to check whether there was no bias in $PM_{2.5}$ concentration due to the size of the bakery, the correlation function from the *analysis toolpak* described in 3.3.2 was used to test for correlation between the amount of stoves in a bakery and indoor air pollution. The calculated correlation-coefficient between the number of mitads and $PM_{2.5}$ concentration in the bakery and personal exposure was -0.07. When the largest bakery (35 mitads) was omitted in the test, the correlation-coefficient was observed to be -0.03. These values show that in this research there is no reason to assume there is a direct correlation between number of mitads used in a bakery and indoor air pollution.

### 4.5.2 CO measurements results

Another aspect of the indoor air pollution research was to conduct CO measurements using passive exposure tubes. The results from these measurements are shown in Table 13. As this data was normally distributed, no geometric mean was determined, and the t-test was conducted on untransformed data.

TABLE 13 DIFFERENCE IN COMBINED EXPOSURE TO CO BETWEEN LAKECH AND ELECTRIC BAKERIES, T-TEST CONDUCTED ON UNTRANSFORMED DATA

| | *Lakech* | *Electric* | *Difference* |
|---|---|---|---|
| **Unit (where applicable)** | PPM CO | PPM CO | PPM CO |
| **Mean** | 27.1 | 3.7 | **-23.4** |
| **Standard Deviation** | 20.1 | 4.7 | |
| **Minimum** | 2 | 0 | -2 |
| **Maximum** | 66 | 18 | -38 |
| **Count** | 46 | 40 | |
| **P value (Two tailed)** | | | <0.001 |

The cell marked in green shows that the average reduction in CO concentration is 86% when Lakech bakeries are compared to electric bakeries. The significance of this difference is explained in section 5.3.1 in the discussion.

# 5 Discussion

This research set out to improve knowledge and available data on climate and health related issues connected to the indoor preparation of Injera in Ethiopian Injera bakeries. Due to the inefficient design and inherent properties of small scale biomass cooking, electric cooking as an alternative brings great improvement in energy and material use efficiency, as well as in indoor air pollution. Improvement in these fields is substantial, with savings in primary energy use of up to 95% (section 4.4.1) and a reduction in indoor air pollution by 48-66% (section 4.5.1). In this chapter, first a general discussion on the research itself is described and then a more specific discussion on each research question follows. After this the limitations and weaknesses of the research are discussed, followed by the implications and recommendations.

## 5.1 General discussion

To make sure that focus is retained during the research, certain boundaries have been set in advance. As this research is part of the track Energy & Materials of the Master programme Sustainable Development, this research focuses only on the possible prevention of indoor air pollution and saving energy and materials used for Injera baking in Ethiopia and the author’s expertise is also mainly in the field of sustainability, energy and materials. The field research comparing different types of Injera stoves in Addis Ababa has spanned a timeframe of 6 months, between December 2015 and May 2016. As a result of this timeframe, a limited number of samples (30 bakeries) and categories were assessed (electric vs non electric, with and without other visible sources of $PM_{2.5}$ nearby).

### 5.1.1 Sample bias

The bakeries have been selected from different regions of the city, and they were selected by whether they were using biomass or electricity as fuel, sold Injera to customers outside of their own family and were willing to cooperate with the data collection for the research. Self-selection where for example bakeries that were aware they have high pollution were not cooperative might have occurred, but to which degree is impossible to determine. If this form of self-selection has indeed occurred, then it would only mean that the differences between biomass and electric cooking in indoor air pollution were even bigger than reported. A sample bias that would significantly weaken the conclusion or results from this research is therefore unlikely. However, comparing households with bakeries becomes more uncertain if this sample bias was indeed present.

### 5.1.2 Cooperation

The arguments to convince the bakeries to participate were not always effective. Several reasons for not cooperating were given, including being an unlicensed business, no interest in a research project, bad previous experience(s) and lack of benefit for the bakery. The bakeries and employees that did cooperate usually did so for a specific reason which may have influenced results. In some cases the employees were reluctant, but the owner encouraged them to cooperate, in some cases this lead to the subject not taking the personal measurement for a full shift, but instead took it off after a few hours of measuring. Although results are slightly less accurate this way, it should still be a reliable measurement for the average concentration during work, as it is not expected to have major variations during a workday.

### 5.1.3 Generalizations

As the study only contains samples from Addis Abeba, generalizations cannot be made for aspects where a difference in situation in rural areas is expected. Not every region uses the same type of biomass for the biomass stoves, and the stove types can also be different in the countryside than in Addis Abeba. Other factors can also be of influence such as altitude, wind and local climate.

### 5.1.4 Measurements and data collection

In data collection, a few issues arose. The biggest category was measuring issues. While relevant values on electricity consumption could be collected in 9 of the bakeries, for the biomass bakeries only 4 yielded useable data on fuel consumption. This data also relies partially on self-reporting of the data from estimates of the employees, instead of direct measurements as was the case with the electric bakeries. A good example here is that literature shows fuel use in biomass based stoves ranged from 508g/kg to 1031g/kg in CCTs (Energypedia, 2011). The 4 samples measured in this study however, averaged 1400g/kg. This is a result of the difference in practice with CCTs, small sample size and also likely because of erroneous self-reported data.

Another issue mainly related to the survey, was that of language. During the research most of the communication went through an unlicensed translator with no previous experience with translating or academic research. Also, even though Amharic is the official language in Ethiopia, it is not the first language of some inhabitants, adding to possible miscommunication.

### 5.1.5 Literature

Some of the results obtained in this study show an inconsistence with literature: Literature shows 15% efficiency for biomass and an electric efficiency of 70%, in the measurements however, the regular plates have been measured to be almost 10 times more efficient than the biomass plates, which would assume efficiency over 100%. This is likely related to the point raised in the previous section (5.1.4), that self-reporting is not an accurate measure of obtaining data.

Another issue is that of Incomplete/outdated data. Data from major energy statistics sources (IEA, IPCC) is not up to date on Ethiopia and sometimes missing, due to lack of reporting from its government and institutions. Especially with the recent and near-future developments on hydropower, using the older data does not reflect reality properly, and estimates have to be made using the sources available.

## 5.2 Energy and materials

The research questions can be answered using the results obtained in the study, in this chapter the 3 research sub-questions related to energy and materials are discussed:

### *5.2.1 "What are the realized savings on energy and materials compared to current cooking methods when a switch to efficient electric cooking is made?"*

By conducting a mass flow analysis on the materials used in the lifecycle of the mitad and measuring the fuel use over its lifetime, the climate impact of the different steps in the process were quantified. It became apparent that the climate impact of the materials used to build the mitads and maintain it, is just a fraction of the impact from energy use during the use-phase. Table 10 shows that the impact of the materials is less than 0.5% of the total impact in the lifecycle of an electric mitad, and even less for the conventional biomass mitad. A study that set out to compare the lifetime emissions when replacing three-stone fire stove with a more efficient biomass stove showed that the emission equivalents in the use-phase accounts for 99.9% of a stove's lifetime emissions in the case of biomass stoves (Wilson, Talancon, Winslow, Linares, & Gadgil, 2016). Comparing these results to the ones in this study (Table 10) shows that reduction of total lifetime climate impact of a stove can be realized by focusing almost exclusively on use-phase emissions. This is not just valid for the switch from biomass to electricity, but also when switching out electric stoves for high-efficiency electric stoves. The material impact of the higher efficiency prototype could not be accurately determined as tests were conducted with an unfinished prototype. However, if the material impact would be twice as high compared to that of the conventional mitad (which due to its expected lower weight is likely to be an overestimation) at double the efficiency, the impact of the embodied energy in the materials would still only be 2% of the total.

As a result of the calculated impact in each of the phases, energy consumption and/or fuel use in use-phase of a mitad is the most significant portion of total lifetime impact. Total impact can be minimized by focusing on the use-phase emissions, as there is a lot of room for improvement. The energy savings realized when a biomass stove is switched out for an electric stove can be over 90% (3405GJ per year to 330GJ per year), and a switch to a more efficient electric plate reduces it by another 50% (to 174GJ per year), totalling more than 95% possible savings in primary energy use per stove. Efficiency for conventional biomass stoves in literature differs, where most results range from 5% to 20% (Jetter et al., 2012; Quist, Jones, & Lewis, 2016) in Clean Cooking Tests[12] (CCTs). This result implies that efficiency in the stoves from this test could not have been more than 5%, as otherwise efficiency above 100% for the high-efficiency plates would be realized.

When the impact in terms of yearly GHG emissions is assessed, there is a much smaller improvement when comparing the regular and more efficient electric plate. Annually, up to 29.5 megatons of $CO_{2eq}$ emissions can be saved in the best-case scenario in the transition to an electrified cooking system, and this is only considering Injera production, not other cooking practices. When this value is compared to the estimated total emissions including Land use change and forestry in Ethiopia from 2012 which is 144Mt$CO_2$e (KNOEMA, 2015) the value is in line with the expectation that a significant part of the country's emissions can be prevented. However the 144Mt value incorporates all types of emissions. If only $CO_2$ emissions in 2012 are considered, a total of 33.4 Mt$CO_2$ was emitted. In the research only half of the cooking energy was assumed to be used for Injera preparation, 50% of savings (16.7Mt) in $CO_2$ emissions should therefore be the highest savings possible (assuming that the country's reported statistics are correct and consistent) if just the Injera mitads are replaced with electric. This is a consequence of the difference in approach, and the result is likely to be somewhere in the middle of these values. The absolute value should therefore be used with caution, and the observed relative savings from Table 10 are more suitable to communicate to policymakers.

What the research also shows in section 4.4.1, is that the main reason to prefer the higher efficiency plate over the regular electric mitad is that it puts less stress on the local and national electric power system, and can be used with more versatility. These advantages hold even though the climate impact

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[12] A CCT is a controlled cooking test, where under standard circumstances efficiency is measured, for example by boiling a precise volume of water or dough. In the CCT tests using dough, wet dough is weighed and measured, instead of the finished product which was the case in this study.

compared to regular electric stoves is not as big when comparing it to the replacement of biomass stoves. The relative savings in GHG emissions are much less significant. This can be explained by the extraordinary clean electricity generation sector in Ethiopia, with over 99% of the electricity being generated from renewable energy sources such as hydropower and wind power.

### 5.2.2 *"What is the renewable electricity potential of Ethiopia, and what would a large scale transition to electric cooking mean for the power sector?"*

Ethiopia has no natural energy resources such as oil or coal that are currently in use for power generation. This may be seen as a major disadvantage, but it helped the country to develop a renewable electricity system, mainly based on hydropower. However, this does pose the question whether large scale electrification in Ethiopia would lead to issues with availability of capacity to generate the extra electricity that would be needed.

Ethiopia already generates more than 95% of its electricity from hydropower, but this is only 4.6% of the theoretical capacity available in hydropower in Ethiopia. In the short term there is already a major expansion planned that should cover the increased demand in electricity, even assuming the most demanding scenario.

It is not up to the author to determine which portion of the electricity generated will be used for a large scale electric cooking transition. However, in press releases, the Ethiopian government has stated that they aim to export energy to other countries in Africa, with an increase in total available capacity to 15.000MW (from 2.200 in 2015) (Reuters, 2016). If the importance of the transition to electric cooking is recognized, it can be prioritized over export of energy to other countries. Scenario 3 is the most demanding scenario due to high penetration but not using the high-efficiency stoves (Scenario 3: 100% replacement using regular electric plates), requiring a total of 58.2PJ of the 95.3PJ new capacity provided by the Grand Ethiopian renaissance dam. The "Rural Electrification Fund Office" in Ethiopia stated that in a new five-year project among other things, they plan on purchasing and distributing 600.000 improved[13] stoves (The Ethiopian Herald, 2015). It is not stated what type of stove, but if they are all about Injera stoves, it would be a replacement of 34% of the conventional Injera mitads. Only half of the governments' requested funding for this project has been approved, so it is still uncertain whether this project will be executed in its current shape (ibid.).

Total capacity is not the whole story however. Another major barrier to implementation in regards to the power sector is that not everyone in the country has access to electricity. Currently 55% of the Ethiopian population has access to electricity (The Ethiopian Herald, 2015) which is self-reported by the Ethiopian electricity company, but (IEA, 2014a, page 127) shows that geographically speaking, more than 80% of Ethiopia still does not have access to the electricity grid and the World bank states that in

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[13] It is not mentioned in the source, but because the project is arranged by the Rural Electrification Fund Office, "improved" is assumed to be electric.

the period from 2000 to 2012 the access to electricity went up from 12.7% to 26.6% (The World Bank, 2013) In the last 2 years of this data, an annual growth of 1.8% is realized. If this trend continued, then 32% of Ethiopia had access to electricity in 2015.

The scenarios presented show that from a generation capacity point of view, the 100% scenarios are both feasible in the short term, however since only an estimated 32-55% of the Ethiopian population had access in 2015, the 50% scenarios are the closest to the “Technical potential” at the moment. The 100% scenarios are currently the “Theoretical potential” because of the limitation in electric connections, as there is no limitation in generation capacity in the country. The scenarios advocating a 10% increase in the use of electric stoves are the most likely to be executed within the short term, but show clearly that there is a linear scaling in climate benefits when a larger portion of the mitads is replaced.

Even though the difference between regular mitads and the high-efficiency mitads in terms of direct climate impact seems small, the benefit it has in reducing the required power has many other benefits. The extra electricity that is saved by using the HE mitads can be used to electrify other sectors, export electricity or reduce the need for future expansion of the power generation network. Smaller scale benefits of the HE mitad are discussed in section 5.2.3.

### 5.2.3 *“To what extent is electric Injera cooking an alternative to current cooking stoves in practice?”*

The large scale issue with electric cooking in Ethiopia is the availability of a strong and robust electricity network. Users of the conventional biomass mitad have mentioned several reasons why they are not using electric plates at the moment:

- The investment costs are too high
- There is no suitable (high power) electricity plug available
- Total costs are perceived to be higher
- Afraid that the electric mitad is damaging to their health
- Reluctant to change “something that works”
- The electricity network is unstable, sometimes there is no power for a couple of hours or even days

Some of these concerns are legitimate, where others are mainly attributable to a lack of knowledge. For example the bakeries that switched to electric baking in the past have reported a reduction in cost after the initial investment. There is also no evidence that there is any detrimental health effect in switching to electric mitads, on the contrary, the reduction in $PM_{2.5}$ concentration should be beneficial to their health.

The issues that do stand, however, are the ones related to the quality of the electricity network and the initial investment. A bakery needs to bake new Injera every day, if they cannot supply them due to a power cut, they might lose customers. Also some bakeries are not equipped with an electric connection capable of supplying enough power for the amount of mitads they require to produce the desired amount of Injera. Data on which type of plug is available to bakeries is a challenge to collect on a larger scale, especially since many bakeries are not registered at the municipality.

Even though the prototype of the Magic Mitad is not yet developed into a finished project, early testing showed that the electricity savings per unit of production can be more than 50%. This does not only mean that there is a lower requirement in power, but also that on the same connection, more mitads can be utilized. In some cases it could mean that where the connection does not provide enough power for one regular electric mitad, it might work with a mitad that has a lower power requirement. The initial testing also showed that it requires a slightly different cooking technique, but it can be mastered in less than an hour. Therefore once the product is finalized, implementation in bakeries already using electric mitads should have no major issues switching to a plate with a higher efficiency, however since these plates have not been used for an extended period of time and is still in development, future research will show whether other problems can arise.

The switch from biomass mitads to electric mitads can prove to be more problematic, because of the issues mentioned earlier, but the benefits are clear and the government and local organizations can bring major improvements to its people by prioritizing to address the issues hindering implementation of electric cooking.

## 5.3 Health and indoor air pollution

The last research question, related to health and indoor air pollution is discussed in the following section.

### 5.3.1 *"To what extent is the type of Injera stove used in Ethiopian bakeries associated with the concentration of indoor air pollutants?"*

Another aspect of the research is related to indoor air pollution. Another major reason besides climate impact to electrify cooking in Ethiopia is a matter of health risks. Burning biomass in an open fire results in particulate matter emissions, where especially the smaller particles ($PM_{2.5}$ and smaller) are notorious for their health associated risks. Reducing PM exposure for a large part of the population can have major positive effects on public health.

The CO exposure in Lakech bakeries was also much higher than the exposure in electric bakeries, however none of the bakeries come close to the currently known dangerous levels of concentration above 100PPM CO (Prockop & Chichkova, 2007). The WHO suggests that long-term exposure lower concentration are also harmful (WHO, 2004). But the significance of these values is debated, as smokers can have COHb levels of up to 13% and don't exhibit the same effects as described by the WHO (Townsend & Maynard, 2002) and a meta-analysis of research papers has shown that only longer term exposure to concentrations upward of 100ppm or concentrations causing more than 20% COHb are harmful in the long term (Prockop & Chichkova, 2007). However, as explained in section 2.2, CO is a product of incomplete burning, which leads to numerous possible toxic side-products, but they have not been assessed in this study, therefore the significance was not assessed. The effects of long-term $PM_{2.5}$ exposure are clear however, and are likely to cause negative health effects (Atkinson et al., 2014; Kloog et al., 2013; Strak et al., 2012) and should therefore be a priority.

The results from the measurements show that the average exposure in electric bakeries compared to biomass bakeries is significantly lower, and the impact specifically from the stoves becomes even clearer when only data from locations without other PM sources is used. Even with the small sample size, results are clear. A larger sample size could provide more insight into even more precise subtypes, such as the type of mitad used, more precise fuel type, bakery designs. The measurements are time consuming however, and it is also not always clear before the start of a measurement what the parameters of the bakery are, as they may change on short notice (e.g. they might just use the fuel that is available on a certain day). Due to the nature of the measurements, obtaining a large sample size is a time consuming process, therefore obtaining a sample size large enough to be able to divide bakeries into more sub-categories is a challenge.

Outdoor air quality might also be influencing the measurements, and indoor air pollution might influence outdoor air quality. In some cases the results from the electric bakeries are lower than the average outdoor measurements, and also in some of the electric bakeries without another clear visible source of PM, there is still a significant concentration of PM. Whether this is caused by an unnoticed source of PM, collection of PM from outside or something else is an issue worth studying.

In previous studies, indoor air pollution in households in Addis Abeba has been assessed (Pennise et al., 2009; Sanbata et al., 2014). In the research by Sanbata et al., $PM_{2.5}$ concentration in the households was determined using stationary measurements. For biomass fuel a 24 hour geometric mean of $1134\mu g/m^3$ was observed and for users of clean fuel (LPG or electricity) a geometric mean of $335\mu g/m^3$ is observed. Comparing this to the data obtained in the bakeries (geometric means of $394\mu g/m^3$ and $134\mu g/m^3$ respectively), show that in general, professional Injera bakeries have a lower concentration in $PM_{2.5}$ than households where Injera is prepared. In the research by Pennise, the reported mean (no geometric mean is given) in households using traditional stoves is $640\mu g/m^3$ for a 24H time period, compared to $591\mu g/m^3$ in this study.

A study focusing on household emissions from biomass stoves in Rwanda reports a geometric mean of $510\mu g/m^3$ with traditional stoves and $330\mu g/m^3$ for improved biomass stoves (Thomas, Wickramasinghe, Mendis, Roberts, & Foster, 2015). The emissions from the households using improved biomass stoves are similar to the emissions from the biomass stoves examined in this research. However, comparing the different studies is difficult here, as the stoves used to prepare Injera (Mitads) are bigger than a regular stove, and environmental factors in Rwanda may not be the same as in Ethiopia.

The study showing the most similarities with this study is the study by Sanbata et al., and this study shows significantly higher values for indoor air pollution in households compared to the values for indoor air pollution in bakeries obtained in this study. However, other studies report lower values, close to the measured values. To be able to conclude whether bakeries are indeed lower in indoor air pollution, a single study examining both households and bakeries is necessary.

Regarding the results from the CO measurements, there is a significant difference in exposure to CO in Lakech and electric bakeries. In most of the electric bakeries, even the lowest value of 8.7PPM set by the WHO (See section 2.2) is not exceeded, whereas the levels in the Lakech bakeries are usually at least on the level that could theoretically be harmful after 8 hours of exposure. Other sources claim however, that long-term exposure to the low levels measured in this study are not a major health risk, as dangerous symptoms from acute CO poisoning only start arising from 200 ppm (Goldstein et al., 2008; Townsend & Maynard, 2002) where the highest recorded value from this research is 66ppm.

## 5.4 Implications and recommendations for future research

This chapter provides a short summary on the findings of this study and their implications and recommendations regarding future research.

### 5.4.1 Energy and Materials

When the material flow analysis of the stoves was compared to their material and energy use during the use-phase, it became apparent that the material used during the production and maintenance of the stoves is not nearly as significant in climate impact as the fuel/electricity use during its lifetime. Therefore making another material flow analysis specifically for the finished high-efficiency product is not likely to be a useful exercise. The main direction of follow-up research should instead be in implementation and a more diverse geographical spread (within Ethiopia) for implementation of electric mitads. This research shows that the theoretical savings in primary energy use and national GHG emissions could be significant, but lacks in assessment of practical application outside of Addis Abeba.

Another aspect that has not been touched on in this study, is cost effectiveness. As Ethiopia is a developing country, economic costs and benefits might have a higher priority than climate and health. The total economic benefits from both health and climate/energy savings should therefore be expressed in economic value to underline the benefits of a transition even more.

### 5.4.2 Indoor air pollution

This research indicates that the air in bakeries is cleaner in terms of $PM_{2.5}$ than households using the same cooking methods compared to another study done in Addis Abeba (Sanbata et al., 2014). It also shows that bakeries using electric mitads have lower exposure to $PM_{2.5}$ than their biomass counterparts, as is to be expected. However in future research, there should also be a focus on other sources of PM, as the electric mitads themselves should not emit any PM at all, but concentrations in the electric bakeries can still be hazardous for respiratory health. One possible explanation is that the dough to make the Injera produces $PM_{2.5}$ when prepared on a mitad, this should be investigated.

In future research an intervention using a high-efficiency mitad could shed more light on the challenges of implementation and provide a more direct 1 on 1 comparison without environmental factors playing a role in the measurements. Expanding the research to rural areas and other cities will also provide a better insight on what national policy should be for the transition to cleaner cooking.

### 5.4.3 General implications and recommendations

In this study, the main focus has been on physical effects of the transition. Social, political and economic factors have not been discussed in this research, but these aspects are essential to fully describe any transition in society. As Ethiopia is still a developing country where money is scarce, decision-making is largely driven by direct costs and benefits. This paper expresses the improvements in terms energy efficiency and health which can be compared to other projects in value, so the best investment opportunities for the country can be implemented.

# 6 Conclusion

This study set out to assess the impact of preparation of the number one staple food of Ethiopia, the Injera. As many of the Injera stoves (also called mitads) are fired using solid biomass fuel, low efficiency and indoor air pollution are common. The aim of this research was to compare several baking stoves (Mitads) on the impact in terms of primary energy use and greenhouse gas emissions, implications for the national electricity generation sector, barriers to implementation of a large-scale electrification in the cooking sector and their impact on exposure to indoor air pollution on bakery employees. The data was collected in the field by direct measurements of energy use and indoor air pollution, in conjunction with literature research and a survey. These tools and methods were used to obtain an answer to the main research question of this research:

*"What is the impact of the implementation of efficient electric stoves on the Ethiopian national energy and material consumption and indoor air pollution inside bakeries?"*

The key findings in this research can be split into two categories: Energy and climate related findings, and findings regarding indoor air pollution.

The key findings regarding energy and climate are:

1. The relative emissions that can be attributed to material use in the cooking plates are negligible compared to the impact of their fuel use
2. Lifetime emission savings per mitad are on average more than 95% when replaced by a regular electric mitad, and more than 98% for the high-efficiency electric mitad. When scaled up to a national scale, this transition can save several megatons of $CO_2$ emissions

3. Ethiopia’s electricity supply exceeds current demand when the major Dam project is finished, even if a large scale transition to electric cooking is realized. Even though aggregated energy supply should be sufficient, local electricity networks are still of low quality and a large portion of the country still does not have access to electricity

It can be concluded from these findings that regarding a climate and energy perspective, the improvement potential is massive. The main barrier to implementation in the electricity supply is the low quality of the local electricity networks and unavailability of connections in many regions of the country.

The key findings regarding indoor air pollution and health are:

1. Bakeries show a lower $PM_{2.5}$ concentration than households using the same type of stove
2. Personal exposure to $PM_{2.5}$ from indoor air pollution in bakeries using biomass mitads is approximately 2.5 times higher than exposure in electric bakeries. When the average bakery indoor air pollution is considered, biomass bakery concentration is more than 3 times higher

These massive improvements in indoor air pollution could have a major positive effect on public health if a large scale transition is realized. If the improvement from Lakech bakeries without other sources of $PM_{2.5}$ to electric bakeries without other sources of $PM_{2.5}$ is considered (326 $\mu g/m^3$ to 175$\mu g/m^3$) and the odds ratio of 1.4 increase in PM related disease per 10$\mu g/m^3$ from section 2.2 is used, prevalence of PM exposure related disease could be reduced by a factor of 160.

Large scale implementation of electric cooking could have a major positive effect on material and energy use in Ethiopia as well as indoor air pollution in Ethiopia. The savings from more efficient electric stoves compared to regular models are less significant when it comes to climate impact and non-existent when it comes to indoor air pollution. However, their implementation is easier due their lower power demand from the network, making them more viable for large scale implementation in Ethiopia, a country where the quality of the electricity network is low.

### *Final thoughts from the author*

*Conducting multidisciplinary research is a challenging endeavour. Delivering a product that satisfies the requirements from the different disciplines involved can sometimes lead to contradictions. Approaches that are deemed essential by experts in one discipline, might be regarded as incorrect by experts from other disciplines. However, the advantages it can bring by exposing synergies between disciplines is invaluable. As this research shows, a single solution (replacing biomass stoves with electric stoves) can bring major benefits to both public health and climate. As opposed to the monodisciplinary approach, the multidisciplinary approach allows for solutions from one sector to be tested for problems in another sector, possibly generating a multitude of the benefit initially expected from the solution.*

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# Appendix

## I. Survey (English version)

# Survey of air quality, bakery conditions and respiratory health effects in women working in Injera bakeries

1 General information

1.1 Age : ___

1.2 Gender: Male/Female

1.3 Level of education (completed):

• No schooling completed | • Primary/elementary school | • High school | • Trade/technical school | • Bachelor’s degree | • Master’s degree or higher

Or

Years of (formal) education:

____

1.4 What is your monthly income (in Ethiopian Birr): __________

1.5 Current marital status:

• Married | • Divorced | • Widowed | • Single

1.6 Have you ever consumed alcoholic beverages?

• Yes | • No

1.7 Do you regularly consume alcoholic beverages?

• Yes | • No

1.8 Have you ever smoked cigarettes?

• Yes | • No

1.9 Do you currently smoke cigarettes? (If not, jump to question 1.12)

• Yes | • No

1.10 For how long do you smoke cigarettes? (in years):

__________

1.11 How many • cigarettes/ • packs of cigarettes do you smoke per day? __________

1.12 If you smoked in the past, but not anymore, for how long? (in years): __________

1.13 How many • cigarettes/ • packs of cigarettes did you smoke per day? __________

1.14 Do you share a living room with someone who smokes?

• Yes | • No

1.15 What type of fuel is used for cooking/baking at home?

• Wood/other biomass | • Charcoal | • Kerosene/other liquid fuel | • Electricity

| • Other: ____________________________

1.16 Have you ever chewed Khat?

• Yes | • No

1.17 Do you currently chew Khat?

• Yes | • No

2 Working conditions

2.1 How many hours a day do you spend in the bakery baking Injera?

_____________

2.2 How many days a week do you work?

• 1 | • 2 | • 3 | • 4 | • 5 | • 6 | • 7

2.3 How many years have you been involved in commercial Injera baking?

_____________

2.4 Do you usually take a break (for drinking/eating) while baking?

• Yes | • No

2.5 If yes, for how many hours per day?

_____________

3 Bakery conditions

3.1 How many Injeras are produced per stove per day?

_____

3.2 How many stoves are generally in use in the bakery?

_____

3.3 What type of fuel is used for the stoves? (if more than one type, only mark the type most often used)

• Wood/other biomass | • Charcoal | • Kerosene/other liquid fuel | • Electricity | • Cow dung| • Other:

____________________________

3.4 What are the average operating hours of the stoves per day?

____

3.5 How much fuel is used per stove per day (estimated)?

_______________ Kg/Liter/money paid

3.6 Only if electric stoves are used: Are the stoves powered off during the working day? If not, how long are they powered on, on average?

• Yes • 1/4th of the time • 1/3d of the time

• Half the time • 3/4 the time • Almost the entire day

3.7 What type of roof is used for the bakery building?

• Wood | • Concrete | • Mud | • Stone | • Other: ____________________________

3.8 What type of floor is used for the bakery building?

• Wood | • Concrete | • Mud | • Stone | • Other: ____________________________

3.9 What type of walls are used for the bakery building?

• Wood | • Concrete | • Mud | • Stone | • Other: ____________________________

3.10 Are there any ventilation measures installed? (For example: Vents, filtering systems, fans)

• No | • Yes:______________________________________

4 Air quality / respiratory symptoms

4.1 Do you usually cough on most days for 3 consecutive months or more during the past 12 months?

• Yes | • No

4.2 Do you bring up phlegm on most days for 3 consecutive months or more during the 12 months?

• Yes | • No

4.3 Does your chest ever sound wheezy or whistling, apart from colds?

• Yes | • No

4.4 Do you have to stop for breath when walking at your own pace on level ground?

• Yes | • No

4.5 Have you ever been diagnosed with asthma by a physician?

• Yes | • No if Yes, what is the year of diagnosis? ____

4.6 Have you ever been diagnosed with pulmonary Tuberculosis by a physician?

• Yes | • No if Yes, what is the year of diagnosis? ____

4.7 Have you ever been diagnosed with pneumonia by a physician?

• Yes | • No if Yes, what is the year of diagnosis? ____

4.8 Do you have any nasal allergies including hay fever?

• Yes | • No

4.9 Did you have one or more episodes of rhinitis in the past 12 months?

• Yes | • No

4.10 Have you ever had eczema or any kind of skin allergy?

• Yes | • No

4.11 Have you had one or more episodes of Eczema in the past 12 months?

• Yes | • No

Thank you for taking the time to fill out this survey!

## II. Used tools, measures and metrics

The following measures and metrics have been used as main indicators in this research:

- kWh/W used by the stoves
    - In bakeries using electric mitads, kWh (per unit of production) is the main indicator for energy use and because of this it is also an indirect indicator of climate impact when combined with the emission factor of electricity in Ethiopia. To measure this, two different methods were used, depending on the situation in the bakery. When there was a regular European wall-plug available to plug in a mitad, the direct kWh meter Christ Elektronik CLM210 (Figure 14) was used. When this is not the case the power was measured by multiplying the current (A) with the voltage (V) measured using a Trotec BE40 clamp meter (Figure 13).

FIGURE 14 TROTEC BE40

FIGURE 13 CHRIST ELEKTRONIK CLM210

    Using a kWh meter is a proven method, which has been used in many earlier researches assessing energy use of household appliances (Bertoldi, Ricci, & de Almeida, 2012; Pihala, 1998; Ross & Meier, 2002). The method of using a clamp meter is less well known, and also requires some extra steps as this method does not directly provide a value in kWh. This method is used in some researches because of its advantages in terms of safety and wider usability (Kamil, Shalf, & Strohmaier, 2008; Liu, 2010). The values that can be obtained from the clamp meter are in Watt when Amperes and Volts are multiplied. This means that to get a value in kWh, the average of the value of W over the time of baking has to be calculated by combining multiple measurements.

- KG fuel used by the stoves
    - When a bakery is not cooking on electric mitads, the main indicator for energy use is the amount and type of fuel used for cooking, and again an indirect indicator for climate impact when multiplied with the emission intensity of the used fuels. The weight of the fuel is measured with a portable digital scale of the brand BASETech, model No. LS-40S (Figure 15) for weights up to 40kg. For heavier weights a local scale is used where available, or the weight is split into even parts weighing less than 40kg and then measured with the BASETech scale. When this method is applied, it is important that it is correctly documented which fuel is used, so that the correct caloric value can be applied to determine the amount of energy used.

**FIGURE 15 BASETECH LS-40S**

- Material and energy used in a stove’s lifecycle
    - To obtain the materials used in the lifecycle of a mitad, producers and users were interviewed about materials used in the production and extra materials needed during its use phase. The different resources used all have their associated energies to be turned into manufacturing materials, and the assembly of the mitads also requires energy. All these energies are added to the energy used during the use-phase.
- Climate impact
    - The total climate impact (and possible improvement in this area) is assessed firstly by translating the energy and materials used in their lifecycle into a value of $CO_2$ impact, making use of Ethiopia’s emission factor for electricity, and the emissions from the solid fuels used and material production and manufacturing emissions. Secondly, these

impacts per stove are combined with data on the stoves that are currently in use, so the current impact and possible improvement can be determined in terms of $CO_2$.

- $PM_{2.5}$ concentration and absolute exposure
    - $PM_{2.5}$ concentration is one of the two indicators chosen to assess indoor air pollution in bakeries. To measure the $PM_{2.5}$ concentration in the bakeries, along with the absolute exposure during a working day for the women involved in baking Injera a system utilizing a combination of pumps (BGI 400-S, Figure 16), batteries (custom made Ni-MH batteries), SKC cyclones and Teflon filters. This system gathers only $PM_{2.5}$ and smaller particles for the duration of the measurement on the Teflon filters, providing both a measurement on the total exposure for a working shift (Mass/time) as well as a concentration (Mass/volume of air). This method is also a standard method used in other research assessing air pollution in cook stove related (intervention) studies (Clark et al., 2010; Li et al., 2011)

**FIGURE 16 BGI 400-S AIRPUMP**

- CO concentration and Personal CO exposure
    - Personal CO exposure and concentration are measured using passive diffusion tubes (type 1DL by Gastec, Figure 17) and are reported in parts per million (ppm). The functioning of the passive diffusion tubes is based on the change in colour of the tube whenever CO passes through. The length of the colour stain is proportional to the average CO-exposure in ppm concentration during the working shift. CO tubes are read on site after the working day, stored in a closed and cool container, and read blind again within 24 hours (Rollin et al., 2004)

FIGURE 17 AN EXPOSED CO GASTEC DOSITUBE (DISCOULORATION JUST ABOVE 200PPM*H)

- Bakery characteristics
    - Bakery characteristics are assessed by obtaining the details on the following metrics:
        - Dimensions of the bakery – measured using measuring tape
        - Materials used for floor, walls and roof
        - Presence and type of ventilation measures
        - Presence of other smoke/pollution producing elements
        - Amount, type and usage pattern of mitads
    - These metrics are asked in a survey which is attached in the appendix, section I and where possible crosschecked with observation by the researcher.
- Health impact*
    - Health impact is not assessed in this research, but data is collected using survey questions, which can also be found in the survey in section I.a

## III. Procedures for placement and timing of measuring equipment

- The personal measurement backpack is first worn and set-up, and only when the mitad is turned on or the first biomass is lit, the measurement is started. The nozzle is clipped on at shoulder height, and the tube is connected over the shoulder of the subject.
- The bakery measurement is placed centrally in the bakery if possible, with the nozzle at 1.40-1.60m height. If central placement is not possible, a distance of at least 2m from the closest mitad is chosen to have a reliable measurement of the concentration in the room, not just in the vicinity of the stoves.
- The outdoor measurement is placed in sight from the bakery for safety, avoiding direct external PM sources where possible, also at 1.40-1.60m height.
- Where possible the pumps were started simultaneously. Due to different situations in each bakery this was often not possible. To make sure all results are comparable, total runtime for all

the pumps is recorded. By comparing the runtime with the total time a normal work shift entails, total work shift exposure for each of the measurements can be calculated.

- Every measurement is conducted *in duplo*, repeating the same measurement in the same bakery, as soon as possible, but at least within a week time.
- Measurements for the whole work shift are preferred, but due to the nature of the measurements this is often not possible. In any event, a minimum exposure time of 3 hours is aimed for, especially when exposure is expected to be low, such as in Electric bakeries.
- In the event of a power cut in an electric bakery, measuring continues unless the power cut lasts for longer than half an hour. If the exposure time is not high enough, repeat the measurements until a good sample is obtained.

## IV. Cooperation of the subjects

To convince the owners and employees of the bakeries to participate in the research, firstly the goal and benefits of the research are explained to them. The cooperation with the Addis Ababa University and possible benefits in terms of health and climate for the people in Ethiopia are pointed out and the contents and workings of the measuring equipment were demonstrated.

For the electric bakeries, the extra bonus of being able to tell them directly how much electricity is used per Injera is also a convincing argument for the bigger, more industrial bakeries. Secondly, the owners of the bakeries were given the opportunity to test a new high-efficiency mitad in their bakery, and thirdly, a small compensation for the time and effort the employees spent on the research was given (200 birr).

## V. Detailed dimensions for each stove type and extra data

TABLE 14 GENERAL DIMENSIONS OF THE STUDIED CLAY/LAKECH MITAD

| Dimension of interest | Size | Unit |
|---|---|---|
| Outer diameter | 70 | cm |
| Cooking plate diameter | 58 | cm |
| Height (excluding table) | 17 | cm |
| Clay plate weight | 4 to 8 | kg |
| Clay isolation weight (case study) | 40.1 | kg |
| Steel structure weight (case study, excluding table) | 6.25 | kg |
| Total weight without plate | 46.33 | kg |

TABLE 15 QUOTES ON RECYCLING NUMBERS

| Mitad type | Part of the mitad | Recycling | Explanation |
|---|---|---|---|
| **Lakech** | Plate | 0% | "Plates are not recycled, because once the clay plate is baked and broken, there is currently no system in place to replace the clay, also because it is very cheap." –Mulugeta from Mulugeta bakery |
| | Frame | 0% | "The frame is used until it is broken or rusted until it no longer has any value, sometimes the iron is collected, but we don't know where it ends up." – Lakech stove manufacturer in Gulele |
| **Electric** | Plate | 0% | See Lakech plate |
| | Frame | 0% | See Lakech frame |
| | Isolation | ~80% | "The isolation can either be completely reused or is thrown away, 'most of the time' (4 out of 5) it can be reused." – Meraf from Mama fresh Injera |
| | Wire | ~90% | "The wire usually breaks at weak points, a small piece of wire is then soldered on at the weak point and the rest of the wire is melted to be used as wire again, but small pieces don't get re-used." – Meraf from Mama fresh Injera |

TABLE 16 DETAILED DIMENSIONS OF CLAY PARTS IN STANDARD LAKECH MITAD

| Clay parts | Size (cm) |
|---|---|
| Outer mitad diameter | 70 |
| Inner mitad diameter | 58 |
| Clay isolation | 5.8 |
| Height outside | 17 |
| Height inside | 15 |
| Ventilation gap height | 12 |
| Ventilation gap width | 17 |
| Input hole height | 13 |
| Input hole width | 26 |
| Bottom clay thickness | 1.0 |

TABLE 17 DIMENSIONS OF STEEL PARTS IN STANDARD LAKECH MITAD

| Steel parts | Size (cm) |
|---|---|
| Sheet metal thickness | 0.060 |
| Inside edge width | 2.0 |
| Outside edge width | 4.8 |
| Input hole plate width (including flaps) | 32 |

| | |
|---|---|
| Input hole protector strip length | 3.0 |
| Input hole protector strip width | 60 |
| Bottom diameter | 70 |
| Round sides height | 17 |
| Round sides length (circumference - input and ventilation holes) | 163 |
| Steel on top width | 16 |
| Steel on top length | 201 |
| Chimney block width | 25 |
| Chimney block height | 17 |
| Chimney block depth | 17 |
| Chimney diameter | 15 |
| (Built-in) Chimney length | 20 |

Figure 18 New, unused Lakech mitad (without clay plate, own picture)

## Electric mitad

Table 18 General dimensions of the studied electric mitad

| General dimensions | Size | Unit |
|---|---|---|
| Outer diameter | 68 | cm |
| Cooking plate diameter | 58 | cm |
| Height | 10 | cm |
| Wire weight | 0.038 | kg |
| Isolation weight | 1.02 | kg |

| | | |
|---|---|---|
| Clay plate weight | 9.5 | kg |
| Body weight | 3.22 | kg |
| Total weight | 13.8 | kg |

**FIGURE 19 EXAMPLE OF A COMMONLY USED ELECTRIC MITAD** (Energypedia, 2014)

## Magic mitad

**TABLE 19 GENERAL DIMENSIONS OF THE "MAGIC MITAD" (UNFINISHED PROTOTYPE)**

| General dimensions | | |
|---|---|---|
| Outer diameter | 57 | cm |
| Cooking plate diameter | 53 | cm |

| | | |
|---|---|---|
| Height | 10 | cm |
| Isolation weight | ? | Kg |
| Ceramic/glass plate weight | ? | Kg |
| Body weight | ? | Kg |
| Total weight with plate, without table | ? | Kg |

**TABLE 20 MATERIALS AND THEIR ASSOCIATED EMBODIED ENERGY AND CARBON INTENSITY** (Hammond & Jones, 2006)

| Material | Energy | Carbon intensity |
|---|---|---|
| | MJ/kg | Kg $CO_2$ per kg material |
| Brick(clay) | 3 | 0.24 |
| Steel | 20.1 | 1.37 |
| Glass wool insulation | 28 | 1.35 |